The Affordances of Robotic Production

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ABSTRACT: The paper delves into the unique affordances of robotic production in architecture and their growing potential to reshape the discipline when paired with Artificial Intelligence (AI). Over the past decade, a range of robots have been engaged within architectural production processes including fabrication, assembly, construction and real time responsiveness to materials and situational variances. The paper emphasizes the differences between the two-decade old paradigm of digital fabrication and the emerging paradigm of what we have termed and defined as robotic production.

KEYWORDS: Robotics; Manufacturing; Robotic Production; Computation

INTRODUCTION

Over the past twelve years, we have witnessed a shift in full force through the rise of robotics, and more specifically, robotic production within the discourse of architecture and design. Driven through interdisciplinary collaborations and corporate/government partnerships and the advancing of AI, we are witnessing the moving of robots from far-off factory floors into classrooms, studios, laboratories, fabrication shops, design firms and more recently, out onto streets (Daas and Wit 2018). Rapidly becoming indispensable tools and collaborators for designers, architects and fabricators, robots are aiding designers in revolutionizing our known world through the redefinition of materials, processes as well as in how space is imagined, made, assembled, constructed and sustained (Bloem, Van Doorn et al. 2014, Gramazio and Kohler 2014, Rouse, Villagaray-Carski et al. 2015). Whether at the scale of the component, artifact or more recently the building, designers are quickly beginning to understand and exploit the affordances associated with what we are defining as "robotic production." In this paper we examine the affordances of robotic production through the lens of various typologies of robotics, and their potential for rapid evolution and assimilation through the integration of AI.

Although over the past several years we have witnessed a rapidly increasing number of robotically produced projects and typologies appear within the discourse of architectural research, we have yet to see the development of a comprehensive framing of how these projects, the tools developed/used as well as how the affordances of robotics are furthering the discourse of architecture and design. For this reason, we often witness researchers struggling to initiate and complete robotics research that in most cases, has already been investigated, tested and completed by others. We also see a lack of coherence and understanding of what constitutes robotics research in architecture, especially when viewed from the outside by other disciplines. Expanding on a taxonomy laid out in or recent book "Towards a Robotic Architecture" which describes (Daas and Wit 2018) the current state of architectural robotics, this article aims to further document, categorize and explain how robots can/are reshaping how designers, architects and fabricators are approaching design.

1.0 WHAT ARE ROBOTS?

The simplest definition of a robot is physical agency that can sense, think and respond to its environment. Robots are often termed embodied intelligence, which distinguishes them from computational agents that operate solely within virtual environments without physical repercussions. Robots are also called "computers turned inside out."(Long 2012) The stereotypical image of a robot is either a humanoid or an industrial articulated arm robot. From this standpoint though, we can see how most tools we currently define as robots do not actually embody the necessary intelligence nor sensing abilities to be considered a true robot in fields outside of architecture. For instance, many factory based industrial robots function more similarly to the computer numerically controlled (CNC) machines such as CNC mills, laser cutters or water jet cutters that we have grown accustomed to in digital fabrication paradigm. These tools are automated, preprogramed, and do not respond to changing environments, materials or designs without human input. Hence, error compounds if the tool is left unattended. Despite this, robots are already more pervasive in our society than we realize.

Robots come in many forms:

Table 1: Morphological Framework: Robots considered by form (Daas 2018)

A. Biomorphic	**B. Mechanomorphic**	**C. Polymorphic**	**D. Amorphic**
Robots that resemble animals, humans, insects, trees and other living beings.	Robots that resemble machines or embody mechanical characteristics in their form.	Robots that assume different forms.	Robots with no identifiable form.
RUR, iRobot, C-3PO, AIBO toy robot pets, ASIMO	R2D2 (Star Wars), Wall-E, Roomba vacuum cleaners, drones, industrial robots, automated farming machines	Transformers, TARS (Interstellar)	HAL 9000 robot ship

Another way to look at robots is through the role robots play in the design and construction process:

Table 2: Process Framework: Role of robotics in architecture (Daas 2018)

A. Robots for design	**B. Robots for fabrication**	**C. Robots for construction**	**D. Robots for operation**
Robots used in the design process, to inform the design process, observation and prototyping.	Robots used for bespoke or mass-customized manufacturing off-site.	Robots employed in the building construction process working alongside human workers.	Robots with autonomous, teleoperated or semi-autonomous robots integrated into building operational tasks such as surveillance, hazard mitigation, maintenance, etc.

Robots as tools have found their way into architecture predominantly by way of industrial manufacturing, similar to the tools associated with digital fabrication. However, robots come in different forms and formats. Some predefined, others created by designers for specific tasks. Industrial robots, mobile robots, drones, humanoids and custom fabricated non-standard autonomous machines are redefining how designers look at and solve complex problems within their design, manufacture and assembly processes. Whereas in digital fabrication designers were constrained by fixed toolsets and preprogrammed numerical controls, as seen in many recent examples around the world, robotic production opens new avenues of making.

Traditional digital fabrication tools allowed for the realization of digitally designed forms into physical artifacts by means of a pallet of standardized material systems, manipulated through the implementation of numerically controlled devices, robotics now allows for emergence of a completely new typology of forms and structures. A typology not centered around individual, pre-determined machine-based operations (i.e. geometry, tool pathing, fabrication, etc.), but rather based on holistic and/or haptic approaches where design, computation, materials, manufacture and assembly function as a single continuous process, with the inherent ability to be manipulated, redefined and simultaneously verified by human or machine at any point throughout the design and production process in real- time. This bridging of the realms of design, simulation, production, feedback and revision creates new opportunities where the lines between digital environments, machines and humans are blurred.

2.0 THE SPECTRUM OF AFFORDANCES

Following James J. Gibson's framework, affordance could be understood as a particular relationship between an entity and its environment by virtue of the entity's innate abilities to effect change. Affordance points to the space of possibilities offered by the physical, kinetic, cognitive, formal and positional abilities of an entity. In the case of robots, its form, adaptability, maneuverability, malleability, kinetic abilities and levels of artificial intelligence all point to a set of affordances. The affordances of robotics are distinctive and different from other kinds of tools such as digital fabrication technologies exemplified by CNC mills, 3D printers, laser cutters, etc.

Unlike digital fabrication, the list of affordances of robotic production is ever expanding because of the inherent flexibility within robotic systems. Milling, drilling, cutting, carving, welding, printing, photographing, spatial positioning, bending, brick laying, sewing, folding, fastening, forming, assembling, weaving, spraying, dynamic casting and any number of other pre-existing or novel tasks can be accomplished through the implementation of different effectors. Although these affordances allow for the expansion of the designer's production capabilities, they currently lie within the same realm as digital fabrication, rather than pushing beyond the pretexts that were established by previous CNC based systems. As Mark Cabrinha describes,

> Conventions of use in digital fabrication have already formed that instrumentalize these tools as printers of form without engaging material as a medium in itself. These conventions of use amplify the tendency in digital design to output to material at the end stage of design, rather than the preparatory and evaluate role of digital fabrication as material feedback into the design process. (Cabrinha 2010)

The problem with the default affordances of robotic production are similar to those with digital fabrication. They can tend to be fixed to a specific standardized tool, (i.e. the articulated robot arm), and are applied similarly in most applications without any awareness of, or feedback to the given materials, their programmer/collaborator and their environment.

Where robotic production sets itself apart from previous tools and techniques is with the integration of mobility, machine customization, machine learning, haptic feedback/responsiveness/programming, awareness and artificial intelligence into a continuous design/production loop. (Daas and Wit 2018) Previous methods of fabrication were based around the simple pre-programming of a machine through numerical code. Robots though, through the application of internal or external sensors, can begin to not only verify their work, but also begin to situate and understand themselves within space without human intervention. This can afford robots the ability to adapt in real-time to given, changing or unknown conditions such as variations in material properties, human or externalized feedback or even changes within the robots' work area without needing the designer to manually reprogram the robot and their work paths. This flexibility allows for robots to move from the realm of mere tools of production, into the realm of active collaborators, throughout the design and production process.

Figure 1: Innochain: Adaptive Robotic Carving. Source: (Giulio Brugnaro)

These affordances can be witnessed in research and projects realized in projects such as "A Bridge Too Far" by Paul Nicholas discussed below (Zwierzycki, Nicholas et al. 2018); "Innochain // Adaptive robotic carving" by Giulio Brugnaro where Artificial Neural Networks are leveraged to train adaptive robotic systems in the carving of wood based on human craft (Brugnaro and Hanna 2017); the “ICD/ITKE Pavilion 2014-15” by the ICD/ITKE Institutes at the University of Stuttgart where real-time feedback between sensor data, software and robot allow for the placing of carbon fiber roving’s on the interior of a constantly changing surface of a large-scale ETFE balloon (Doerstelmann, Knippers et al. 2015); “Force-Adaptive Hot Wire Cutting” by Gramazio Kohler Research where a robot team consisting of two robots work together to coordinate the movement of a hot wire cutter with the ability to adapt wire tension based on the creation of a desired ruled or doubly curved surface as well as to the resistance of a given cutting material (Rust, David Jenny et al. 2016); “On-site Robotic Construction” also by Gramazio Kohler Research which investigates adaptive building systems for robotic production on-site in uncertain environments (Dörfler, Sandy et al. 2016); among others.

Although currently production robotics are typically viewed through the lens of the traditional industrial robot, there is a rapidly expanding realm of semi-autonomous or fully autonomous mobile/non-standardized robotic systems that are being developed and implemented, expanding the potential affordances of robotics within design and construction. While typical robotic production methods are limited to a fixed area such as a fabrication shop, these mobile robots will allow for autonomous navigation and production not only on the ground level of the site, but also on walls, navigating upstairs or even flying overhead.

Figure 2: Mobile Robotic Fabrication System for Filament Structures. By Maria Yablonina. @ICD. Courtesy ICD.

These affordances can be witnessed in research and projects realized through the use of autonomous fabrication robots such as those utilized in “Swarmscapers” completed within the Digital Craft Lab at the California College of the Arts where swarms of custom built autonomous mobile robots can 3D print structures in difficult terrain using locally harvested materials (Kudless 2016); the “Minibuilders” project completed at the IAAC where three custom fabricated robots (wheeled, gripper and wall climber) work sequentially, controlled through sensors and positioning data to create structures much larger than themselves (Nan 2015); the “Mobile Robotic Fabrication System for Filament Structures” by Maria Yablonina at the ICD institute at the University of Stuttgart where a custom wall climbing robot was created that could, through sensing, navigate and compute paths through unpredictable vertical environments while winding carbon fiber roving’s between intersecting walls (Yablonina, Prado et al. 2017); which looks at the use of large-scale autonomous cable-based robots for on-site construction with the ability to adapt their trajectories and work paths based on live sensor feedback taken from ever changing construction site conditions over long periods of time “SpideRobot” (Sousa, Palop et al. 2016); the mobile, legged construction co-robot “OSCR” prototypes that can navigate complex terrain and even climb stairs as they assist in the human brick laying process (Silver 2018); or even with the aerial rope bridge building drones (i.e. drones) utilized in “Aerial Construction” (Mirjan, Augugliaro et al. 2016), or the 18' tall autonomous foam block laying drones utilized in the project "Flight Assembled Architecture" (Gramazio, Kohler et al. 2012) and most recently in the ICD/ITKE Pavilion 2016-17 which utilizes a drone to span carbon fiber rovings between two articulated arm robots. (Doerstelmann, Knippers et al. 2015).

