3D Printing & the Construction Industry

An essay mapping the current status of the technology and why it is relevant when solving the housing crisis of the Global South

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1 Introduction

As attachments to this essay, there is a "List of abbreviations and definitions" as well as a "Timeline covering a compact version of the industrial revolutions". These are very useful for the reader, since there are definitions and references in this essay which are in need of clarification.

The purpose of this essay is to show illustrate a building technology which has been developing since the 1950s –3D printing with large scale industrial, Cartesian and other robots on construction scale. (Papanek, 1984) The essay could just as well cover more innovative construction methods, but for the sake of consistency and clarity, only one has been chosen. The sub-purpose of this essay is not to apply the technology as is to solve the housing crisis in the Global South, but to indicate what the technology is representing and why it is of just as much importance.

The secondary focus, when the subject is translated into an architectural proposal, is the consequence in the PHL (the Philippines, part of the GS) and why it is relevant when trying to solve the current housing crisis of that specific country.

As stated, the essay will focus on 3D printing as a construction technique, but it is worth noting that 3DP (3D printing) isn't the sole innovative construction technique connected to the 3rd and 4th industrial revolution (please see timeline). The proposal as is will therefore not only focus on 3DP, but innovative

construction techniques as an entity and what that means to the construction industry. This will be covered in the “Discussion” section.

To introduce the benefits of an innovative construction technique such as 3DP, here listed are the benefits of the technology out of three different perspectives: The architect’s, the client’s and out of a sustainable perspective.

3DP4BE (3D printing for the built environment) is interesting for us as architects since it gives us more control compared to our more common involvement in the CAx chain (the CAD based manufacturing process) of the building industry. This is because we can produce the CAD model which is directly translated to the 3D print. This, of course, is highly individual from project to project and should not be generalized. But, one is mostly correct when stating that the architect of 2017 have less impact in general over the final building compared to the architect/building master before the 1st industrial revolution. The standardization which the 1st and 2ond industrial revolution and the world wars have led to within the building industry has impacted our *influence on* as well as *the possibility of* (affordable) customized designs. (Bock, 2014) The 3rd industrial revolution is in many ways only a more effective version of the manufacturing chains offered to us by the past revolutions. (Menges, 2015) In theory, the more control we have over the CAx chain, the truer the result will be to our intentions. Even so, as the timeline and analyses say, the 4th industrial revolution will bring a different manufacturing chain all together. This actually makes the control focused focus of the architect less applicable in a large, long-term sustainable solution for the Global South and the PHL specifically. More to come in the “Discussion” section of this essay.

3D printing structures on site is interesting for the client since you can to save costs up to 70% compared to building with regular blocks. (Khoshnevisk, 2004) One also saves construction time, up to 99.6% when the procedure goes smoothly. (Cor, 2017) Time and cost is referring to 3DP with concrete on site, different techniques. 3DP4BE is interesting for the client as a general concept for several reasons. It will give the client a result more true to the intentions shown by the architect to the client. Since its additive instead of subtracting as a manufacturing technique; it generates less waste and needs less material which is cost saving. Additionally, the technique enables a client with a smaller budget to obtain a more customized housing solution compared to constructing with standardized elements.

3D printing structures on site is beneficial for our CO^2 situation and future disaster management. Compared to CMU (construction using concrete masonry unit), CC (contour crafting, using extruded concrete and all other wall materials such as insulation) only produces 14 % of the common solid waste. The CO^2 embodied into one square foot of wall made by CC is 25% of one made with CMU, embodied energy is 50%. (Arhami, 2009) Regarding disaster victims, one can imagine the possibilities regarding extremely fast construction for comfortable long-term use housing. (Khoshnevisk, 2004)

To clearly map out the current possibilities of 3DP4BE, presented next are several cases sorted by the material possibilities of the technology.

