Methods for In-Silico Environmental Resilience, 2018 to 2100

T Spiegelhalter¹, L C Werner¹,²

¹ Miami Beach Urban Studios, College of Architecture and the Arts, Florida International University, Miami, FL 33139, USA

¹ tspiege@fiu.edu, ²lcw@tactile-architecture.com

Abstract. The research focuses on Genetic Water-Energy-Food Nexus Design Research Scenarios for Miami’s Greater Islands. The Paris Agreement - 21st international Conference of Parties (COP 21) to the United Nations Framework Convention on Climate Change (UNFCCC) supports professional and municipal architecture and urban design practice emphasizing greenhouse gas reductions and carbon-neutral city planning and operations. In this respect, Miami benefits through multiple large-scale grants focusing on strategic solutions to combat and adapt to the effects of global warming, sea-level rise, flooding, hurricane impacts, and saltwater intrusion [1]. This paper presents research findings funded by a four-year transdisciplinary research project CRUNCH by EU agencies and the US-National Science Foundation in partnership with nineteen partners from six countries. It illuminates two transdisciplinary methods to produce bio-inspired infrastructural, architectural, and urban scale scenarios from 2018 to 2100. The silico-oriented research location is in Miami, proposing a trans-locational application envisaged in Berlin. The first method is based on parametric-algorithmic, generative design research workflows. The second utilizes synthetic biology through bio-scripting in collaboration with Autodesk. Both methods merge through the integration of cloud-based artificial intelligence and machine learning simulation engines. The research goals are to support international governments regarding sustainability master plans, and secondly, to raise and increase awareness towards urgent and societal relevant resilience topics for the future of human habitats. Scenario simulations are generated by the Florida International University (FIU) Miami research team at the Urban Living Lab (ULL), the GIS department, and two coastal cities in Miami Dade with low-lying areas. The ULL’s research sectors include green-blue infrastructures to combat sea-level rise, synthetic biology scripting, robotic urban farming, local food production and hydroponics, mixed renewable energy design. In addition, and carbon-neutral power generation with adaptive infrastructure projects that support the local and regional Food-Energy-Water Nexus.

Keywords: Sea-level Rise, Artificial Intelligence, Carbon Positive Urban Simulation, Synthetic Biology, Bio-scripting

1. Introduction

Climate change threatens South Florida communities primarily in heat waves, hurricanes, saltwater intrusion, subsiding soils, rising groundwater tables due to rising sea levels (SLR) [2]. During recent years, SLR has accelerated the corrosion of steel and weakened infrastructures and buildings, prone to collapse [3]. Forensic investigators, engineers, and scientists do their due diligence to analyze the causes of this destruction [4]. They use diagnostics tools, AI-assisted science data of sensor real-time support systems to mitigate further destruction and create adaptive scenarios and relocation efforts. CRUNCH Miami research complements this by investigating future urban environments that are affected by sea-level rise rate (SLR) and storm surge up to 10 meters [5]. The SLR is not constant around the world and
shows large local variations, therefore adaptation to changes in water level and planning has a strong local component and every coastal area must consider its own unique characteristics [1]. In the next 80 years, humanity will encounter an overwhelming variety of disruptive technologies and innovations, such as blockchain, AI, and robotic labor, known as industry 4.0. This will not only affect communication, education, commerce, or culture, but also the Architecture, Construction and Engineering (ACE) industries [6]. They are likely to sweep away current city organization, building systems [7], and mobility infrastructure, to slowly replace them with ones that— from today’s point of view— have attributes that are recognizably superior throughout the lifecycle of a building or a city [8]. A trigger for the current development in political and governmental decisions and guidelines is the 2015 report ‘Renewable Energy in the Water, Energy and Food Nexus’, investigating how “renewable energy technologies can address trade-offs between water, energy and food, bringing substantial benefit in all three key sectors.” [9]. This includes physical resource systems [10], and the incorporation of environmental, economic, political, and social dimensions [11]. Thus, the UN Sustainable Development Goals [12] were developed to pinpoint the challenges in all fields of life on a global scale. The Glasgow GOP26 Agreement finally completed the list of tasks and goals as a “legally binding international treaty on climate change.” [13]. All three suggest paths for designing sustainable urban environments. Computationally calculated simulation of future urban scenarios for spatial or social analysis based on data to either develop options of guiding design and/or to support decision-making reaches back to the 1960s [14]. Since then, numerous tools for the Integrated Decision Support Systems have been developed. Based on a systemic and statistical approach some follow pre-set calculation rules, more recent ones are powered by machine learning and artificial intelligence. A research gap identified was the lack of a comprehensive and easy-to-use urban scenario modelling and interactive visualization from now to 2100, targeting policy makers, practitioners, and civil society organizations alike. Specifically including projected Sea Level Rise (SLR), storm surge, heat impact, and urban greenhouse gas emission until 2100 using open-data and AI for urban scenario forecasting.