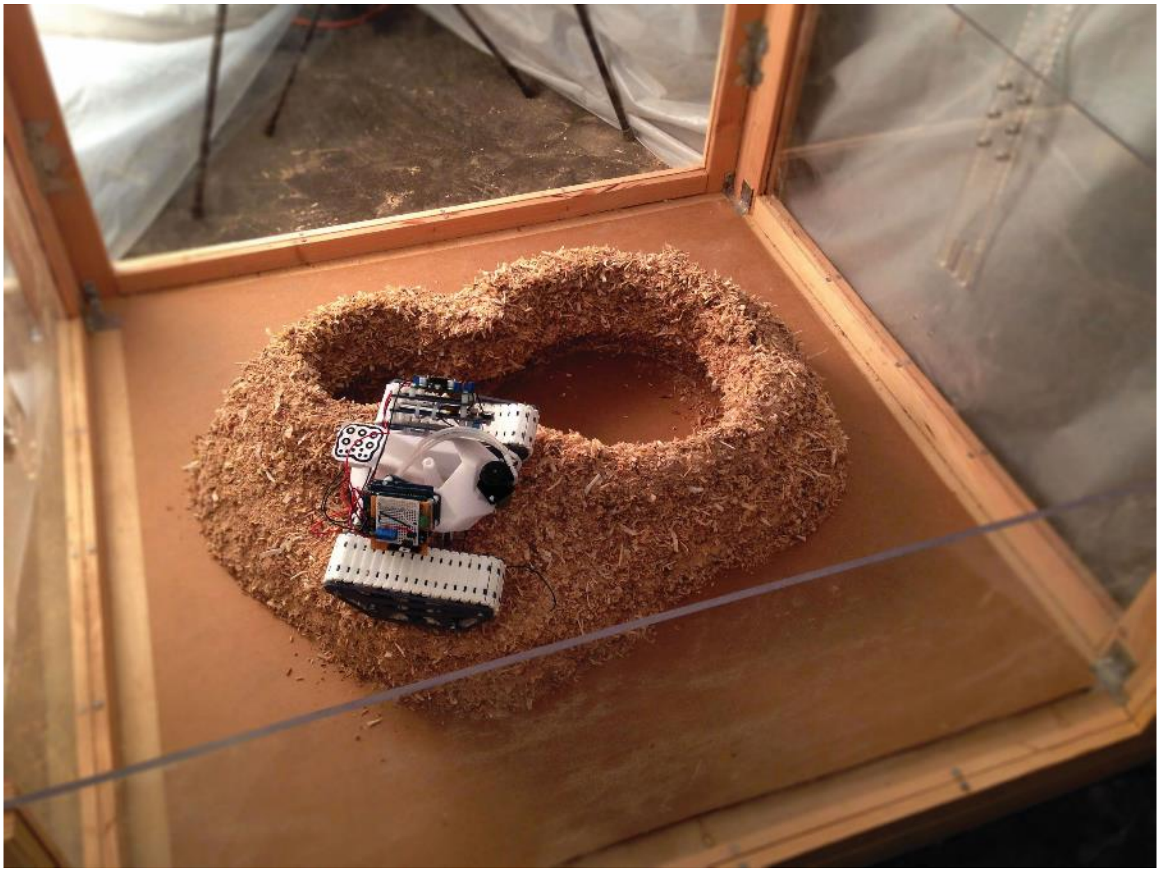

Figure 3: Swarmscapers. Source: Alan Cation, Clayton Muhleman and Adithi Satish, CCA. Instructor: Jason Kelly Johnson

3.0 DUETERO CUSTOMIZATION

Unlike traditional machines utilized in digital fabrication that are limited to specified end effectors (drill bits, print nozzles, etc.), industrial robots can work with virtually any tool attached to them—analog or digital, pre-defined or custom built—allowing for a new level of flexibility in prototyping and fabrication. Simply attached to the end of the robot, defined within the computational model, and linked into the robots control hardware if necessary, these "end effectors" allow for the rapid manual, programmed or automatic reconfiguration of the robot as well as its fabrication and assembly capabilities.

In addition to flexibility afforded by end effectors, additional degrees of freedom can simply be added to a robotic production system allowing for the expansion of a robot's capabilities. Additional axes can come in many forms, including but not limited to the addition of an external secondary device such as a 2-axis positioner the addition of additional robot arms working together as a robo-team, adding degrees of freedom and expanding the working area. Degrees of freedom can also be added to the robot directly by fastening the robot to another axis such as a vertical gantry expanding the Z - direction as seen in the project "Rock Print" by Gramazio and Kohler Research with the Self-Assembly Lab (Aejmelaeus-Lindström, Thoma et al. 2017); to a linear track expanding the work area in the X & Y directions as seen the project "Periscope: Foam Tower" by Matter Design (Clifford and McGee 2011); to a multi-axis gantry as seen in the ETH Zurich's new "Robotic Fabrication Laboratory" (Gramazio Kohler Research 2018); or to a mobile platform as was previously mentioned with Gramazio and Kohler Research's project "On-site Mobile Construction" (Dörfler, Sandy et al. 2016).

Mass customization was a phrase used with a range of traditional digital fabrication technologies. Mass customization refers to the ability to customize the end product without incurring costs throughout the manufacturing process. With robotic production, we not only achieve mass customization, but gain the ability to customize the manufacturing process itself, which unleashes many new possibilities. Moving beyond digital fabrication, we can see the affordances of robotic production systems expand even further, allowing for an exponential shift in scale, as well as the blurring between the processes of design, manufacture and assembly.

4.0 TOWARDS AI AND INTELLIGENT PRODUCTION

Just as computers, computation and digital/robotic production have reshaped how architects currently design, build and view the world, recent advances in AI assisted robotic production within the realms of design, production and post-occupancy will no doubt and opens the doors for virtually unprecedented possibilities that broaden the affordances of robots. For the robots to have awareness of immediate context, their sense making abilities provide us a limitless palette of affordances that we are only now beginning to understand in architecture.

At the scale of construction, we are beginning to witness the growing integration of robotics driven by AI in countries such as Japan. Fueled by the countries shrinking workforce teamed with their demands for a high level of construction quality, robots are not only being utilized for their ability to interact with, and aid human workers with complex tasks in real-time, (Yasuhara 2017) but have also began to appear being utilized for the large-scale control of construction sites. For instance, Komatsu has integrated ground scanning drones into construction sites in Tokyo, which relay data to semi-autonomous diggers which sculpt the construction site. (Firth 2018) The merging of real-time data collection, machine learning and robotic production will no doubt have the ability to reshape how buildings are assembled but are currently still focused around current production techniques. Where architectural production can be redefined can come through the utilizing of AI for the redefining of architectural materials, fabrication and assembly methodologies.

For instance, the project “A Bridge Too Far”, by Paul Nicholas (Nicholas, Zwierzycki et al. 2017) employs machine learning, neural nets, real time sensing and a continual feedback loop that inform the robot arms to adaptively form sheet metal. Nicholas’s project goes well beyond the typical digital fabrication methods that rely on predictive models to translate desired forms into material realities. Instead, he employs real time measurement of material deflection and thickness using 3D scanning. He integrates sensory data into the feedback loop of modeling and fabrication. The more the machine operates on sheet metal, the more the model learns the material conditions and is able to predict a more accurate material response, which informs the tool paths and operating parameters. Given all the advances taking place in AI applications virtually in every field, we can expect some breakthroughs in broad applications in robotic production of architecture.

CONCLUSIONS

Understood through the framework of affordances, robotics open up a whole new world of possibilities in architecture that were previously not available. The complexity of robotics can be framed through their form, their physical or cognitive agencies, through their relationship to humans and their environments, and through their adaptability. Understandably we are at the beginning of comprehending robotic production and artificial intelligence applications in architecture. The combination of these AI and robotics technologies opens new avenues of designing, making, and operating our built environment.

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Finding Perfection in Imperfection: A Case Study in Designing Industrial Solid Waste using a Circular Economy Approach

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ABSTRACT: The United States' manufacturing industry generates approximately 7.6 billion tons of non-hazardous solid waste each year, a significant portion of which is either recyclable or reusable. Emerging ecosystem concepts such as cradle-to-cradle, design for disassembly, sustainable manufacturing, and most recently circular economy, are promoting the reusing or recycling of non-hazardous industrial waste. Empirical evidence suggests that there are significant economic, environmental, and social benefits to reusing industrial waste rather than recycling it. This paper presents and discusses and synthesis six speculative case studies in designing new solutions for building skins made from standard automobile stamping operations. The goal of the experiment was to transform the linear approach in making building components, particularly, exterior metal skins and cladding systems, to a closed-loop approach, which ensures multi-dimensional economic, social, and environmental benefits. The results of the study are expected to aid in the reduction of energy used for producing new materials and change the focus of the current waste management practices in the manufacturing industry from conventional recycling to creative reuse. The imperfection of the manufacturing industrial waste and the aging of galvanized steel can both be transformed into unconventional and potential architectural products.

KEYWORDS: Automobile Solid Waste, Circular Economy Design, Building Skins, Galvanized Sheet Metal

INTRODUCTION

Imperfection is a quality that is fundamentally inseparable from any human effort, particularly in, the act of building. Imperfection in architecture carries aesthetics worth in itself that should be accepted and celebrated. The work of Louis Kahn profoundly elevated architectural imperfections to an established notion of perfection. This refinement was elaborated in his concrete work at both the Salk Institute and the Kimbell Art Museum by preserving the marks of the construction process, which profoundly revealed how things were made. While the concrete work exposed the imprints of its formwork and the pour joints became an architectural opportunity in tectonic expressions, contemporary work of architecture has heavily invested in shiny complex curved surfaces that are often clad in a variety of sheet metal from zinc to titanium. Metal fabricators such as Zahner have shifted their focus, in the last decade to architectural metal surfaces and have profoundly assisted well-known architects in the realization of their work. Development of sheet metal cladding systems has undoubtedly benefitted from digital fabrication processes; however, reliance on sheet metal production methods and the open-loop supply chains has remained the same. This study aims to provide alternative methods of design exterior metal skins using sheet metal from the car industry that can be populated and extended directly by architects.

Metal has been used for assemblies and ornaments in buildings for more than 9000 years. In the 19th century, the use of metal grew substantially, and metal was even used for cornices and storefronts. Literature suggests that the Reliance Building in Chicago, designed by Frederick Baumann in 1894 was the first building where metal cladding was used. The Alcoa Company in Pittsburgh had a keen interest in construction with sheet metal walls, which was reflected in the design of their headquarters (Yeomans 1998). The interest in sheet metal as a cladding material grew with the technological advancement in galvanizing techniques. Galvanization using a process called "hot-dipping" was first introduced in the 1840s, and it made iron more suitable for exterior applications. Over the years, experiments carried out resulted in the mass production of metal thereby reducing the cost and making it available for construction purposes. Metal cladding made from galvanized steel was adopted because painting only was unable to protect the metal over an extended period of time. Exterior cladding was perceived as lightweight, non-load bearing, and able to be used as a membrane for the building, allowing air and daylight to pass through it to its occupants. The trade catalog was the chief marketing tool for sheet metal and created the link between manufacturers and consumers. Contractors collected brochures from building journals, to show potential customers the possibilities of metal cladding. As the uses of metal in interior and exterior cladding began in the late19th century. During that time, galvanized sheet metals were not coated but painted with bitumen on site. The introduction of galvanized sheet metal cladding accelerated construction time and enabled designers to introduce more significant building spans and more complex shapes (Howell 1988). In particular, the coatings based on zinc were widely used to protect steel structures against atmospheric corrosion (Ferretti, Traverso, and Ventura 1976). It is in the nature of architecture that the appearance of new building materials would be accompanied by theoretical explorations of its possibilities (Yeomans 1998). Natural aging of zinc coating comes with a variety of change in the appearance of zinc coated galvanized sheet due to aging known as patina. The study highlights the relationship between design and application of sheet metal cladding and its aging.