2 Case Studies

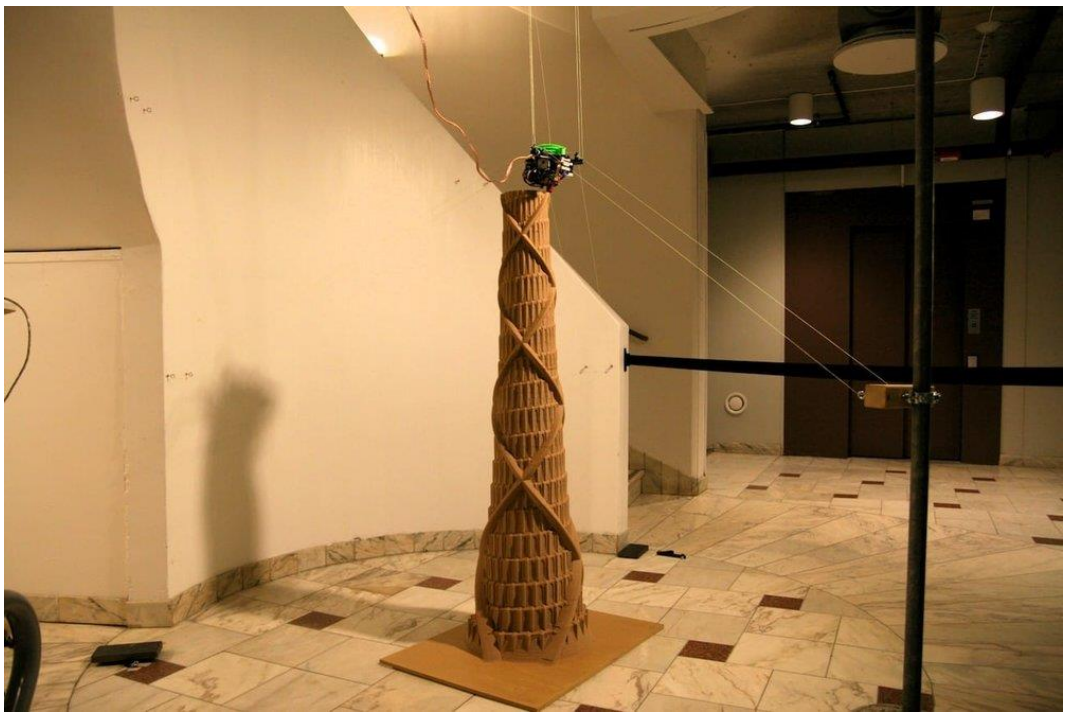
2.1 Wood Dust Blended PLA- Sliperiet - The HangPrinter – 2017

The HangPrinter is interesting for several reasons. The first is its choice of material for this specific project, the Tower of Babel. What is common for a printer like this, is to use PLA (plastic) as a material. What Torbjørn Ludvigsen did was to mix it with 30-40% wood dust. (Jackson, 2017) This gives a more tactile, interesting and mat surface. Mixing PLA with different dusts can speculatively be applied for interiors when a dust-type is available close to construction. Saw dust from a wood factory, stone dust from a quarry, crushed ceramics from a close-by demolition site, etc. Worth noting is that a printer like this isn't really restricted to using PLA, it all depends on the extruder and the way of feeding the material. One can speculate in using clay, concrete, other plastics, rubber or resin.

The second thing which makes this project worth noting is it's innovation regarding print sizes. Normally, a Cartesian printer (please see appendix) is restricted by a box which holds it. This printer can be hung in any space, which makes a permanent box unnecessary. The unrestricted scale application of the print makes it very interesting for interiors where furniture, walls, floors or ceilings should be printed.