1.1 CRUNCH – a four-year transdisciplinary research project

CRUNCH Miami provides a data and mapping baseline for the city's needs in 2100, developing tools and framework, testing, with data-driven models using different self-sufficiency strategies, carbon-positive, and resilient scenarios from now to 2100 [15]. Scenario simulations were generated by the Florida International University (FIU) Miami research team at the Urban Living Lab (ULL) [1], the GIS department, and two coastal cities in Miami Dade with low-lying areas. The ULL’s research sectors include green-blue infrastructures to combat sea-level rise, synthetic biology scripting, robotic urban farming, local food production and hydroponics, and mixed renewable energy design. In addition, carbon-neutral power generation with adaptive infrastructure projects that support the local and regional Food-Energy-Water Nexus [1]. The ULL approach for the CRUNCH Miami Integrated Decision Support System (IDSS) considers a combination of the SLR and the worst-case storm surge scenario of Hurricane Cat 5. The work is based on the National Oceanic and Atmospheric Administration Data, the U.S. Department of Commerce. Figure 1 shows the research results. Specifically, the projected SLR and Hurricane Category 5 storm surge impacts with hypothetical population change and carbon-neutral infrastructural adaptation scenarios from the baseline 2018 (90.108 ppl.), to 2040 (45.054 ppl.), 2070 (180.000 ppl.), and 2100 (360.000 ppl.) at Indian Creek, Miami Beach [15].
Figure 1. Diagram of the projected Sea Level Rise and Hurricane 5 storm surge impacts with hypothetical population change and carbon-neutral infrastructural adaptation scenarios from 2018-2100. Source: CRUNCH MIAMI PI-Team of Prof. Thomas Spiegelhalter [14].

2. Method: In-Silico Adaptation Scenario Simulations for SLR and Storm Surge affected urban Areas using IDSS

In 1987 the American computer scientist and co-founder of the research field Artificial Life Christopher Langton (*1948), coined the term in-silico, referring to the usage of silicon-based computers. The new discipline bioinformatics was developed to support the natural sciences with a methodology to create simulations of biochemical processes; in short computational biology [16]. The CRUNCH Miami (IDSS with the Carbon-Positive City Scenarios Tool were both developed by the FIU-CRUNCH team, the FIU-GIS Center, and FIU’s International Hurricane Research Center (IHRC) (Figure 2). The former was developed for citizens and decision-makers, and the latter for professional engineers, architects, and town-planners. The IHRC provided advise on SLR inundation modeling and use of storm surge "Sea, Lake, and Overland Surges from Hurricanes” (SLOSH) model for the Miami basin. All SLOSH storm surge heights are referenced to the NAVD88 vertical datum. The North American Vertical Datum of 1988 acts as one of five standard reference lines to measure points on the earth’s surface. It is region dependent. The application uses the Maximum of the Maximum Envelope of High Water (MOM) grid layer at high tide for all scenarios of the CRUNCH Digital Twin modeling of new high-rise communities on 10 meters stilts. The main objective for testing the in-silico simulation is to use two different methods. The method of Parametric Open Data Integration and the method of Synthetic Biology Growth Computation called Bio-Scripting. Both methods quantify social and economic impacts of SLR and storm surges for the design of adaptable green-blue infrastructures and buildings from 2018 to 2100. The results of both methods were that multiple combination scenarios for differently sized units within the study area were developed. US census blocks seemed appropriate as spatial units [17].

2.1 Method 1: Parametric Open Data Integration System

The Parametric Open Integration System [18] defines a systemic design approach in which relevant open data is integrated in one system to achieve a certain goal. The goal of CRUNCH Miami was to simulate urban scenarios that would feed into the development of an IDSS. The IDSS scenario tool allows users to select a geographic area within the boundaries of South Miami and Miami Beach and to slide through different scenarios of SLR and storm surges between 0 and 10 meters with up to hurricane category 1 to 5 storm impacts [19].