1.0 STATEMENT OF THE PROBLEM

The rise in sheet metal market size comes with an inevitable increase in scrap waste, even with maximum optimization measures in place. Existing literature on scrap management of sheet metals shows that stamping operations, particularly in the automobile industry, generates an enormous volume of scraps. For example, almost two decades ago at General Motors Company, 1.6 million tons of scrap metal per year was generated (Koros, Hellickson, and Dudek 1995). Scrap management of sheet metal (especially steel and aluminum) consists mostly of recycling, which carries its own set of problems such as enormous energy consumption sorting, and de-galvanization issues. As the current practice of blanking and stamping sheet metal continue to generate a substantial volume of galvanized scrap, the creative reuse of scrap as suggested in this study by the authors, offers the most logical solution over recycling processes. The problem of recycling galvanized steel has its roots in the chemistry of steel making. Steel mills require specific raw material “recipes” to produce steel products with the properties needed by the builders and manufacturers who will ultimately use the steel. These recipes contain narrow margins of error. Scrap shipments to mills that have too much zinc—the material present in galvanized auto bodies can create problems and reduce the quality of steel during the melting stage.

According to a recent report published by the GVR group, the world's largest and most trusted market research database, the market size of global metal stamping (a manufacturing term for forming sheet metal) was estimated at 204.6 billion dollars in 2016 and is expected to reach 299.6 billion dollars by 2025, The increasing use of sheet metal particularly in the automotive and consumer electronics industries, is expected to drive the demand for stamping due to its use in manufacturing automotive chassis, transmission components, and interior & exterior structural components of electronics. Technological innovations in the form of improved stamping processes have seen commercial usage in the recent past. In addition, regulatory policies aimed at improving working conditions & safety standards, waste disposal, and materials used are imperative for shaping growth and sustainability strategies of the stamping companies over the forecast period (Grand View Research 2017). The scraps to be discussed in this paper, are limited to the category of bulky ferrous metals from the automotive industry. The American Society for Testing and Materials (ASTM) has guidelines for treatment of scraps stated in ASTM E702. This study is limited to standards governing galvanized sheet metal for the automobile industry.

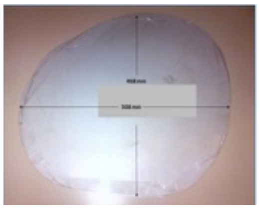
2.0 AUTOMOBILE SHEET METAL OFFAL

General Motors’ (GM) sheet metal offal is a surplus material generated by its stamping operations as shown in Figure 1. The GM offal is a resilient material comprising of steel sheet and zinc coating; it is galvanized to preserve the steel in a process known as hot-dipped galvanization or Electro-galvanization. This waste-flow is generated as consistently sized; high-quality irregular shaped sheets of light gauge steel that are produced when windows and other car components are stamped out of body panels on the assembly lines. Because of their predicted and consistent size, shape, and quality, these pieces are assumed to be valuable for much more than traditional scrap markets. Offal pieces are usually sized between 0.5mm to 3.2mm thick, have various coatings thicknesses (mostly zinc), and total at 1,500 metric tons per year. Enormous cost-benefit values are available through the reuse of these materials for GM and future users of the reclaimed steel. One plant in Flint, Michigan generates approximately 40,000 pieces per month alone in about 11 different shapes and sizes (Figure 2). In 2014, GM announced that it generated nearly one billion dollars in annual revenue through reusing and recycling its by-products and avoided releasing over 10 million tons of CO_2-equivalent emissions into the atmosphere.

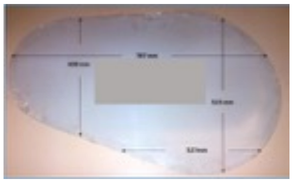
2.1. Imperfection in Stamping Processes and Zinc Patina

Although the car industry has pushed stamping operations to the maximum optimization methods, it is yet unable to achieve zero waste strategies. It is inevitable that the car industry will continue to generate a sizable amount of sheet metal waste as long as the stamping operations are the dominant manufacturing process in the making of the car. On the other hand, architectural zinc has had a long history of application on buildings for almost three centuries and has been increasing in popularity in North America since the early 1990s (Kweton 2017). Zinc is a resilient material and is used for many purposes in the environment. According to the American Zinc Association, the average vehicle now contains 37 pounds of zinc (17 pounds in the form of corrosion-protection coatings and another 20 pounds in the form of zinc die cast parts) such as door handles and locks. Imperfection in zinc is often related to its aging patina. Zinc cannot be specified without an appreciation for the patina and aging process. The material is long-lasting, lends itself to unique detailing, and is versatile, but an understanding of the maturation process manages client expectations and allows a specification to leave a legacy long after the project is complete. Zinc, if specified properly can last for 100 years (Kweton 2017).

Figure 1: Car Stamping Diagram (USA 2009)



Offal # 05



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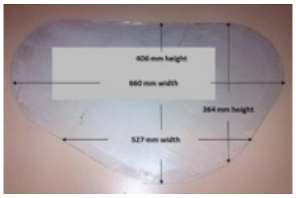

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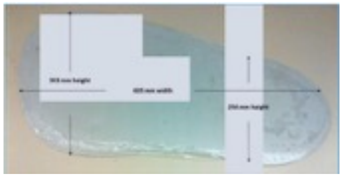

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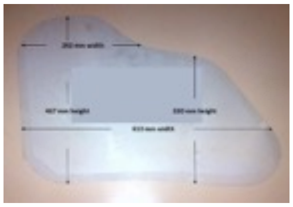


Offal # 09

Offal # 11

Figure 2: Different Size Offal Available as Scrap Materials from General Motors (GM, 2016)

3.0 RESEARCH METHODOLOGY

This study utilizes a quantitative approach limiting variables to one single material (galvanized sheet metal) in one single thickness investigating its possibilities. The study was conducted in two phases. First an ideation phase, and second is an assessment phase. Six designs proposed by the authors' collaborative team were designed, illustrated and modeled, then were analyzed based on the feasibilities of manufacturing processes and the comparison cost of the raw and upcycled materials used. The design and engineering team worked in an interdisciplinary model which involved feedback and feedforward process in an academic setting. The focus was limited to the process of production implied by each design solution and the cost of obtaining material for each design. The cost of production of each design proposal was compared to show the effect of the use of new material for building skins against the use of a consistent waste-flow material. In the following sections, a description of each design followed by illustrations is presented. Then a comparison in manufacturability and cost savings are discussed.

4.0. PROPOSED DESIGN SOLUTIONS FOR METAL BUILDING SKIN

It is common for individual industries to develop its processes without involving other industries. And too often in manufacturing, engineers may not have the time or opportunity to work closely with designers. Some of the specific properties of the metal offal included their lack of stiffness, the vulnerability of their edges, their tendency to be shaped or dented by powerful forces, along with the noise that would be generated when they came in contact with another force, for example, heavy rain. All these factors had an impact on the design process. To develop a synergy between the car industry and the building industry, the following proposals are primarily focused on exterior building skin applications that ranged from metal paneling to sun-shading screens. Each design solution utilized a different offal type to match the unit geometry closely and to minimize materials waste. See Table 2 for design proposal analysis.

4.1. Design #1: Passive Cooling Triangulated Perforated Skin

The proposed triangulated skin allows fresh air to flow from a positively pressured exterior into a negatively pressured cavity space and the air would be captured as potential cooling by an in-ground passive cooling system. While minimal waste is still being produced through the maximized geometry of the offal, the function of the skin and the passive cooling system allows for more significant energy waste reduction over time. Offal #6 has an estimated monthly production of 1,000 pieces. Using 80 percent of the offal, with an area of about 592 square inches, yields two pieces per offal. Upon folding and perforating, the offal is transformed to a standard paneling system which contains 60 pieces per panel.

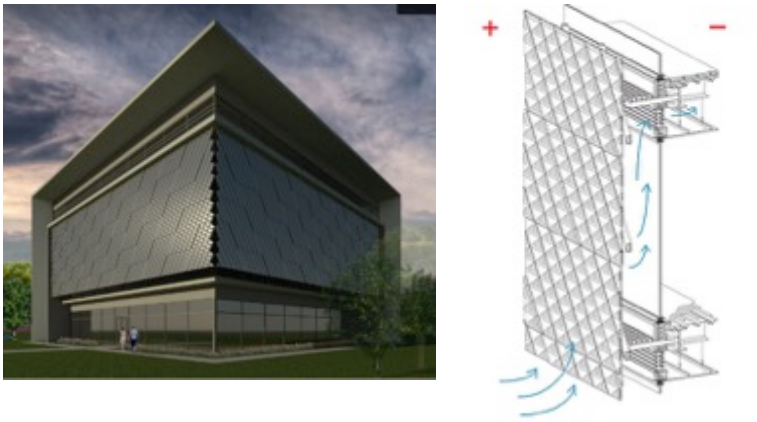


Figure 3: Passive Cooling Skin made from offal #6 (Buckley, 2017)

4.2. Design #2: Breathable Skin

The design allows air and light to penetrate the building. By altering the geometry of # 8 offal, four different components were created. The pieces were bent at varying degrees at the center of the panel, bringing the two-dimensional flat offal into a three-dimensional object. When assembled, these components can create an opening of varying sizes in the building envelope, allowing the building to breathe. The “breathing” of the envelope encourages the circulation of fresh air against the facade of the overall structure, thereby reducing the need for cooling systems within the interior spaces. Additionally, by strategically placing the openings in front of the subsequent fenestrations, the envelope can bring natural light into the building.

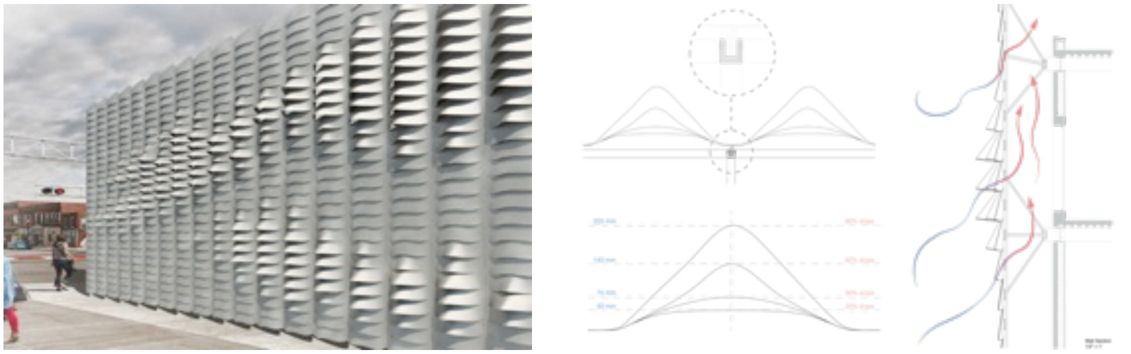
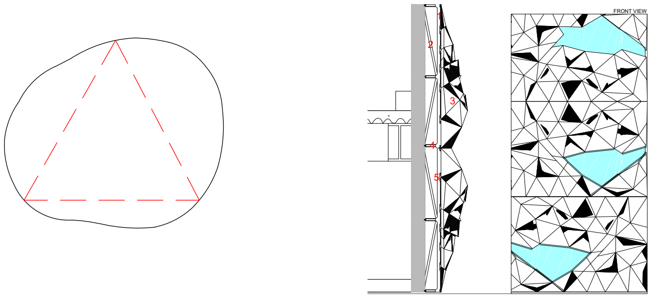


Figure 4: Breathable Skin made from offal #8 (Lopez, 2017)

4.3. Design #3: Faceted Complex Curvature Skin

The design introduced a triangulated modular system for building skins. By folding offal #5, which has the closest geometry to a circle, a triangular pyramid emerged. Placing the pyramids in groups of six created hexagons, which were assembled to form a complexly curved surface building skin.



1. Steel tube frame
2. Steel X-Bracing
3. Offal #5
4. 6 x 10 Steel tube
5. Bolted Connections

Figure 5: Faceted Complex Curvature skin made from offal #5 (Escalente, 2017)

4.4. Design #4: Metal Brick Façade System

This metal-masonry system is made from offal #11, which is the closest to a rectangular shape and would create minimum waste while shaping a volumetric module. Four pieces of the offal were folded to form a rectangular box module measured at 500mm x 285mm x 140mm in size. Utilizing this offal module as a façade element creates a building envelope visually similar to an exposed masonry façade. A dry sealant is used as an adhesive for units to prevent water penetration.