For your information, the printer is a RepRap (please see appendix) suspended by three points in a space. The blueprints of his invention is shared in an open source

manner, to ensure collaborations and further development of the printer. (Santos, 2017)



2.2 Concrete - Apis Cor – 2017

The concrete mixture which the 3DP4BE focused company Apis Cor used for this building (a project without a clear name but presented by Apis Cor as “the world’s first on-site 3D printed house”) is specified as a “specially developed mortar mix on cement base with the addition of special additives, including reinforcing ones” by the company themselves. (Benedict, 2017) This definition is unfortunately quite vague but implies a concrete mixture re-enforced by fibers and with possible quick-dry additives.

The material is only possible to print with in an environment of 5 degrees Celsius or more, which explains the construction tent used when printing this project in Stupino, Russia. (Gazette, 2017) The printer itself though is operational down to minus 35. Apis Cor promises to develop new fills for the printer, such as geopolymer, which has less of a temperature restriction.

Apis Cor markets the project as having had extremely quick on-site printing time. By February 2017, the first 3D printed house in Stupino town (multiple are planned) was ready for the media. According to their website, Apis Co and their engineers PIK started printing in December 2016. “The house was printed in 24 hours.” According to other sources though, that was not the case. The Danish company 3D Printhuset is investigating 3DP4BE and visited Apis Cor during the process of the Stupino house. Apis Cor started the first layer in June. When 3D Printhuset visited again in November, there were three layers of print. 3D Printhuset went again in February, but Apis Cor wasn’t ready to show the building. According to Ana Goidea, part of the teaching team of Spatial Experiments Lund University, even to say that it takes 24 hours to print two layers of this concrete technique is a stretch.

It is interesting to note that we're not really there yet regarding extremely quick construction times, but the technology enables for it on later stages of its development.

A final note, Apis-Cor claims that they have a mission. "We want to help people around the world to improve their living conditions. That's why the construction process needs to become fast, efficient and high-quality as well. For this to happen we need to delegate all the hard work to smart machines." (Cor, 2016) Most professionals within the construction industry and most clients would agree with this statement, even though the general resistance regarding the last sentence is evident amongst most workers. As it has was before the 1st, the 2ond and the 3rd industrial revolution.

2.3 Polyurethane framework - Digital Construction Platform MIT – 2017

Just as for the case study "30-40% wood dust blended PLA- Sliperiet - The HangPrinter - 2017", this project is not only interesting because of its material use but also because of its geometric freedom.

The DCP (Digital Construction Platform) is simply put a system with a large KUKA industrial robotic arm aided by a smaller, precision-motion robotic arm at its end. These mounted on a larvae wheels carried tracked system and an additional wagon for the material stock. It's been developed by the Mediated Matter Group of MIT (Massachusetts Institute of Technology). The "polyurethane framework project" was published April 26, 2017. (Chandler, 2017)

The project shows how the printer travels, seemingly on energy supplied by solar cells, over a flat asphalt site and printing a large, tapering, cylindrical foam structure. The purpose of the structure is to be filled with concrete, thereby acting as a framework for construction but also as insulation. The foam should be left intact and covered by wall finished. Another interesting addition is that the nozzle used for this print can vary the density of the material being poured as well as mix different materials into the structure step by step. (Chandler, 2017)

The developers claim that the reason for this specific project (the foam) was that "we also wanted to show that we could build something tomorrow that could be used right away." One can add that Mediated Matter Group visions the DCP being able to perform any needed construction fabrication process. It can already also pre-dig and flatten the construction site by itself.

Printing with an industrial robotic arm is different from a Cartesian printer, since the arm is a system of its own and can carry any nozzle and extruder system. Additionally, a robotic arm is a system which can direct any fabrication method. You can attach a gripper, a mill, an extruder, a welding machine... Basically, anything you use your physical arm for and more. Because of this, the DCP can actually do anything needed on site.

Media Matter Group are very enthusiastic about the future usages of the DCP. Since the aim is for it to run on solar panels, it could be used remotely for quick disaster relief or housing in space. As an addition to doing normal constructions, that is.

2.4 Glass - The Glass II Installation MIT – 2017

The technology (called G3DP2) was displayed at Milan Design Week, April 2017. The Mediated Matter Group of MIT displayed it through several illuminated glass columns.