2.1.1. Data Model for the Scenario.

The application visualizes the extent of flooded areas in response to these scenarios and returns associated statistics about their potential impact on the local population, properties, transportation
networks, key services, community facilities, and other service infrastructures such as energy, water, and food. The SLR scenarios were developed using a bathtub model. A detailed description of the algorithm used can be found in [20]. The Digital Elevation Model (DEM) used in the computations derives from 2015 Lidar data of Miami-Dade County given in the NAVD88 vertical datum [1]. The original raster DEM dataset was resampled to a raster DEM at a 5m resolution with mean higher high water (MHHW) as a reference surface (tidal datum). This model is intended to capture the worst-case high-water value at a particular location for hurricane evacuation and city scenario planning for 2100. Socio-economic statistics are based on Census 2010 block level and 2018 Miami-Dade County Property Appraiser datasets. GIS into the software packages of Autodesk Infraworks, Civil 3D, Navisworks, ESRI ArcGIS Pro, Revit-BIM, AI-Spacemaker, Insight360, Dynamo, Grassshopper for Rhino in Revit, Python, GeoPanda, Bootstrap, Turf, popper.js, Mapbox GL, JS, Open Map Tiles for analyzing, coding, designing, scripting, and optimization of cities and buildings. Figure 2 shows the system architecture; specifically, the general workflow of integrating open-source applications and data.

Figure 2. CRUNCH IDSS open data for integration into FEW Nexus solutions and green-blue infrastructure workflow. Source: CRUNCH Miami, Prof. Thomas Spiegelhalter

Figure 3. Left: IDSS web-dashboard dynamically visualizes 90cm of SLR and reports potential impacted resident demographics. Right: web-dashboard in 3D mode shows a perspective view of inundated Miami Beach. Source: CRUNCH Miami, Prof. Thomas Spiegelhalter [17].

Figure 3 illustrates the Rapid Energy and Resource Modeling with Open-Source GIS with buildings displayed with the correct height. The WebGL technology used in this application also supports 3D rendering and the view can be shifted and rotated freely.

2.1.2 Geo-spatial Coding for the Scenarios 2018-2100. All scenarios were geo-coded and, thus, location-specific. The calculation was based on SLR projections, NOAA research forecasts, the US census bureau, and the Southeast Florida Regional Compacts Climate Change Statistics from 2019. All
scenarios were based on incremental green-blue infrastructural and building adaptations to SLR, clean-ups of contaminations and sewage spills with phytoremediation techniques and microbes. The design experiments incorporated hydraulically raised and, just in time, adaptable new buildings and infrastructures. The new service infrastructure and buildings’ ground levels were calculated and suggested for 10 meters above mean sea level. The location of the adaptation scenario analysis presented in (Figure 1) is Indian Creek in Miami Beach (25.83 -80.123).

2.1.3. Results of Method 1. Using the specifically developed IDSS all design typologies demonstrate parametric resilient geometries with real-world engineering applications, and feature potential upcoming disruptive technologies and innovations according to the FWE-Nexus. The scenarios included multi-functional systems, modules, and renewable energies from solar/wind/water/kinetic building tectonics, autonomous transportation, artificial intelligence, deep neural networks, the internet of things, robotics, and urban outdoor and indoor farming with self-healing facade tectonics for climate emergencies in 2100.

Figure 4. Possible architectural scenario in the Miami Bay. Left: floating habitat with tower on elevating stilts. Right: parametric geometry development and building optimization dashboard. Source: CRUNCH Master Thesis Studio Prof. Thomas Spiegelhalter, Sadiel Ojeda [14].

Figure 5. The American Institute of Architects (AIA) MIAMI 2020 Design Award project by Master Thesis Student Amalia Tomey. Source: CRUNCH Prof. Thomas Spiegelhalter, Amalia Tomey [14].

Figures 4 and 5 show two carbon-positive selected scenarios, one as a floating habitat, the other as a stilted timber-high-rise. The research team developed the generative Miami Beach Dynamo-BIM script workflow to a test series of carbon-neutral space schedules, occupancy, façade, shape, orientation, with blue-green infrastructural contexts. Figure 4 shows a hypothetical high-rise scenario in the Miami Bay. Figure 5 presents an Urban Live-Work High-Rise Lab located at the dynamically changing shoreline of Miami beach. The program includes self-sustaining systems, materials, climate regulation and food production, and educational amenities.

