ARCHITECTURAL APPROACHES DEALING WITH THE PROBLEM OF SEA LEVEL RISE
FLOATING AND AMPHIBIOUS BUILDINGS

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EXTENDED ABSTRACT
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ABSTRACT
Global sea level rise has been projected to reach values of 1.5 to 1.8 meters by the end of the century (DeConto & Pollard, 2016). An alarming new estimation that has its most harmful consequences in low elevation coastal areas around the world (Zevenbergen, et al., 2013). These will suffer from higher flood risks, amongst other associated effects, which will exponentially increase the vulnerability of human settlements. Further within the area, the Least Developed Countries and the urban poor have been identified as the ones most likely to suffer from the rise (UN-Habitat, 2011).

Architecture can play a major role in reverting and mitigating the tides on the matter, rendering cities and future expansions around the globe resilient, sustainable, and at the same offering shelter to those mostly in need. In this thesis, the megacity of Dhaka, the fastest growing in the world, capital of Bangladesh, is the stage of an amphibious, low-cost and sustainable architectural proposal which intends to serve such purpose, constituting the main objective of the thesis.

KEYWORDS: Climate change; Sea-Level rise; Floods; Low elevation coastal areas; Resilience; Sustainable architecture; Amphibious structures; Dhaka.

INTRODUCTION
This extended abstract concerns a thesis which focuses on floating and amphibious architectural approaches dealing with the problem of sea level rise in LECA (low elevation coastal area(s)) (less than 10 meters above mean sea level) and the consequences which are dragged along with it, but mainly higher flood risks (the most destructive). The document is divided in five sections: Context – where the author frames climate change and its consequences on demographic, urban and socio-economic spheres; Approaches on Water – where some approaches towards sea level rise’s consequences (mainly floods) are discriminated; Case Studies – 4 projects and their generation processes are analyzed for future reference; Project for Dhaka, Bangladesh – where the information gathered in prior chapters is used to create an amphibious approach for Dhaka; and Project Recommendations – a set of recommendations withdrawn from the author’s research and design proposal. The main objective of the thesis founds the contents of the two last chapters (4 and 5): an amphibious, low-cost and sustainable architectural proposal which intends to serve the most vulnerable against climate change’s elevated flood risk.
Data was collected through extensive research on publicly available data, such as in websites, books, thesis, journals, etc. A great number of these were edited and/or written by members of scientific organizations (like the IPCC, NASA and UN), non-profit organizations (Village Volunteers, Hunnarshālã Foundation, etc.), university teachers and students (Technische Universiteit of Eindhoven and Delft, Waterloo University, Faculty of California Polytechnic State University, etc.), independent researchers, architects (NLÉ, Bacca Architects, etc.) and companies (Dura Vermeer, etc.). It was necessary to complement findings with information requests to relevant entities (Rijskwaterstaat, Prof. Dr. Han Meyer, World Bamboo Organization, etc.) as well as interviews to experts on the matter of floating structures: Willem Visser, owner of the ABC Arkenbouw factory in Urk, Netherlands; Instituto Superior Técnico’s naval engineering and architecture Prof. Dr. José Varela; and sustainable design Prof. Dr. Manuel Guedes, the author’s supervisor.

The design process of the proposal in the final chapter followed those of the case studies in chapter 3: problem-solving oriented design after conducting research identifying current and future issues of the country, city and site. Thereafter, structural options were complemented with further investigation, the experience of the author and advice acquired from the consultations of W. Visser, M. Guedes and J. Varela.

1. CONTEXT

Climate change’s genesis (global warming in this case) can be traced back to greenhouse gases warming up the atmosphere (burning fossil fuels accounts for around 75 per cent of the total increase of CO$_2$) (UN-Habitat, 2011). Even if Man were to stop greenhouse gas emission at this moment, temperatures will continue rising for several centuries (Nuccitelli, 2016). As a consequence, one can witness increasingly severe weather events (more intense tropical cyclones, heavier precipitation, sharper droughts, heat waves, etc.) and sea level rise (due to ice sheet and glacier melt, and thermal expansion of the water) (UN-Habitat, 2011).