This is not an on-site technique, but the latest regarding architectural scale 3D printing with glass. The manufacturing platform could be called Cartesian. It is top loaded. The system is described as follows: “It has a digitally integrated thermal control system—to accompany the various stages of glass forming—as well as a novel 4-axis motion control system permitting flow control, spatial accuracy and precision, and faster production rates with continuous deposition of up to 30kg of molten glass.”
(Visnjic, 2017)

2.5 Bio-Degradable Plastic - Dus Architects et al: Urban Cabin - 2016

This is a “mini-retreat” built in 2016 in a former industrial area of Amsterdam. It is printed in 100% bio-degradable plastic which is 100% recyclable into a new printing process. The material is interesting, since plastic is relatively easy to print with but is normally regarded as less sustainable since it isn’t biodegradable in its common chemical composition. It is merely 8 m2 and 25 m3, but houses two persons relatively comfortably and offers a retreat in the busy city. (Daily, 2016)

The cabin is a part of a larger scheme, the “3D Print Canal House” which is both a project and a large MAKE-tank in Amsterdam. For the Cabin, the architects responsible, DUS, developed (within the scheme of the Canal House) a large 3D printer called “Kamer-Maker” together with Ultimaker and Fablab Protospace. KamerMaker cannot print an entire room at once (as the name implies) but can print rather large structures out of different plastics. The printer is movable as the last image implies. (Kaelin, 2013)

2.6 Portland Cement Composite - Bloom by Emerging Objects – 2015

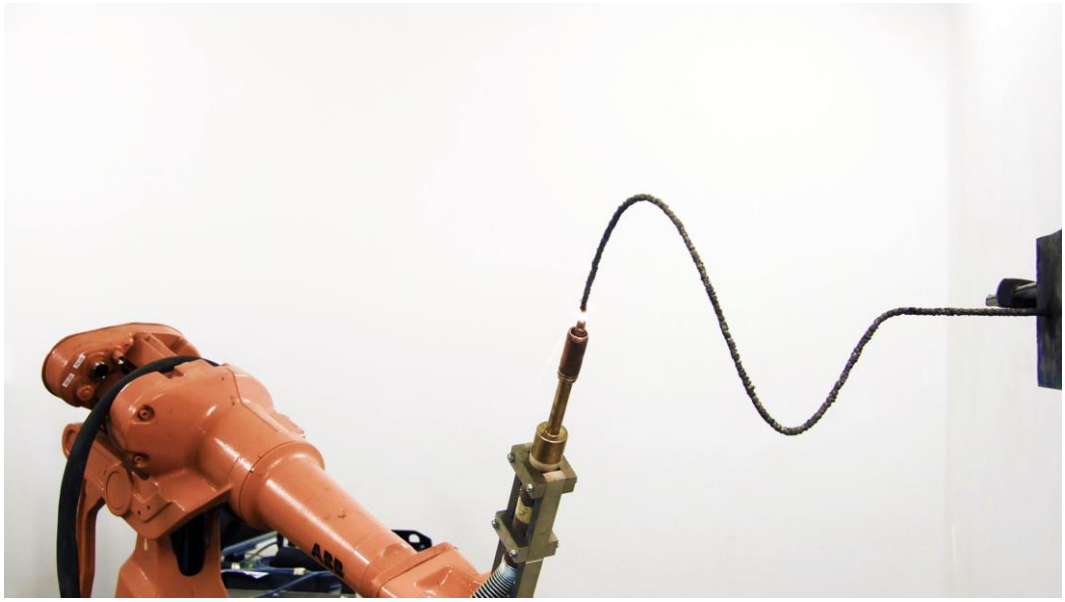
“Bloom” is a 2.7 meters tall, 3.6x3.6 tempietto made by 840 printed blocks of a cement composite formulation comprised chiefly of iron oxide-free Portland cement. The smaller blocks were assembled off-site into 16 large, lightweight panels which were assembles on site during a few hours. (Objects, 2015)