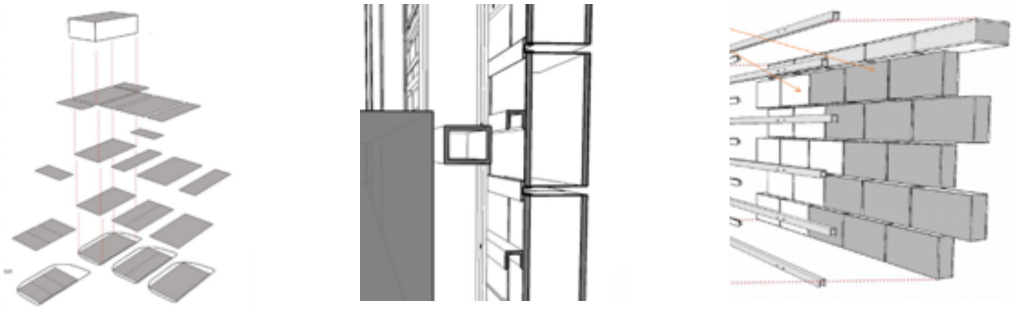


Figure 6: Metal Brick insulated units envelope made from offal #11 (Mathews, 2017)

4.5. Design #5: Trapezoid Zigzag Sunscreen

The skin system is made from offal #9 and maximizes the surface to create a triangular box. Two triangles were made into one object to form a box; holes were drilled for connections. The two-triangle units make trapezoids, which are arranged in a zigzag pattern as a shading screen for the building exterior.

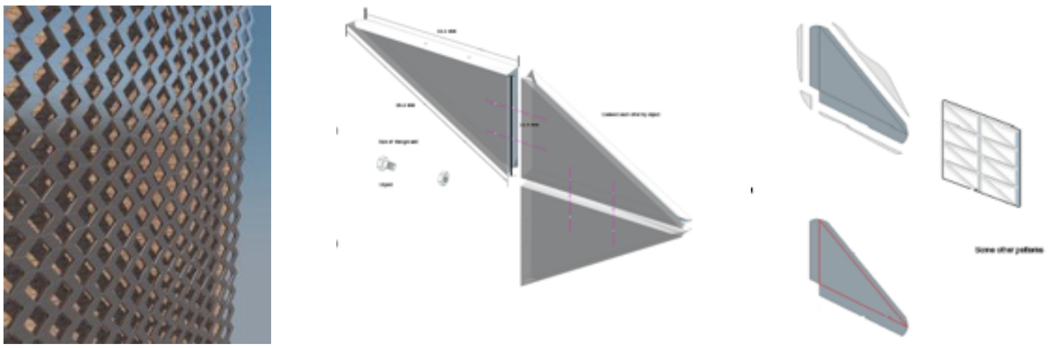


Figure 7: Trapezoid zigzag sunscreen made from offal #9 (Lang, 2017)

4.6. Design #6: Zero Waste Cladding System

The cladding system is conceived as rhomboid structure folded on the diagonal in a 7-degree angle. To retain a whole rectangle as much as possible, offal #11 was distributed in a 200mm x 450mm rectangular pattern in the center and on four sides with surplus parts around it. Long sides of the rectangle were folded flat to strengthen the sheet edge, and short sides were folded to form a double lock connection to keep rainwater out of the building. Compared with the horizontal dimension, the vertical dimension components carry more functions like lighting and ventilation. Thus, the units arrayed in a repeating sequence mirrored each row on the vertical level and retained a gap to encourage the circulation of air and draw natural light into the building. The combination of each unit formed the different texture of the façade and reflected the sunlight differently to reduce the impact of light pollution on pedestrians.

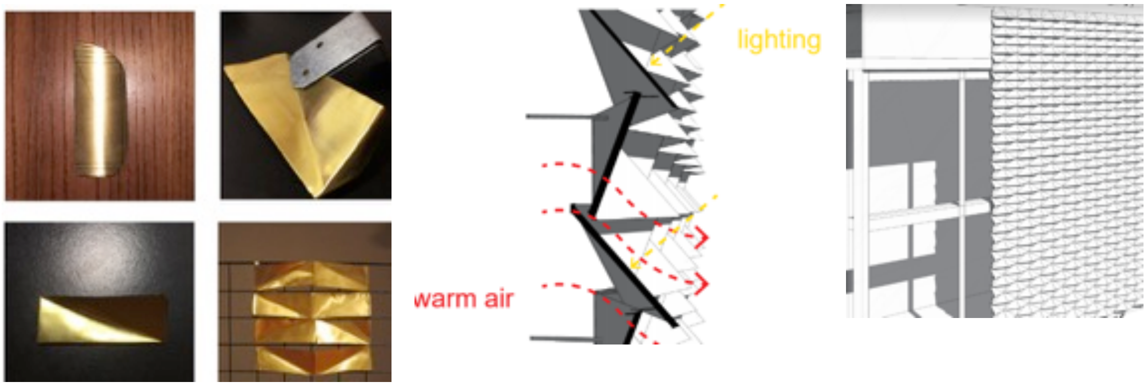


Figure 8: Zero waste cladding system made from offal #11 (Ma, 2017)

5.0 COST COMPARISON BETWEEN RAW AND SCRAP GALVANIZED SHEET METAL

The current cost of raw galvanized sheet metal was obtained by comparing prices from different companies, see table 2. Alibaba sells coils of sheet metal ranging from $0.25/lb to $0.5/lb (Alibaba 1999), the cheapest of which places a minimum on the quantity of the order. The cost of scrap metal was obtained from recycling companies such as Montgomery Scrap Corp. at $0.07/lb. (Scrap 1949), Rockaway Recycling Company rate is at $0.06/lb - $0.1/lb. (Recycling 1977) and Scrap Monster at $0.11/lb. (Monster 2009). The cost for raw galvanized sheet metal is averaged at $0.45/lb., and for Offal as scrap, it is at $0.08/lb.

5.1. Manufacturability Analysis

To understand the cost of the automated manufacturing processes performed on the six proposals, a basic quantitative assessment was performed. This process revealed the influence of design on the manufacturability of the materials for use. Assessments of manufacturability specify a choice of cutting done by a waterjet cutter to calculate cutting energy; for the purpose of this study, design proposals were analyzed based only on the number of folds and cuts. The proposed designs were analysed according to the number of units of offal used in the system, the number of cuts per unit, the size of cuts, the number of folds per unit, the size and degree of folding, the number of joints in the system and the types of joints as shown in Table 3. Further analysis regarding the cost of manufacturability will be presented in future publications.

Table 3: Manufacturability of the Design Proposals. Source: (Authors 2018)

Design Solution	# of Units in the System	# of Cutting per Unit	Size of Cutting	# of Folding per Unit	Size/Degree of Folding	# of Joints in the System	Type of Joints
1	15 units / m^2	3-4 (irregular)	60 cm	6	30 cm/90°	60 bolts / m^2	Bolts
2	5 units / m^2	0	0	1	0	30 bolts / m^2	Bolts
3	10 units / m^2	3	40-50 cm	0	0	60 bolts / m^2	Bolts
4	5 units / m^2	15-20	30-60 cm	0	0	50 bolts / m^2	Bolts
5	2 units / m^2	16-20	30-60 cm	6	30-60 cm/90°	20 bolts / m^2	Bolts
6	10 units / m^2	0	0	4	20-50 cm/90°	60 bolts / m^2	Bolts

Table 2: Analysis of Six Design Proposals. Source: (Authors 2018)

Design Solution	**# of Units in the System**	**Type of Offal**	**# of Cuttings per Unit**	**Mass of Offal per square meter**	**Cost of raw material @$0.45/lb.**	**Cost of scrap@ $0.08/lb.**
1	15 units / m^2	Offal #6	3-4 (irregular)	2340.95 x 15 =35,114.25g (77.4lbs)	$34.83	$6.2
2	5 units / m^2	Offal #8	0	1116.98g x 5 =5584.9g (12.3lbs)	$5.54	$1
3	10 units / m^2	Offal #5	3	1087.53 x 10 = 10,875.3g (23.98lbs)	$10.79	$1.9
4	5 units / m^2	Offal #11	15-20	1068.63 x 5 = 5343.15g (11.78lbs)	$5.3	$0.9
5	2 units / m^2	Offal #9	16-20	1244.862 x 2 = 2489.724g (5.49lbs)	$2.47	$0.4
6	10 units / m^2	Offal #11	0	1068.63 x 10 = 10686.3g (23.56lbs)	$10.6	$1.9

While each design proposal is unique and different in application, the design proposal with the lowest cost is solution #5 as shown in Table 1. Solution #3 and #6 have the same cost of $1.9 per square meter showing that different designs can arrive at the same cost. Figure 9 presents the comparison of cost when manufacturing the proposed solutions using offal versus raw materials. From this comparison, we observed that designers who were presented with the same materials provided unique solutions for building skins. After an analysis of optimized use and material flow, results show that design plays a significant role in the final cost of using the waste-flow material. Further study will be done to emphasize the need for manufacturability and embodied energy analysis at the early stages of design to save both cost and energy.

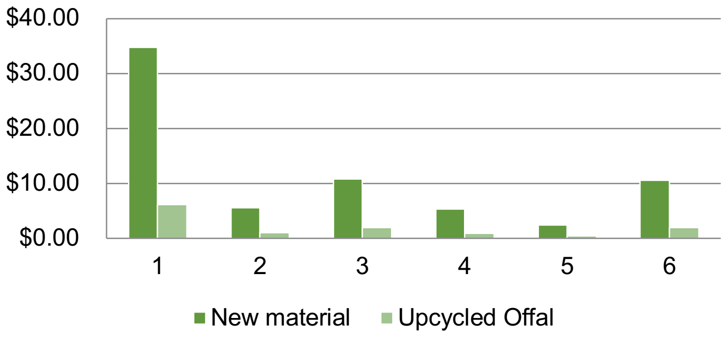


Figure 9: Cost Comparison between raw and offal sheet metal (Authors, 2018)

CONCLUSION

Factors responsible for the total cost of production of design proposals are design, materials, and manufacturing. This paper introduced a novel approach in designing a symbiosis between non-hazardous automotive waste and the building industry. Particularly, creating building skin systems from by-product galvanized sheet metal from the automotive industry. A similar resource reuse revolution is making way for a new architectural paradigm shift, which is emerging through the integration of creative reuse, synergistic business processes, and a circular economy. To establish a market for reusing galvanized metal scraps, the design should be considered as a value-adding factor of which both the building industry and the car industry could benefit from. Using the sizable scrap metal encourages a return of materials at the end of the life of a project. When there is a strategy to use returned materials for building skins, the cost is reduced, and the supply chain of the automobile industry is closed. The fraction of GM offal produced yearly, 1.6 million tons compared to 7.6 billion tons of total waste is minimal. This study has also shown the cost savings for the reuse of and appreciation for the imperfection of the materials and the process. The results of the investigation reveal that design of galvanized sheet metal for reuse influences the cost of production. Perfection is closer to an interdisciplinary approach to the use of new materials. There is no fixed formula to determine the savings of one particular design proposal, but by a unified triangular approach, perfection can be sought. In the future, scrap management can include more processes centered on reuse. Improved scrap management will ensure that there is an established chain of supply for scrap metal, which will increase opportunities for job creation. The environment will improve as it will reduce the demand for raw materials. This will, in turn, reduce the carbon footprint of products that involve the use of metals. A circular economy will be further established, and there will be an elimination of waste and perfection in imperfect waste.