To evaluate how resilient territories are against the effects of climate change (and therefore, sea level rise), there are several indexes to have in consideration: exposure to impacts, urban resilience, development, socio-economic and gender equity, and governance structures (UN-Habitat, 2011). Amongst the most vulnerable and affected areas with the lowest indexes in the world are LECA, with special incidence in the LDC, whose urban poor have the least means to resist (Mcgranahan, Blak, & Anderson, 2007).

By 2100, global sea level rise is projected to reach between 1.5 to 1.8 meters, in the latest estimations (DeConto & Pollard, 2016) (Graph 1), dragging impacts which affect, mainly, LECA of the globe (UN-Habitat, 2011). If Antarctica’s ice sheets and shelves were to melt entirely, together with Greenland, the sea could rise 70 meters (DeConto & Pollard, 2016). A level with which present coastal cities cannot handle. As sea level creeps up, its consequences become notorious: increase in saltwater seepage inland and in groundwater, increased flood risk related incidents (multiplied by heavier precipitations and frequent extreme weather events), increased coastal erosion and loss of wetlands, land loss and other indirect impacts (UN-Habitat, 2011).
Floods are regarded as the costliest of impacts. Without adaptation measures, 14 to 322 million people around the world are expected to be flooded annually under 25 – 123 centimeters of global mean sea level rise (Hinkel, et al., 2014). Settlements in southeastern Asia are the ones where flood related humanitarian disasters are mostly reported (Mcgranahan, Blak, & Anderson, 2007), with the megacity of Dhaka ranking third place globally by population exposure (UN-Habitat, 2011).

Generally, the on-going effect of losing land will be devastating, when considering other data. In 2012, there were about 3.5 billion city dwellers. By 2100, it is expected that 8.5 billion people inhabit cities (Graaf, 2012), with a considerable percentage in the LECA. It is not feasible to accommodate such a number in cities, as usually when they expand to house the growing population, they tend to do so over fertile croplands. As food production is declining (United Nations, 2011), land is being lost and global population is rising, more and more settlements are including areas inland for rainwater storage (like the Room for the Rivers program in the Netherlands). Is it enough? What can be done further? Some cities and countries are searching for answers.

2. Approaches on Water
Cities in low elevational coastal areas are exploring determined architectural approaches when dealing with the consequences of sea level rise (higher flood risk, coastal erosion, land loss, saltwater seepage, etc.), heavier precipitations, stronger storms, etc. by resorting to a number of interventions. They are briefly discussed through some parameters defined by Dutch authors (Bobbink, Meyer, & Nijhuis, 2014) (Meyer & Nijhuis, 2014) (Singelenberg & Nillesen, 2010) for comparing and pondering which are best: flexibility towards uncertain climate change effects (sea level rise’s rate), resilience towards floods and structural performance. Naturally, architecture cannot solve all the problems of the previously stated indexes, but can directly improve urban resilience, development and socio-economic conditions.

The approaches have been divided in two different groups: those that are static with water level rise and those that react to it. In short, the ones constituting the first are terp structures, artificial islands and stilt structures, while the second comprises of houseboats, floating and amphibious structures (Anderson, 2014). Those constituting the second group have the highest flexibility towards sea level rise’s higher flood risk impact, being able to be constructed virtually in any river, lake, sea, canals, and floodplains.

3. Case Studies
Four architectural approaches of which one half are floating and the other amphibious, were analyzed: MFS (Makoko Floating School), ABC
Arkenbouw floating structures, the LIFT House and De Gouden Kust.

The MFS was designed for the lagoon-based waterfront community of Makoko in the city of Lagos, Nigeria. Extensive research on the site lead to the adoption of a floating A-shaped school extension. It was 10 meters tall, wide and deep and built from locally sourced materials (wood and bamboo). Since there was no public supply of both water and electricity, the design was entirely self-sufficient – with rainwater catchment, solar panels and a composting toilet (NLÉ, 2012).