“Emerging Objects” is an “an independent, creatively driven, 3D Printing MAKE-tank specializing in innovations in 3D printing architecture and building components” according to themselves. The MAKE-tank is driven by Ronald Rael and Virgina San Fratello, Rael also being an Associate Professor of Architecture University of California Berkeley and San Fratello an Assistant Professor of Design San José State University. (Objects, 2017)

Emerging Objects experiment with a wide range of materials for 3D printing and are mostly focused on what is called “discrete assembly” (loosely defined as not printing entire solid structures, but pieces for assembly). They have projects printed experiments and projects in salt, tea, chocolate, concrete, sand, plastic (PLA, nylon & acrylics), ceramics, metal, paper, resin, rubber and wood.

2.7 Steel - Amsterdam Bridge MX3D – 2015

MX3D plans to construct a bridge in Amsterdam, the case study here shows the smaller version of the project which they constructed 2015. The material used is steel, extruded by a 6-axis robotic arm with a welding machine at its tip. What is interesting here it the applications freedom, which enables 3D printing in metal in mid-air. (MX3D, 2015)



Tim Geurtjens, CTO MX3D:"What distinguishes our technology from traditional 3D printing methods is that we work according to the 'Printing Outside the box' principle. By printing with 6-axis industrial robots, we are no longer limited to a square box in which everything happens. Printing a functional, life-size bridge is of course the ideal way to demonstrate the endless possibilities of this technique." (MX3D, 2015)

MX3D, a company which researches 3D printing technology, invented their first printer in 2014. They are promising the bridge (design by Joris Laarman Lab) to be ready in 2017, but has since 2014 made several smaller projects with the same technology. They can also print resin in mid-air.

2.8 Clay - “BigDeltaWASP 12m” by WASP – 2012

In 2015, WASP developed a 12 meters high and 7 meters wide multi-extruding printer called “BigDeltaWASP 12m”. On their website, one can see several trials printed with it. It can use local materials, such as clay, mixed with long fibers such as straw. This is interesting since it enables on-site sourced buildings materials in regions where these is good soil. It can also use cement or any other imaginable fill. It can be run by energy supplied by solar panels.

The base company of WASP, which is called CSP, was founded in 2003 by Italian Massimo Moretti, with the purpose of developing innovative projects to help creating a better world based on sustainable progress.

WASP was created in 2012. It's a project which produces solid professional printers, also trying to give and put know-how and tools in circulation. It finds its roots in the world of Open-Source. Their projects are financed by the revenue of these printers. The aim of WASP is to build "zero-miles" home, using local materials and renewable energy. (WASP, 2017) (WASP, 2017)

3 Discussion

The case studies clearly show the current offered range of 3DP4BE materials and the kind geometric freedom it supplies. The case studies are not enough in numbers to give a true representation of the latest progress within the industry, but they give a general hint. So, how come we aren't seeing these technologies on site yet?

The building industry is far behind compared to other industries within the 3rd industrial revolution, much because of the huge sums of money involved in the projects, the timeframes, the complexity and also a general conservative attitude. As a generalization, one can claim that the construction industry is half way integrated in the 3rd industrial revolution (concerning optimization of supply chains of standardized elements, the uses of virtual CAD tools and virtual reality tools) but is not really applying it in a larger scale regarding fabrication/construction. Educational bodies within architecture and research though, such as IAAC (Advanced Architecture of Catalonia), MIT (Massachusetts Institute of Technology), ICD Stuttgart (Institut für computerbasiertes Entwerfen) and USC (University of Southern California) are more real-time integrated and even as far as concerning the 4th industrial revolution. ICD are experimenting with robots who interact, simultaneously as a company called HAL Robotics are doing it with great success. Companies such as Siemens are selling production

lines (for the car industry), which are developed CAx-chains (CAx chains belong to the 3rd industrial revolution). Those developed manufacturing chains are on the brink of being interactive in a 4.0 Industry manner (a term belonging to the 4th industrial revolution, implying big data and interactive controllers) but is not yet. Siemens prove how far other industries than the construction industry are regarding development.