ACKNOWLEDGMENTS

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The raw earth brick: a building material to meet the needs of local populations

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ABSTRACT: This study tests the ways of improving compressed earth bricks by the addition of sugar cane bagasse, alluvial sand and fine aggregates. The objective is to contribute to the valorization of clay resources, with the aim of developing the production of sustainable, local and energy-saving building materials, particularly in the peri-urban areas of Kinshasa in D.R.Congo. Two raw clays were characterized and then mixed with the different additives to obtain raw earth bricks. Those bricks were then submitted to flexural and compression tests to evaluate their mechanical properties. The addition of 0 to 7.5% bagasse increases the flexural strength from 0.66 to 0.99MPa and the compressive strength from 2.54 to 3.14 MPa. The addition of 0 to 50% sand increases the flexural strength from 0.56 to 0.71 MPa and the compressive strength from 2.28 to 3.09 MPa. The addition of 0 to 35% of fine aggregate does not affect the flexural strength, but increases the compressive strength from 2.28 to 3,10MPa. Stabilization with sugarcane bagasse, sand or aggregates is an interesting prospect to improve by a factor of the order of 1/3 the mechanical properties of raw earth bricks. In addition the mechanical properties are also affected by environmental variation in humidity. The durability of the bricks (i.e., its resistance to water) was therefore evaluated by “the wetting drying test” after an addition of cement. The compressive strength after six cycles of wetting-drying decreases by 25% for the bagasse mixture, 6% for the sand mixture and 2% for the aggregate mixture. Likely an addition of cement allows to significantly increase the durability.

KEYWORDS: Raw earth, valorization, stabilization, durability.

INTRODUCTION

The Kinshasa region and its surroundings are experiencing strong spatial and demographic expansion with, as consequence, the development of peri-urban zones in which the habitat quality is a crucial problem (Lateef et al. 2010). To face this challenge, it is essential to value the use of local and regional natural resources. The use of raw earth in construction is a solution that could meet this demand. This study aims to contribute to the valorization of the clay resources of Kinshasa and its surroundings, with the aim of developing the production of sustainable building materials. The choice of the region is justified by the abundance of clay raw materials and by these very important needs.

Clay is a building material widely used in this region. Its exploitation in construction is generally artisanal. The extracted clays are largely used for the manufacture of wood-fired bricks, with the resulting problem of deforestation (Schure et al. 201 1; Wetshondo 2012). Family societies and craftsmen produce quantities of materials which are not accessible to a large part of the population due to their high prices (Wetshondo 2012). Since the early 1990 and the bankruptcy of the Kinshasa Brickyard, the abandonment of building in clay materials was systematic in Kinshasa. Nearly the whole population turned to a local material: the concrete brick. It is a brick made by manual or mechanical compression by mixing grinding fines of a sandstone rock (the Inkisi sandstone) locally called “dust”, alluvial sands (alluvial deposits of the Congo River or the Mbinza, Kalamu and Ndjili rivers) and cement. Sand is taken directly along the rivers. Three companies located in the neighboring province of Kongo Central provide good quality cement. These concrete bricks of 10, 15 or 20 kilograms cost on average, 1, 1.5 and 2 $ the brick. Despite this high cost for most households, concrete brick architecture remains dominant in Kinshasa.

The use of raw earth should limit the cost of production and produce a resistant construction material. Earth is widely available at low cost. The use of raw earth also reduces environmental impacts because they are renewable, biodegradable, CO_{2-} neutral and energy efficient to produce materials (Baley 2005).

The use of the earth as a building material is an old tradition. Due to his abundance, earthen construction is widespread in the history of this region, especially in rural areas. Most of traditional constructions are made with earth associated with other materials such as plant or mineral additions.

However, the earth has the disadvantage of having a low water resistance (durability) and low load bearing resistance. Different techniques are used in earthen construction to improve its strength (Stulz and Mukerji

1988; Houben and Guillaud 1989). The most used technique is stabilization. Stabilization is a set of physical or chemical processes aimed at irreversibly improving the characteristics of raw earth (Gressillon 1978; Bahar *et al*. 2004). For instance vegetal fibers are used to provide a reinforcement to the earth. They reduce drying cracks and increase tensile strength. They accelerate drying, lighten the material and improve its insulation properties. They contribute to the earth's resistance at the grain scale. The fibers can also be associated with other inorganic stabilizers like sand, cement, lime or bitumen (Houben and Guillaud 1989). The addition of sand and aggregates to the earth modifies its grain size and improve its compactness by making the earth denser (Houben and Guillaud 1989). Cement creates an inert skeleton. It improves the resistance to water by creating bonds between sand and gravel particles. An addition of 5 to 8% of cement or lime generally produces an improvement in the compressive strength and an insensitivity to water (Doat et al. 1979; Rigassi 1995).

In this article, we study the behavior of a stabilized raw clay with the incorporation of sugarcane bagasse, sand and fine aggregates in order to increase their mechanical resistance, water stability and durability of earth bricks. The main objective is the study of the impact of the addition of these stabilizers on the resistance of a raw clay.

The research is based on the traditional technique of Compressed Earth Block (CEB) in order to respect the local habitat and reduce the energy consumption for construction material production. The mechanical properties of the compressed earth bricks will be compared to choose the most appropriate stabilizing agent and optimal proportions between the raw clay and the additives. The improvement of the durability of the selected mixture will be done by adding cement, and then tested by the humidification-drying test or alternating wetting drying cycle.

1.0 MATERIAL PROPERTIES

1.1. Raw clays

The samples were taken in two areas from the Kinshasa province and Mbanza Ngungu (Figure 1).

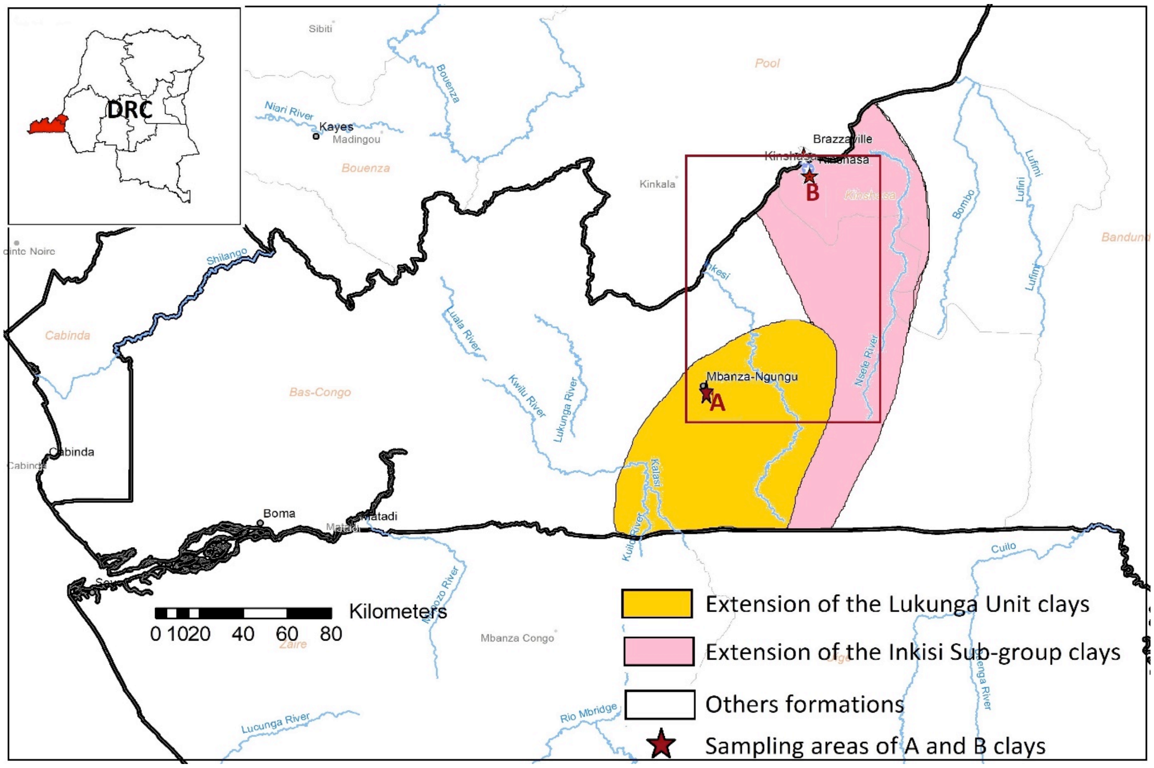

Figure 1: Location map of the study area (red box) showing the sampling zones chosen in the Kinshasa province and Mbanza Ngungu, D.R. Congo. The studied raw clay materials are derived by the weathering alteration of the geological substrate. The colors represent the extension of the two regional geological formations observed in the study area.

The tests focus on two raw clays formed by the alteration of geological formations located in the West Congo Belt. The sample A is formed by the alteration of carbonates rocks from the Lukunga Unit. The sample B is formed by *in situ* alteration of Sandstone from the Inkisi Subgroup. Both clay samples present a yellowish color that is appreciated for the brickyard, widely present in the region.

Each clay sample was stabilized with a stabilizer available in the sampling area where it was taken. Sample A was stabilized with vegetal fibers of sugar cane; sample B was stabilized with sand and aggregate.

1.2. Stabilizers

Bagasse

Sugar cane is an herbaceous tropical grass. Bagasse is the fibrous residue of sugarcane obtained after extraction of the juice. Bagasse is a waste largely present in the southern part of the explored region. It is mainly produced by a local sugar factory located in the region near Mbanza Ngungu. It has been used to stabilize the clay sample A.

The average composition of the bagasse is 45% of fibrous fraction, 2 or 3% of insoluble solids (inorganic fractions), 2 or 3% of soluble solids (residual sucrose molecules, not extracted during the process) and 50% of water (ICIDCA 1990). The chemical composition of the insoluble organic solid fibrous material depends on the sugar cane variety. It consists of polymers made by 15 to 35% of lignin, 25 to 35% of hemicellulose and 30 to 50% of cellulose (ICIDCA 1990; Cuba9 1990; Dinu 2006; Berndt and Hodzic 2007).

Sand

The sand used is an alluvial sand taken along the Congo River. Its particle size is presented in Table 1:

Table 1: Granulometric distribution of the Congo River sand.

>650 µm	>500 µm	>300 µm	>250 µm	>150 µm	>75 µm	>63 µm	>53 µm	< 53 µm
0%	4.1 %	19.1 %	32.6 %	76.8 %	93.8 %	95.6 %	97.3 %	2.7 %

Fine aggregate

It is a fine aggregate of the Inkisi sandstone locally called "dust". Its particle size distribution is shown in Table 2.

Table 2: Particle size distribution of fine aggregate.

>4.5mm	>4mm	>2mm	>1mm	>500 µm	>250 µm	>150 µm	>75 µm	>6 3 µm	<53 µm
0%	1%	23.5%	42.4%	59.2%	76.6%	85.4%	95.1%	97, 4 %	1.5%

Cement

There are different types of cement that differ in composition, strength, setting and hardening speed. The cement used in this study is a composite Portland cement EN - 197-1 CEM II 32.5 R.

2.0 RESULTS AND DISCUSSION

2.1. Properties of raw clays

The two clays were characterized by determining their chemical compositions by X-ray Fluorescence (XRF), mineralogical composition by X-Ray Diffraction (XRD), their Atterberg limits and their particle size distribution by laser diffraction. The results are shown in Table 3.

Table 3: Properties of samples A and B.

Properties	A	B
Chemical analysis (%)		
SiO_2	69.18	72.16
TiO_2	1.3	0.79
Al_2O_3	17.5	14.89
Fe_2O_3	3.54	4.03
MnO	0.01	0.01
MgO	0.01	0.19
CaO	0.07	0.03
K_2O	0.59	0.57

P_2O_5	0.05	0
LOI	7.75	7.33
Mineralogy (%)		
Quartz	53	55
Orthoclase	2	1
Goethite	7	11
Magnetite	2	0
Anatase	1	1
Kaolinite	31	28
Illite	4	4
Atterberg limits		
Liquid Limil LL (%)	34	32
Plastic Limit PL (%)	26	22
Plasticity Index PI	8	10
Particle size distribution		
Sand (2 - 0.063 mm) (%)	15	20
Silt (0.063 - 0.002 mm) (%)	75	68
Clay (<0.002 mm) (%)	10	12

The two clays have very similar properties even they derive from the alteration of different geological substrate. (carbonates for sample A, sandstone for sample B).