ABC Arkenbouw is a factory in Urk, Netherlands. It designs and builds pre-fabricated high-tech wooden-frame floating structures with waterproof concrete hulls as foundations. Their dimensions are highly limited to the size of the dry docks in which they are built and the sluices they need to get through when towed to their site. Energy facilities can vary on demand, but are usually plug-and-play and endowed with flexible piping (Visser, 2016).

The LIFT House was created by Pirthula Prosun for the city of Dhaka, in Bangladesh, when writing her master thesis. It was dimensioned to house 10 people. Its design constitutes a central heavy core with all the facilities which are communal (access to water and toilets) and to which two lateral lightweight bamboo structures with floating capacity are attached through a steel vertical guidance system (Prosun, 2011). Both have different foundational systems: one has 8,000 water bottles inside a bamboo-frame structure (Good, 2011) while the other has a ferro-cement hull based on the Dutch amphibious models. As with the MFS, local materials (bamboo and bricks) are given priority over others and facilities are self-sufficient (rainwater catchment, solar panels and composting latrines).

De Gouden Kust is a set of 32 amphibious (and 14 floating) homes designed by Factor Architecten and engineered by Dura Vermeer, in Maasbommel Netherlands. Built as part of a government initiative to introduce buildings adapted to flood risks in 15 locations (designated EMAB-locations), the houses can cope with up to 7 meters above NAP (Amsterdam Ordnance Datum) (Boiten & Factor Architecten, 2011). Their structure is similar to those of the ABC Arkenbouw factory: concrete hull and pre-fabricated wooden frame. What differs between both is that the hull is thicker, due to standing on land most of the time – weighing nearly 70 tons (hence why little importance was given to the interior distribution of furniture and users). Each pair of houses is moored to two concrete pillars.

4. **PROJECT FOR DHAKA, BANGLADESH**

Prior to designing, research on the country’s resilience indexes was conducted. Aforementioned case studies are as important for analyzing existing solutions.

Approximately 97 percent of the total land area and all inhabitants are at risk of multiple hazards (tropical cyclones, floods, droughts, riverbank and coastal erosion, seismic and tsunami activity) (Alam, 2016). More than 60 per cent of its territory is under less than 6 meters above sea level (low lying lands) (Prosun, 2011) and subsiding (UN-Habitat, 2012).
Periodical destructive floods around the country happen roughly from 3 to 5 years (Prosun, 2011). These are expected to become more frequent as land subsides, sea level rises, heavy precipitation and tropical storms intensify and Himalayan ice melts upstream (raising river levels together with sea level rise).

Figure 1 - Bangladesh in 2060. Colored red are heavily populated areas of the country. In blue, the sea. 1 meter rise would submerge 17.5 per cent of the land and affect at least 17 million people. Adapted from: (Dacca University, 2012) through Photoshop.

26 per cent of the people that migrate, do so due to climate-related reasons (climate refugees), settling in illegal and depleted areas, becoming the urban poor in the process. But the facts do not put a stop to the 160 (ever-growing) million people (ArcGIS, 2015). Just 1 meter rise in sea level will result in a loss of 17.5 per cent of land area and the displacement of at least 17 million people (Dacca University, 2012) – Figure 1. A number which is expected to be reached in the next 40 years (Harris, 2014).

Bangladesh has a subtropical monsoon climate with moderately warm temperatures (average annual minimum of 12°C and maximum of 32°C to 38°C) and a high humidity. Its year can be divided in 3 seasons: a hot humid summer from March to June; a cool, rainy monsoon season (when about 80 per cent of the annual precipitation falls) from June to October; and a cool, dry winter from October to March. Winds usually blow from the North and Northwest, except from March to October, when they blow from the South and Southeast (Robinson, 1988). Inland wind speed has been average around 3.5 meters per second (Khan, Iqbal, & Mahboob, 2004). Although, it may reach 60 kilometers per hour from March to May, and 160 kilometers per hour in the late monsoon season (tropical storms), bringing 6-meter-high storm surges to climb upstream, flooding coastal and inland properties.