Another innovative body are start-ups within 3rd industrial revolution construction technologies and especially 3D printing. One can assume that their progress is more rapid due to less administration, smaller company, less company history (conservative attitudes) and possibly a larger focus on a goal than general profit. They are also fully focused on one specific task and which is the reason for them starting up to begin with. Examples are Apis-Cor and MX3D.

Even though extreme progress has been made within 3DP4BE since early 2000s, especially regarding 3D printing on site, we are a few years to go before it really changes the building industry. As stated before, we do see innovative virtual technologies being applied, such as interactive BIM models used for site and construction management. But the actual physical construction is not entirely there yet, it is still mainly being defined by standardization. Standardization, which derives from the aftermaths of WW2, then an extremely effective solution to the housing crisis which followed the war. (Bock, 2014)

In the world of today, housing crisis's are getting worse in an exponential rate, but not due to such extensive wars as WW2. Today's housing crisis is generally a consequence of rapid urbanization, as in mass migration to large cities and cities expanding in size quicker than the housing market can handle. This usually affects a part of the city population called the "urban poor", a part of the population which also (due to other factors) expand quicker than the part which can compete economically for the little housing available. This problem is also more eminent in the Global South than the Global North.

The case studies shown are progress made by GN countries, such as the Netherlands, the US, Russia and Italy. As a logical transition, the already developed countries (GN) of the world are developing quicker than the non-developed (GS) since they already have a solid industrial background and relatively well functioning social/economical/political systems which have been consequences there-of. There are definitely exceptions though. The Chinese

company HuaShang Tenda (not covered here since they also print in concrete but with reinforcement already in place on their most successful project) have been developing 3DP4BE since 1989. They are implementing 3DP with concrete to build housing. One interesting case being a two story villa they printed in June 2016 in 45 days. (HSTDGM, 2016) A common way of reasoning by companies such as WASP or Apis-Cor is that their technology can be applied in the GS and thereby solving housing crisis's quicker.

On a very personal note, I'd like to disagree with that notion as a one-off solution. I believe that countries which are not yet developed, due to many factors, have the right to develop quickly and sustainably. GS countries can develop is a sustainable manner and avoid mistakes which the GN countries have done (such as two industrial revolutions producing global warming). A housing crisis can indeed partly be solved by producing housing rapidly, which for example on-site 3DP with concrete promises. But it is bound to be solved even quicker if GS countries are developing these new construction techniques alongside the GN countries. By providing GS countries with *tools* to develop, *economical support*, *education* and *collaboration*, we are bound to solve a housing crisis quicker and in a more sustainable manner. As well as, not to mention, hopefully at the end of the day nullifying definitions such as GS and GN.

As a current example, the capital of the Philippines, Manila, currently lies within the GS and suffers from an extreme housing crisis due to rapid urbanization. The housing crisis of Manila manifests itself not by homeless people in that sense, but rather inadequate, unsafe, unhealthy, overcrowded and in many other ways insufficient shelter. Generally defined as informal settlements, looking like slums constructed by MDF, metal sheets, cardboard and other easily accessibly materials to the untrained eye.

Currently, the government of the PHL tries to solve the crisis (more specifically, the "informal settlement issue") by, for example, upgrading and relocating. In other words, building new dwellings (mostly by a governmental body called the National Housing Authority: NHA) and moving the urban poor from the informal settlements to new, more adequate housing. That is a good strategy, but there are not enough housing produced and not quick enough. One could, on the basis of this essay, argue that NHA could apply quicker construction technologies, such as 3DP with concrete, clay and metal. As a concept, that would work. But, the construction techniques are not even generally used by the construction industry

in the GN yet and do not have enough “real” building project history to suffice all safety regulations which other technologies (for example, barn timber frame construction or a curtain wall facade) have proven adequate to by legacy.