2.2. Mechanical tests

We performed flexural and compression tests on raw earth mixtures. Sample A was mixed with 1%, 2.5, %; 5% or 7.5% by weight of bagasse. Sample B was stabilized either by sand (with 35 or 50% by weight) or by fine aggregate (with 20 or 35% by weight)
The manufactured test pieces correspond to the standard dimensions for hydraulic mortar tests: 4x4x16 cm³. The test pieces were stored for 28 days in a controlled atmosphere. The room temperature was continuously maintained at 21°C (± 2°C) and the relative humidity at 60% (± 10%). The mechanical properties are estimated by flexural and compression tests on test pieces of 28 days in accordance with standard NF EN 196-1.

The flexural strength is determined by the 3-point bending test. The specimen is loaded at its center by a force centered and supported by two supports spaced 100 mm apart. The flexural strength is then defined at break. The loading speed during the bending test is 300 N/min. After rupture of the test piece by bending, the two pieces are submitted separately to compression. The compressive strength is determined at break. The loading speed during the compression test is 14.4 kN/min. The results obtained are shown in Table 4.

Table 4: Twenty-eight days flexural and compressive strengths on earth-bagasse, earth-sand and earth-agrregate mixtures.

Stabilizers	Flexural strength at 28 days (MPa)	Compressive strength at 28 days (MPa)
Bagasse		
0%	0.66	2.54
1%	0.84	2.80
2.5%	0.91	2.92
5%	0.93	2.95
7.5%	0.99	3.14
Sand		
0%	0.56	2.28
35%	0.59	2.59
50%	0.71	3.09
Fine aggregate		
0%	0.56	2.28
20%	0.54	2.54
35%	0.56	3.10

Resistance to flexural and compression increases with the addition of bagasse. Flexural strength evolves from 0.66MPa without any additive to 0.99 MPa with 7.5% of vegetal fibers into the mixing. The compressive strength increases from an initial value of 2.54 MPa to 2.80 to 3.14 MPa with an addition of vegetal fiber ranging from 1 to 7.5%. The flexural strength also increases with the addition of sand from 0.56 to 0.71MPa for a 50 % weight mixture. The compressive strength from 2.28 with no sand to 3.09 MPa with 50 wt. % of sand. The addition of aggregate has little effect on the measured flexural strength. However, the compressive strength increases significantly, from 2.28 to 3.10 MPa with an addition of 35 wt. % of aggregate to the raw clay. For all the additives, the best mechanical results are obtained with the highest amount of vegetal (7.5%) or mineral additives (50% sand or 35% aggregates) to the raw clays.

Depending on the standard used and the country of reference, the compressive strength required for BTC differs, ranging from 1.5 to 3.5 MPa (Figure 2). The tested compressed raw clays display compressive strength values higher than 2.2: those values overpass the minimum requirements, except for the New Zeland standard (NZS). The different additives allow to improve their compressive strength above 3 MPa but still lower than the minimum requirement of 3.5 MPa for NZS standards.

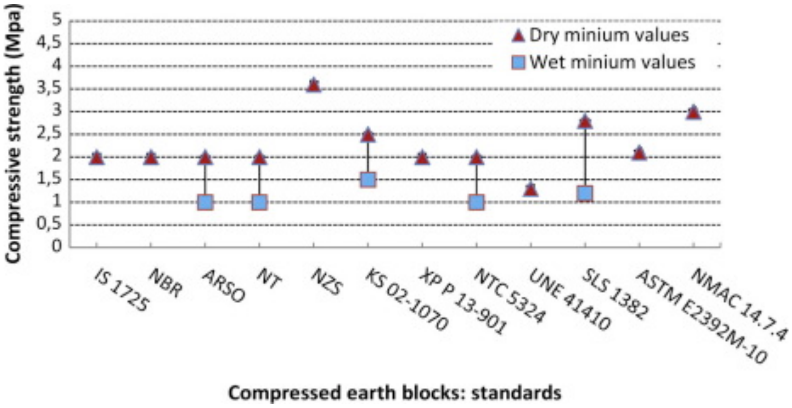

Figure 2: CEB minimum values of dry and wet compressive strength according to different standards: IS 1725 (India), NBR (Brazil), ARSO (Africa), NT (Tunisia), NZS (New Zealand), KS 02-1070 (Kenya), XP P13- 901 (France), NTC 5324 (Colombia), UNE 41410 (Spain), SLS 1382 (Sri Lanka), ASTM E2392M-10 (America), NMAC 147.4 (New Mexico). Source: (Jaime et al. 2012).

Flexural strength is less important than compressive strength in construction. Indeed raw earth constructions are generally dimensioned so that the material is only stressed in compression (Moevus et al. 2012). Therefore there are few requirements concerning the flexural strength of raw earth: it ranges from 0.1 to 0.5 MPa in the few available studies (Moevus et al. 2012). For instance, the New Zealand standard NZS 4298: 1998 recommends a minimum flexural strength of 0.25 MPa (Moevus et al. 2012). The tested compressed earth bricks all reach this minimum value.

2.3. Durability tests

The main disadvantage of the earth construction is its lower resistance to the action of water. To overcome this, we tested the addition of 6% cement on the 3 mixtures that gave the mechanical best results (7,5% bagasse, 50% sand and 35% aggregate). The 3 new mixtures were then subjected to a durability test. This was done by the humidification-drying test or alternating wetting drying cycle. The samples are subjected to six cycles of wetting - drying. They are immersed 25 minutes and then dried at 70°C, 40% humidity for 36 hours. At the last cycle, the compressive strengths of the "aged" samples are measured and compared to "healthy" sample. The humidity resistance coefficient (C_{rh}) is defined by the ratio between the compressive strength after 6 alternating wetting-dry cycles (R_{msa}) on the dry compressive strength R_{dry} ($C_{rh} = R_{msa} / R_{dry}$). The results are shown in Table 3.

Table 3: Values of dry compressive strengths (R_{dry}), compressive strength after wetting - drying (R_{msa}) and humidity resistance coefficient (C_{rh}).

	7,5% bagasse	50% sand	35% aggregate
R_{dry} (MPa)	4.73	3.19	3.71
R_{msa} (MPa)	3.54	3.00	3.64
C_{rh}	0.75	0.94	0.98

This test shows that there is an improvement in compressive strength with the addition of 6% cement. However, durability is not sufficiently improved: The treatment with 7.5% bagasse and 6% cement has a very satisfactory dry strength, however the resistance after wetting drying is altered by 25%. The treatment with 35% fine aggregate and 6% cement has satisfactory dry strength. The resistance after wetting drying decreases by 6%, but remains higher than the previous mixture. Finally the treatment with 50% sand and 6% cement give satisfactory dry strength. The resistance decreases by 2% after 6 cycles of wetting drying, but remains higher than the other two mixtures.

CONCLUSION

On average an earth material with a compressive strength of 2 MPa can be used in masonry. But the minimum value of compressive strength desired is 2.5 MPa. For flexural strength the desired value of the earth bricks for use in masonry is 0.4 MPa. We note that the addition of the different stabilizers (bagasse, dust and sand) allows to reach these values. The best values are obtained with the addition of 7.5% bagasse, 35% dust and 50% sand.

Stabilization with vegetal fiber of sugar cane (bagasse), fine aggregate or sand is therefore an interesting prospect. However, it is essential to do other tests of durability on these materials. The compressive strength decreases by 2 to 25% on the mixing containing 6% cement after 6 cycles of wetting drying. An increase of the percentage of added cement above 6% would lead to maintain the compressive strength values after wetting drying.

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Initial Developments and Projections of 3D Construction Printing

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ABSTRACT: 3D Construction Printing is a novel technology to elaborate building parts by material deposition. This technique is emerging through several university and entrepreneurial initiatives, mostly in developed countries. Some exploratory buildings and/or pieces have been created and diverse companies plan to execute large constructions. This article aims to review architectural and urban projections of this technology based on these experiences and initial tests and developments in Concepción, Chile. Supplies and equipment has been collected and a number of concrete printing trials has been carried out. Additionally, parametric programming of 3D-printed walls is being developed in a BIM platform in order to generate and evaluate architectural models. Also, a robotic installation is being set-up with the support of a national program on building productivity, research centers and industrial companies. The material tests have demonstrated the feasibility of construction printing with local materials, in addition to an important reduction in the time and resources needed to produce pieces with different shapes, although this process does require automation, structural verification and large-scale execution. The parametric programming in BIM shows the integration of the design-to-construction process, in addition to versatility and optimization of architectural designs. The planning of an industrial installation expresses the convergence of different stakeholders in this technology and a particular interest in to develop local supplies and machines. These activities and other experiences suggest the impact of 3D construction printing on the emergence of new manufacturing systems for buildings, that impels an architecture of curved profiles and appealing spaces that can become part of the real-estate market as experimental neighborhoods and/or iconic buildings, related to new social trends.

KEYWORDS: 3D Construction Printing, Digital Fabrication, Parametric Design, Building Technology.

INTRODUCTION

Several initiatives around the world, usually in industrialized nations, are testing the digitally-controlled three-dimensional deposition of fast solidifying fluid material to produce building parts (Fig.1), which has been called "3D Construction Printing" (Perkins and Skitmore 2015; Labonotte et al 2016; Wei et al 2017, Panda et al 2018). In most of these experiences, cementitious mixtures are expelled from a nozzle hung from gantries or robotic arms to apply successive layers as additive manufacturing without formwork (Bos et al 2016, Duballet et al 2017). Certain initiatives have managed to execute small buildings, and some companies have promised to build large constructions, with shorter terms and lower costs than conventional processes (Perkins and Skitmore 2015; Labonotte et al 2016). Although equipment, materials and benefits are still being tested, it has been asserted that this technology will transform the construction industry, architectural design and the building of cities (Hager et al, 2016). This research aims to discuss the projections of 3D construction printing in architecture and towns, based on these experiences and initial developments of this technology in Chile. It includes tests of the mechanical deposition of cementitious compounds, parametric programming of architectural designs in BIM systems, and the preparation of a robotic installation.

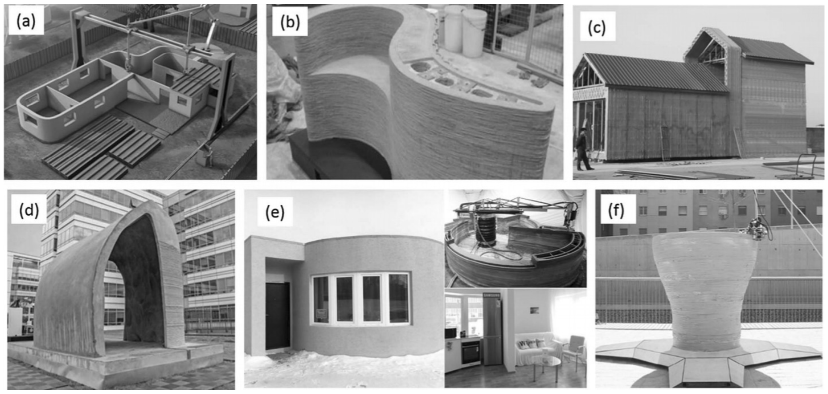

Figure 1: Experimental works created with 3D construction printing around the world: (a) USA, (b) UK, (c) China, (d) France, (e) Russia, (f) Spain. Source: (Panda et al 2018)

1.0 INITIAL DEVELOPMENTS IN CHILE

1.1. Tests of 3D-Deposition of Cementitious Composites

To review the elaboration of building elements through the three-dimensional deposition of cementitious compounds available from local industries, first a mechanical system was developed. Subsequently, diverse supplies were collected to make mixtures, basic trials were conducted, and several concrete machines were used. The tests focused on determining composites with the proper fluidity and early solidification required to lay down a horizontal cord by vertical extrusion in motion, and sufficiently fast hardening to support the next cord in a short period of time and maintain the stability of the sequence (like Malaeb, 2015; Torres, 2016, and Bos et al, 2016). Different mixing and pumping machines has been also tested, as well as the preparation of nozzles, clamping and control, for a large automated installation.