Dhaka has a population of 11.6 million people, growing at a rate of 600,000 per year (Thielegeich, Burkart, & Simmer, 2015). Around 30 per cent of the city’s population is living in marginalized and hazardous slums in the low-lying underdeveloped lands (UN-Habitat, 2007) – mostly in the yellow areas of Figure 2. This lead to a need of 410,000 dwellings per year in 2015 (Rajdhani Unnayan Kartripakkha, 2015).

The architectural proposal designed by the author of the thesis this abstract is referred to, intends to target the city’s poorest (the most vulnerable). As such, it is located in mid-eastern Dhaka, due to the land in the center and east being too expensive (Prosun, 2011). Additionally, the government is already planning to use the area for low rise low income housing (Rajdhani Unnayan Kartripakkha, 2015). Although, 60 per cent of it is submerged yearly under a minimum of less than 1 meter and a maximum of 7.55 meters of water (values which do not have sea
level rise nor land subsidence into account), in the monsoon due to the lack of flood protection measures (Masood & Takeuchi, 2011) – Figure 3. Thus, an amphibious house intends to increase its flood resilience.

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The proposal has approximately 49 square meters (6.9 x 6.9 meters), 93 square meters including the porch (9.66 x 9.66 meters) and offers the possibility of a family up to a maximum of five or six members to inhabit it (the national family household size is of 4.5 (ArcGIS, 2015)). The interior can be divided at will by the family, depending on their number and needs, though it is advised that such is done in a symmetrical manner (Singelenberg & Nillesen, 2010).

The floor is prolonged to the outside, allowing its inhabitants to moor their boats and to walk around the house – Figure 4. This lingering area is protected by a pitched roof.

The materials are based on those found in vernacular architecture (Boruck, Mulli and Jawa bamboo, just ropes and bricks) with exception of the foundation’s plastic barrels and the corrugated tin in the roof – Figure 5. All of them are cheap and locally available. The corrugated tin in the roof is lined on the inside and out with woven Mulli bamboo mats for sound and thermal absorption.

The structure of the house is constituted of pillars and beams spanning less than 1 meter (in order to resist seismic and wind forces (International Federation of Red Cross and Red Crescent Societies, 2009)), and reinforced with diagonals, which support its weight when on land. When flooded, such is ensured by the

Figure 2 - Hazardous flood areas. The green areas are the ones in the least danger from floods (the higher lands), the yellow ones are under moderate threat and the pale red ones are at high risk (both low-lying and in some cases water surfaces). Urban expansion is seeing those territories being taken over. The white circle is where the proposal is located. Source: adapted from (Gruebner, et al., 2014), (Dewan & Islam, 2007) and (Center for Satellite Based Crisis Information, 2004).

Figure 3 - A 100-year flood map of part of the suggested area, where inundation depth is represented through various colors. Red stands where inundation depth is over 4 meters, orange where it is between 3 and 4 meters, light green where it is between 2 and 3 meters, light blue where it reaches between 1 and 2 meters and blue where it reaches less than 1 meter. Adapted from (Masood & Takeuchi, 2011).
floating foundational grid of bamboo beams and barrels, which has, below, a plinth made of bricks to materialize the transition between it and the soil.

This due to the overall weight of the dwelling being 8.5 ton and the impulse given by the 156 barrels in the foundation varying from 39 ton to 25 ton, endowing it with floating capacity (according to Archimedes' principle). Because the foundation's grid is built with bamboo, it is convenient that it has the least contact with water as possible. Measuring structural submergence is, thus, important.

Mooring poles serve as anchoring, avoiding heeling, tipping, listing and preventing the house from drifting away due to flood currents.

Their height can vary from 1.04 m (height from the top of the plinth to the point where the structure is fastened) + 1 m (minimum floodwater depth is less than 1 m) + 1.5 m (expected global sea level rise by 2100) to 1.04 + 7.55 m (maximum floodwater depth) + 1.55 m from the top of the plinth to their highest point. They are retractable for when it is necessary to relocate the house.