The NHA is currently keen to use and certificate new building technologies and has a certification system called AITECH which new building technology has to go through before being used in NHA’s projects. The accreditation is to be applied for by a construction company (part of the private sector) which seeks it and the bureaucratic process is long. This is mainly due to the number of safety and physics tests having to be made in order for NHA to prove the technique sufficient. NHA relies on the private sector to come up with new technologies, which in itself isn’t a bad strategy. What is bad in the strategy is the time it takes before the technology is applied (due to bureaucracy) and the process which usually leads up to the technology. With the process, I mean to say that innovation which is made by a large company seeking credit can be (must not be, Foster and Partners being examples of that) different from innovation made by students or start-uppers. Not to mention that NHA misses out on many new technologies simply because the company developing it doesn’t see a point in having the AITECH accreditation.

4 Urban Shelter Design

Therefore, I suggest in this example that as a parallel strategy to providing governmental adequate housing to solve the crisis, the government of the PHL should act as an innovator regarding building techniques. This is easily said, but NHA or the PHL government cannot do this alone. One can hark back to how innovative construction technologies have been developed in the GN. Many innovations have happened due to collaborations between educational institutes and private companies (such as MIT and collaborations with many companies including Autodesk for example) and/or start-ups combined with the private sector and the public sector (such as Apis-Cor, PIK and Stupino town). The private sector plays a large role, usually within funding (can be licenses, machines or economical collaborations). According to me, the public sector can provide funding as well.

It is all a question of priorities, according to me. I might be terribly wrong. But in the very specific case of the public handling of the Manila housing crisis, NHA

could provide shelter quicker if they didn't have to test all technologies for AITECH but simply be a part of their innovation and thereby being sure about the safety aspects of the technology. They would ensure access to new, innovative technologies (the ones which might otherwise not have applied for accreditation) as well.

Because of these reasons, a catalyst space for the PHL construction industry would be a sustainable sub-strategy when it comes to solving the PHL housing crisis. A catalyst would consist of, I suggest, a new department for the NHA (which focuses sole on developing innovative construction techniques), a fabrication laboratory and offices for start-uppers. The laboratory should be funded by as many architecture schools as possible in Manila and be open to the students. NHA would collaborate with the students, as well as students from other faculties when invited, in workshops. NHA would also collaborate with the start-uppers and they would be able to rent offices plus time in the FabLab (fabrication laboratory). A catalyst like this would help the PHL construction sector enter the last parts of the 3rd industrial revolution (actually implementing the fabrication techniques in a large scale) and the first parts of the 4th quickly and hopefully simultaneously as countries in the GN.

5 The Role of Architects

The role of the architect, or rather the responsibility of the architect, is to stay involved and curious regarding new construction technology and innovative design.

I am not trying to say that everyone within our field must do this, but I would like to insist that everyone who is interested has a responsibility.

Architects tend to let the design come first and the construction problem second, instead of the other way around. This is very good for innovation and development of the construction industry, since seemingly impossible constructions never are – there is simply a need of innovation from the corner of engineering and construction. For example, most of the built projects by Zaha Hadid Architects have been solved in that manner. Architects with design visions combined with clients with a timeframe and budget, can result in innovative

construction if there's a good match between the vision of the architect and the need/desires of the client. If there's a will there's a way!

The way of reasoning of the above paragraph might give an impression of innovative and pushy design only belonging to projects with budget, but this doesn't have to be the case. The architect might have to work with the client and the engineers/construction companies in a different manner (just as much communication but maybe more push from the architect's side regarding the rights of the client) when the client isn't a singular rich person but rather a community in need of help.

Regardless, we need to try to stay involved. One must not work together with the public sector in order to, but one can spur innovation when working in a more common commercial environment or, especially, when working in an educational environment. The educational bodies of architecture carry the load of something which inherits a heavy responsibility but a great promise – the future.