A load elevator, which provided adjustable vertical displacement, is used as the base of the test system, together with a small trolley mounted on rails, with a 1/8 HP electric motor for horizontal displacement, and hydraulic pistons with lateral axes to achieve rotation (with fixed support). The deposition system is made of a 60cm long, 110 mm diameter PVC tube that ended in a reduced 45 mm diameter, with a valve for air intake under pressure from a 2 HP compressor (Fig. 2). In addition, a mechanical mixer and integrated controls for the motors are used to synchronize operation. The tube is filled with the prepared mixture (approximately 5 liters), then the compressor and motor are turned on simultaneously to deposit a cord approximately 8 cm wide and 5 cm high, in a one-meter-long horizontal movement. After each horizontal deposition, the tube must be reloaded, the trolley moved to the initial position and the motor restarted for the following cord, which can be executed in a curve with lateral pistons. In the initials tests, the prepared mixtures were reviewed, and times, speed of deposition, hardening, and dimensions of the results executed were measured.

In the tests, different combinations of aggregates, cement, water and additives were used, in addition to compounds prepared. Currently, tests are also being carried out with micro-aggregates and sieving to achieve proper rheology and review fiber aggregates. Furthermore, standardized tests of viscosity, creep, compression and resistance are being conducted on the compounds, and normalizing a measurement of deposition by video recording, sizing and hardening by Vicat needle. Deposition is also being tested with another set of equipment in which mixtures are projected through a hose using pressurized air (shotcrete), while the nozzle is supported by rails.

Figure 2: Left: equipment to test material deposition; Upper-right: evaluation of sands; Lower-right: sample of material deposition. Source: (Author 2018)

1.2. Parametric Design of Walls with 3D Construction Printing

In order to plan the architectural composition of walls created with 3D construction printing, a parametric programming is being developed in a BIM platform (with Dynamo language in Revit), based on similar works in the field (Raspall, 2015; Kasperzyk et al, 2017; Craveiro et al, 2017; Sacks et al, 2004; Davtalab et al, 2018). The programming assumes a machine-work space of 10 x 3 meters and 3 meters in height, with a capacity for three-dimensional deposition of self-supporting reinforced cementitious mixtures of 10 to 40 cm. in thickness. Thickness may be smaller depending on the curve, height and lateral support required to maintain structural stability. This can be reviewed by exporting the model to a finite element software, with point loads and minimal deformation. This production capacity is achievable both with the planned installation of a robotic arm with an automated rail and with mechanical equipment with rails for three-dimensional displacement of concrete delivery hoses. That is, it is estimated that this type of wall can be executed on site using specific equipment at lower costs than robots. Based on the workspaces to execute the walls, the architectural project is divided into magnitudes equivalent to or smaller than the workspaces, to establish the consecutive locations of the machinery. This operative subdivision also makes it possible to plan the equipment installation sequence according to the progress of execution to ensure clear transportation routes. If necessary, some modules or openings are postponed, in order to remove equipment when closing walls.

In the parametric programming, the main sizes of the configuration must be indicated at the beginning. Therefore, a linear or rectangular arrangement can be initially chosen, which can be applied consecutively in the same horizontal plane or successive vertical levels for larger configurations. The subdivision of parts is then carried out according to the maximum dimensions of operation (with splice margins). Options make it possible to ensure the regularity of parts of the greatest possible length, or a combination of sections, as well as to develop stretches that match at the corners. Afterwards, the sections are traced with random curvatures or those defined by the designer, in a similar way in all the sections or randomly within ranges, and on the same side or sequentially on opposite sides (which gives greater stability, but reduces the internal area). The criterion of structural optimization defines thicknesses according to height, curvatures and continuity, thus establishing parametric families of walls in the BIM environment (Fig.3). Random generation can develop a number of sequentially named alternative BIM models, thereby giving the designer different configuration possibilities.

The various models generated in the BIM environment can be quantified, thereby obtaining the total material required, according to the amount, length and thickness of walls. The number of sections can also be determined, as well as the total length of sections, which in turn can be used to calculate the total operating time (multiplied by the number of cords in height and speed of execution, plus the machine´s transfer time). Then, models can then be compared in terms of material or processing costs, which are normally different depending on the curvatures, in addition to their spatial configurations, from interior or exterior perspectives. The process can also be planned based on steps, according to work schedules, by defining the work route and machinery installation positions, and anticipating the requirements involved. Likewise, this plan can be integrated with the rest of the BIM model to combine with other elements, such as floors or covers (which can also be executed with construction printing), including doors, windows, services, and terminations, among others. Furthermore, climate, structural, or infrastructure management can be incorporated into analyses. The programming developed is currently being completed with the ability to generate variable height configurations and combined splices to ensure continuity, parallel, cross-linked or embedded layouts for structural performance and material reduction or combination with different performance requirements (i.e. resistance, thermic, acoustic, chromatic). Finally, the model generated is exported with the elements of parametric families, in solid production (STL) and/or the format for machine control (KRL).

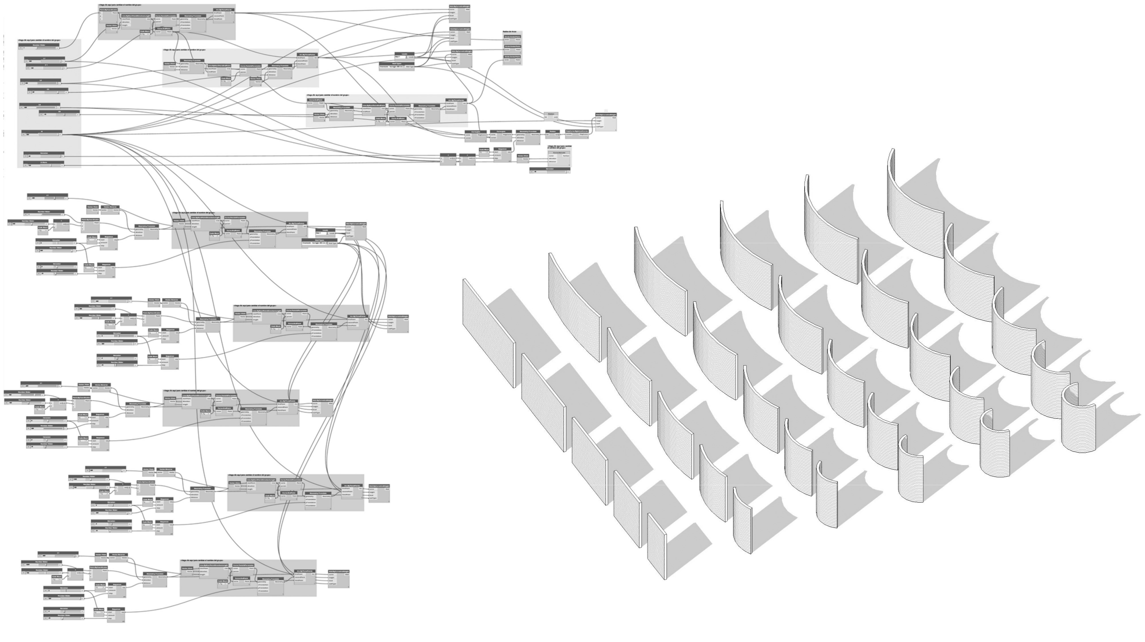

Figure 3: Parametric programming and examples of walls generated. Source: (DGNL Studio 2018)

1.3. The Implementation of a Robotic System for 3D Construction Printing

To boost the productivity and sustainability of construction, the Chilean government established a national development strategy (Corfo, 2014; Gutierrez, 2016) that included the creation of technology centers adjudicated by a consortium of local universities, with public financing and private collaboration. At the Universidad del Bío-Bío, located in Concepción, the main city in the south of Chile, which is characterized by its regional services and forestry resources, a large workshop is planned. This facility is targeted to elaborate prototypes in two areas of development: elements made of concrete, the primary construction material in the country; and prefabricated components made of wood, a material with environmental quality and local production. Both areas will be related through a mounting crane and integrated with a robotic system.

In order to experience 3D construction printing with concretes, polymers and/or biomaterials, the installation of an industrial robotic arm (Kuka KR120R2500) on a 10-meter rail with a concrete pump for a 120-liter pond with a 30 meter hose was approved through additional state funding. This installation will have a 140 m^3 workspace (Fig. 5) in which the arm and pump nozzle are able to make continuous walls of up to 15 meters in length and 3 meters in height, with six degrees of freedom. This will be the first 3D construction printing installation in the country and the most versatile and largest in Latin America. It will be managed by Universidad del Bío-Bío with the support of Universidad Santa María of Valparaíso; as well as the Research Center for Advanced Polymers and the Center for Nanotechnology and Bio-materials of Concepción; the PRODINTEC Foundation of Spain, which has been conducting research in 3D construction printing for five years; and Cementos Bío-Bío, Ready Mix and Bottai, the largest companies in the country devoted to cement production, concrete manufacturing and cement-based prefabrication, respectively. Financing has also been approved for additional research with a small-scale installation of robots with cars and 3D plastic filament printers that reproduce construction printing processes to experiment with multi-robot coordination in the execution of buildings.

2.0. PRELIMINARY RESULTS

2.1. Preparation and Samples of 3D-Deposition

To date, the equipment to test 3D-deposition has been used to carry out partial and complete elements, as well as review different compounds, machineries and procedures. In the test facility, 18 deposition samples have been completed with supplies available on the local market. The first twelve produced continuous cords, and the following six resulted in overlapping cords. In addition, other partial tests conducted with different mixtures were not able to produce continuous cords or regular finishing. In this way, the compound that was able achieve adequate flow and early hardening was determined to be a mix for quick concrete called "Topex”. In the first samples completed, adjustments were made in the configuration of the equipment in terms of operational control, working speeds, video recording and measurements. The average horizontal deposition speed of the initial samples was 22 seconds/meter, for cords 10 to 15 cm. wide and 4 cm. high. With additional time of around two minutes to load and reposition the trolley and by mixing in parallel, a production speed of 0.4 meter/min was obtained. Small linear and curved walls of up to 9 cords in height were formed, during a total production time of 24 minutes, with 3 minutes of deposition, which corresponds to an execution speed of 0.8 m^2/hour. Hence, a two-meter high wall could be made in 2.5 hours per meter of length, or in a more continuous process, without intermediate tasks, in 20 minutes per meter. This means that a wall of several meters can be completed in a few hours. Although production speed has not yet been verified for large pieces, it should be similar to other experiences reported (Malaeb et al, 2015; Torres, 2016; Ma and Wang, 2017), and is reduced in comparison with the various days required for the traditional execution of a similar wall, which involves formwork, reinforcement, pouring, curing, removing formwork, and repair of failures. Also, conventional construction of these elements entails more materials, personnel, accidents, quality control, administration, waste, transport and environmental impact.

Additionally, different inputs, mixers and pressure pumps has been tested. Therefore, mixtures with improved rheology (regular distribution of particle sizes of materials) were prepared to get pasty compounds. Seven samples of fine aggregate from local producers were collected, sieved and combined with cements and accelerators to develop preliminary tests. The expulsion nozzle was mounted on a longer-range horizontal rail (2 meters), with a larger capacity motor, and the vertical lift and transverse displacement system was designed to achieve a working space for samples up to 1.8 meters long and 1.2 meters high. In the future, these capacities must be industrialized, by means of mechanical or automated equipment, regular supplies and specialized staff. However, these experiences demonstrate the initial feasibility of creating building elements through construction printing with products available in the country, and their adaptability to different circumstances or local conditions, resulting in a significant reduction in time and resources in relation to conventional construction.