Joints of the shear lashing type are ensured by jute ropes and bamboo pegs/rods.

Facilities need to render the house self-sufficient and independent of the public grid. As such, rainwater catchment and its storage, a composting toilet (on two barrels) and solar panels (twenty-two 120 watts) were merged in the design. A 48 000 liters storage capacity for a 5-member family household to get through the dry season. But the house only has the capacity for storing 5 600 liters, in the 28 barrels southern
and northernmost barrels, which is enough only for 21 days. Natural ventilation was given priority when considering other types, which, together with the solar panels, required proper orientation. The house is, thus, south-north oriented – Figure 7.

5. Project Recommendations

Prior to resorting to any design solutions and approaches, one should conduct a thorough research (geographic, demographic, climate, technologic, urban and socio-economic aspects and vernacular architecture) on the country, city and site where the problem-solving oriented architectural proposal takes place;

Local climate and vernacular architecture are of the outmost importance for facility design, orientation (natural ventilation and solar exposure) and overall shape of the project;

One must, in the first place, be aware of the nature of the site: river bed, floodplain, beach, etc. to adjust the structural design accordingly;

It is of the outmost importance to be acquainted with expected maximum floodwater (should be an updated forecast with climate change effects, sea level rise and land subsidence into account);

It is mandatory to verify if the impulse provided by the water is higher than the weight of the design, otherwise it will simply not float;

The mooring poles should be a minimum of 2 (to prevent the structure from tipping, heeling, listing and rotating) and removeable, if possible as it allows it to be towing in emergency situations and simple relocations;

It is best to design the building and its structure as symmetrical as possible, equally distributing the weight amongst its plan and maintaining its
center of mass in the middle. Verifying these circumstances is easier in square shaped plans; it would be ideal to quantify heeling, listing and tipping conditions of the structure;

It is advised for the foundation to be the heaviest of the structural components and to come up with a way of measuring its submergence (if such is bound to compromise the materials and parts of the construction) and security thresholds (the limits of what can be supported; extreme cases);

In terms of urban design and arrangement there should be enough space for people to circulate both when the land is dry (by foot, car, bicycle, etc.) and flooded (by boat) and, if allowed, to tow the house;

Maintenance plans designated for the users, with regards to materials’ service life, and overall durability should constitute an important factor in one’s design.

CONCLUSION

Even though architecture cannot present itself as a single solution or approach to adopt in the fight against sea level rise and other climate change induced effects, as cities and human settlements around the world will have to assess several other aspects, it can surely play one of the most important roles towards urban resilience, development and socio-economic improvement. Perhaps the utmost direct approach is in the generation of capable structures, which are flexible against nowadays’ uncertainty hovering over sea level rise. Offering flexible solutions, such as floating and amphibious buildings to those most vulnerable in future expansions or obsolete locations becomes essential.

Further research regarding the proposal expressed in chapter 4 should be conducted in the form of heeling, listing and tipping thresholds quantification. Answering the question How much weight could there be in one corner before the structure started tipping? might reveal itself important. Since Prof. Dr. José Varela ascertained the proposal would not easily suffer such effects because of the mooring poles, they were not quantified. But it is the author’s position that it would be safer if they were determined. The same is applied for earthquake and wind resistance, in the case of bamboo structures, as only general statements were found in the sources: How much velocity can the structure withstand both in water and in the ground?

It is also important to determine flood water depth with consideration for future sea level rise and land subsidence precisely in future replications of the design proposal. In the thesis, predicted sea level rise was just added to the maximum flood water depth of the site, though this is probably not the correct procedure.

Other water storage solutions are of great interest, as dimensioning and designing for such, in low cost amphibious housing, may be the most challenging aspect of the design and yet one of the most important. Wider capacity for water storage is essential.

Another important point that should be stressed concerns the building materials recommended in the project. Their prices are hard to account for precisely. It would be of great interest if they were completed,
in order to give a more precise value for the cost of the amphibious proposal.

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