6 List of Abbreviations and Definitions

3D4BE – Three dimensional printing for built environment (abbreviated by the author for the sake of simplicity)

CC – Contour Crafting

USC – University of Southern California

NOZZLE – (For 3DP) spout at the end of the extrusion pipe.

EXTRUDER – The extrusion enabling machinery which in a 3D printer forces material through a tube and out through the nozzle.

CARTESIAN ROBOT– A robot where the nozzle can be moved in a linear fashion x, y and z. Common type 3D printer, an example is a MakerBot.

INDUSTRIAL ROBOT– A robot arm which can move freely in six axis because of its joints. An example is an ABB IRB1600.

ADDITIVE MANIFACTURING & RAPID PROTOTYPING– Two phrases both referring to the action of 3DP in layers.

THE GLOBAL NORTH/SOUTH DIVIDE- A simple way of classifying countries into relatively richer and poorer countries. Based on the Brandt Line from the 1980s. One should definitively note that the definition isn't definite, since many poor countries now a days are experiencing significant economic development. (Society, u.d.)

GN - The Global North. "The concept of a gap between the Global North and the Global South in terms of development and wealth." (Society, u.d.)

GS - The Global South.

PLC "THE MODICON" - A control system used within almost every industry in the world of today. Marks the start of the 3rd industrial revolution (1969), by introducing an industrially hardened computer based unit to replace the former control units which were relay controls (electrically operated switch). The PLC is more effective than the relay, since it doesn't expand in size to the same extent when you introduce more logic to the programming. Relays within industry use to cover several walls and consist of several terminal blocks and masses of wires. The smaller PLCs are the size of a brick, the larger systems cover a wall. (Romero Segovia, 2013)

THE CAx CHAIN - Industrial production and design chains introduced by the shift to the 3rd industrial revolution. Examples are computer-aided design (CAD), computer-aided engineering (CAE) and computer-aided manufacturing (CAM). (Menges, 2015)

INDUSTRY 4.0 - Not to be confused with the 4th industrial revolution since it only defines a manufacturing technique and the revolution effects the world on a larger scale. The term "Industry 4.0" was accepted by the German government, presented to them by a group called Industrie 4.0 Working Group in 2011. (Prof. Dr. Henning Kagermann, 2013) As a follow up on the computerized

manufacturing chain of the 3rd industrial revolution, Industry 4.0 represents a manufacturing chain which is "smart". A general understanding of the term does not exist yet, but as a concept it is currently top priority for many research centers, universities and companies. In a loose manner, a smart chain is defined as a complex system where cyber-physical systems (a mechanism controlled or monitored by computer-based algorithms, tightly integrated with the Internet and its users) monitors physical (production) processes with/by a constant feedback to the physical-go-cyber world and its users (us). (Herman, 2016)

CYBER PHYSICAL SYSTEMS - As a control/manufacturing industrial system, this connects the physical processes of making (as milling or printing) with the virtual domain of computation and big data (the Internet). A manufacturing chain does not only consist of robots and PLC controller, but they also interact with each other, their virtual version of reality and the users/programmers. (Menges, 2015)

FABLAB – MIT defines FabLab (fabrication labs) as spaces which provide means for innovation. "Projects being developed and produced in fab labs include solar and wind-powered turbines, thin-client computers and wireless data networks, analytical instrumentation for agriculture and healthcare, custom housing, and rapid-prototyping of rapid-prototyping machines." FabLabs usually include technical training etc. as well as an adequate number of (digital) manufacturing machines such as laser cutters, 3D printers, manual tools, milling machines etc. (MIT, 2017)

REPRAP – "is humanity's first general-purpose self-replicating manufacturing machine." A RepRap is a 3D printer which anyone can produce at home (by another 3D printer). It is open source. (RepRap, 2017)

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