2.2. Generation and Assessment of Parametric Models

The programming developed to generate models of walls according to 3D construction printing features made it possible to implement a procedure for the design and evaluation of architectural alternatives in a BIM environment. A number of production assumptions are taken into consideration and used in a planning method with computational support to determine more effective and meaningful compositions. The design process is then integrated in a BIM platform, with parametric families of building elements determined by specific construction printing equipment, and the capability to generate and assess models, as well as to export information for analysis, quantification and visualization, and later, plan the execution and control of the machinery (such as Davtalab et al, 2018).

A building framework is first established by proposing a sequence of work spaces with fitting ranges to ensure continuity of production, in addition to equipment operating conditions such as thickness, deposition speed, and the resistance capacity of the material, among others. With these properties, geometric rules are programmed by means of graphic components and relationships through Dynamo in Revit software, with some instructions in Python to determine conditional recursive sequences and families of walls. The procedure then generates a set of models and also a schedule of quantities that can be exported. Furthermore, a macro is created in Excel to examine the data extracted in the analysis of models.

After several preliminary tests with different generation values, the programming was tested with an exercise to create an enclosure of 20 x 40 meters, with wall segments of a maximum of 10 meters, which may have a regular curvature, like an arc. It assumes that curvature implies different structural capacities (Martens et al, 2018), and therefore diverse thicknesses in different wall families. The programming makes it possible to develop 30 simultaneous models with different amounts of wall segments and curvatures (Fig. 4). Each model is assigned a code of variables, and subsequently elements are tabulated and exported to the spreadsheet. Thus, models are used to quantify the project, considering the total length proportional to the execution times, and the volume of material equivalent to the cost. Then the fastest and the cheapest models are identified and also the appropriate combination of both. From these three models, interior and exterior views are generated. In this way, the models are quantitatively and qualitatively evaluated. The process must be validated with the operational capabilities of the equipment, as well as in actual design activities. However, it facilitates the systematization of the design and execution processes with construction printing through digital integration targeted at developing the versatility and optimization of the building.

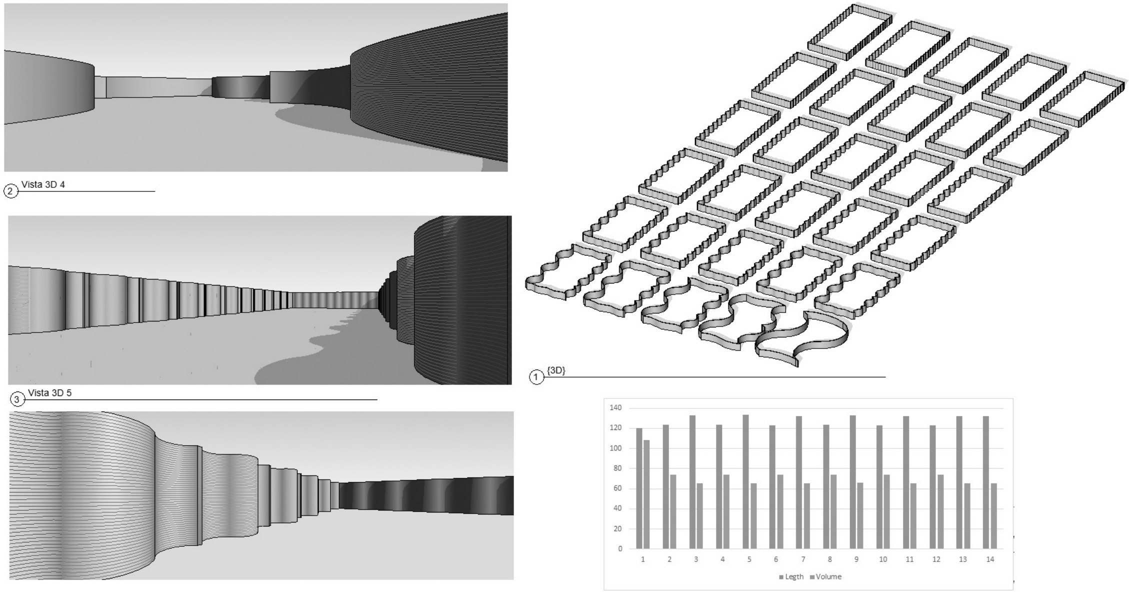

Figure 4: Models generated, visualizations and quantitative assessments. Source: (DGNL Studio 2018)

2.3. Agreements on and Plans for a Large-scale Robotic Installation

State, industrial and academic stakeholders have converged in a plan to install a large-scale robotic system for construction printing in Chile in order to move towards more efficient building with less environmental impact (Bogue 2018). The provision of state funds oriented towards the productive and sustainable development of the country; university interests in professional training with a perspective on the future; and the motivation of private companies aimed at maintaining or increasing their participation in the construction market, express trends that come together in the planned installation and which have been consolidated through financing approval and specific work agreements.

A technical board has been formed with representatives from the participating institutions and companies, collaborative developments have been prospected and joint tests are being carried out. Cement companies have provided concrete injection equipment and various materials to conduct pumping tests. The Research Center for Advanced Polymers has supplied samples of polymer blends and injected polyurethane to test printed elements. The Center for Bio-materials and Nanotechnology is preparing cementitious compounds with nanocellulose fibers for testing, to develop local products with low environmental impact, and better resistance and thermal performance for construction.

The agreed installation expresses a joint development perspective in the building sector. It involves the production of cementitious mixtures for deposition in: a plant for prefabricated elements, the site-work for the execution of the main parts of buildings, as well as the manufacturing of products and equipment, and large-scale construction in medium and larger dimensions, with the participation of local companies, state programs and national standardization. It also represents a motivation to promote new compounds with polymer blends and bio-materials, in search of lower execution costs and greater constructive and environmental functions. The agreements and plans developed should materialize in the installation and joint experimentation, with the adequate provision of resources and coordination of activities. They are evidence of the relevance of this technological innovation and its potential to have a productive impact on the local construction industry and to link stakeholders and society.

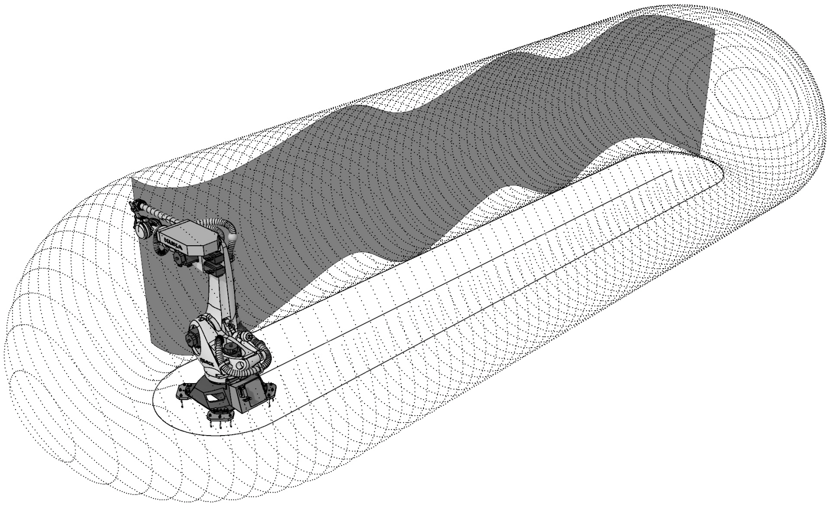

Figure 5: Working space of the installation. Source: (DGNL Studio 2018)

3.0 ARCHITECTURAL AND URBAN PROJECTIONS

3.1. Architectural Compositions

According to the experiences detailed previously and reports of diverse initiatives around the world (Perkins and Skitmore 2015; Labonotte et al 2016; Wei et al 2017, Panda et al 2018), the developments in 3D construction printing have mainly focused on the main vertical elements of buildings. Some cases have involved inclined or vaulted coverings, or prefabricated pieces or sections that are later moved and mounted on the ground (Yuan et al, 2018). The vertical printed elements are self-supporting planes and diverse in form, usually with rounded corners and/or curved parts; so that the first printed constructions have mostly been horizontal buildings, low in height with sinuous shapes, and integrated with conventional products for roofing, fenestration, services and/or terminations. There is great interest in increasing the insulation, finishing and resistance of these vertical compounds, as well as in curved fabrication, which together provide more stability, better performance and novel spatial experiences and meanings associated with new technologies, environmental requirements and/or cultural attributes. Most stakeholders and entrepreneurs of 3D construction printing are motivated to develop large-scale housing projects with short construction terms and innovative features, but it is also possible to construct buildings for commercial exhibition use, industrial workshop or public services. Due to the incipient conditions of 3D-printing technology, which depends on new and large equipment, in addition to unique supplies and specialized personnel, the buildings could be concentrated in new urban complexes promoted by local developers.

3.2. Building Processes

The planning and design of buildings with 3D construction printing should integrate this technology early on in the process, thereby taking advantage of its technical and expressive features (Delgado et al, 2018). The available local suppliers must be taken into consideration, together with the formal, constructive and economic condition of the architectural configuration. Previous experiences should be used to determine the specific attributes of the buildings, while also testing some parts or characteristics that have not previously been developed. Hence, traditional design documents, construction management and experienced personnel must be combined to progressively integrate these new technical capabilities. The digital management of the process should motivate an increasing exchange of documents, and agreement on formats, tasks, protocols and analysis potential, especially related to visualization, planning, structural, environmental and/or economic features. This implies the need to normalize and regulate some constructive conditions, systems and commercial products in relation to the scope of elements and buildings that can possibly be executed, for example in functional properties, articulated with their commercial and social projections. Development will most likely concentrate on specific products (buildings, elements or applications), which call for commercial and constructive advantages, in sufficient magnitudes and with a permanent demand to sustain them. This can impel productive synergies, or perhaps also financial bubbles, which will enable new close linkage between the market, society and the construction industry, along with flexible and intense professional developments with promising capabilities.

3.3. Urban Perspectives

3D construction printing has been promoted to reduce work time and resources, which was confirmed in the first experiences with deposition and digital integration capabilities, although they do require industrial development. These conditions are crucial in construction due to the large costs and duration of planning and execution that involve previous expenses in materials and personnel with late exploitation, and require high amounts of financing and management efforts. Consequently, decreases in time and resources should result in lower costs and enable the participation of smaller companies and stakeholders than in conventional construction. However, initial actions depend on advanced capabilities and equipment, which require greater technical and financial support, waiting for dispersion through entrepreneurship. It should also be considered that the lower costs of printed construction should be linked to lower value lots, usually located in the peripheries of cities, which may be close to production sites, thus encouraging experimental neighborhoods or exceptional buildings in these sectors. The versatility of technology and digital processes enables local adaptation that must be oriented towards the relevance and effectiveness of buildings and reducing social and economic gaps. In the long term, the development of 3D construction printing should motivate real estate decompression, the acceleration of the industry and social initiatives, and connection with new cultural trends and environmental commitments, thereby promoting the achievement of a collective well-being.

CONCLUSIONS

This work presents initial works with 3D construction printing in Chile to explore its architectural and urban possibilities. The results of material tests, design programming and the planning of a large installation demonstrate local feasibility, architectural features and sectorial interests related in particular with biomaterials and large-scale construction, which would enable the production of singular buildings and urban complexes. Like also others initiatives around the world are showing. Nevertheless, there are also important challenges in the development and industrialization of this technology. These experiences demonstrate the capability for fast execution and process integration, and the potentialities of curved patterns, performance and novel constructions based on natural resources and infrastructure needs. This technology can promote projects for new city sectors and exemplary buildings associated with commercial, environmental and/or cultural motivations. Through experimentation in developing countries such as Chile, local adaptations and specific initiatives can be achieved that complement the global emergence of this technology, thus establishing a more varied horizon of architectural and urban evolution.

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