2.2 Method 2: Bio-Scripting – Synthetic Biology Growth Computation
The CRUNCH Miami research team complimented the Parametric Open Data Integration method, which mainly resulted in cartesian building scenarios with bio-scripting. It describes an alternative data-
driven design approach for adaptive structures as strategic urban design within the same problem area of dynamic changes in SLR plus storm surge. The significant difference to the Parametric Open Data Integration System is its emergent nature based on natural growth, inspired by biology. Like the first method, design proposals were subjected to a computational fluid dynamics (CFD) process, which benchmarked the global geometry against weather conditions, climatic comfort, and renewable energy building operation according to the WEF-Nexus and structural soundness. The urban design CRUNCH studios in 2020 and 2021, featuring a fitness tested research-by-design approach. The case study focuses on the development of a high-rise building scenario in downtown Miami. In Spring 2021, thirty-four CRUNCH graduate research students under the leadership of Prof. Spiegelhalter and Theodoros Galanos applied the method for an urban scale planning of 17 carbon positive highrise building designs for 2100. As one research team, we tested multiple open-source software and scripting tools for the CRUNCH Miami project evolving area. ‘Layered’ model scenarios described the relationship between synthetic or semi-synthetic organisms and cells to natural organisms derived from evolutionary processes and applicable to architecture. It is also a vital issue to understand length scales from nanometers (nm) to kilometers (km) and scales for the development time from bioengineering to living infrastructure, including sensing, maintenance, and renewal of resources and systems or repair. The research was carried out in two approaches. First, simulating the natural/biological growth behavior, computational biology based on the organism Physarum Polycephalum, and second utilizing biological material based on the organism, a Myxorhizal, a hybrid between plant and fungi. The latter proposes a naturally growing architecture of information [21], [22]. Both approaches feature ‘Design Coding Experiments with Natural and Synthetic Biology Growth Computation’.

2.2.1 Emergence over Planning. For the generative design iterations, BIM-Grasshopper plugins for agent-based modeling mimicking the basics of Physarum polycephalum were used. The algorithm in the plug-in is stigmergic in nature, similar to an ant colony algorithm. Physarum polycephalum is a slime mold that inhabits shady, cool, moist areas, such as decaying leaves and logs. In 2000, Toschiyuki Nakagaki published “Intelligence: maze-solving by an amoeboid organism” on the smartness of the organism [23]. He observed the intelligent decision-making behavior for finding the shortest path between a series of attractor points [24]. In its plasmodium stage, the single cell organism shows geometric, morphological and cognitive principles potentially relevant for future complexity within architecture and urban design [24]. The English computer scientists Andrew Adamatzki and Jeff Jones adopted a synthesis approach and a mobile multi-agent system with elementary individual behaviors employed [25]. The geometric growth behavior of the network was researched and explored in [26].

2.2.2 Synthetic Biological Coding. The research aims to utilize a circular design method that leads from computational biology as simulation via biological computation as material programming to an incrementally implemented material system. Based on the AI Google and FIU-IDDS SLR map, the port of Miami will be 90% underwater, equaling 2.55 meters on average, and prone to partial soil subsidence in 2100. Within 80 years, the research team envisioned a metabolism of dynamically flexible and shape-changing growing structures with symbiotic living roots and foundation soil microbiota networks transforming the flooded Port of Miami. The research team collaborated with FIU researchers of Computational Biology to first study the material of the plant-fungi hybrid organism Myxorhizal, and second to explore the network developing capacities. Mycorrhizal is a natural architecture combining network principles plus material properties and intelligence. Special attention was drawn to interspecific communication, which are multiple fungi that encapsulate long thread-like structural sound roots that reinforce over time caused by dynamic environmental load and soil conditions. The new network includes incremental adaptation for new green-blue infrastructures growing climate-resilient adaptive typologies based on renewable resource flows for cargo, passenger, and civil transportation nodes and networks. For example, mycelium is a long thread-like geometry and is an entirely biodegradable material with extraordinary properties. In addition, these embedded mycorrhizal networks connect individual plants to carry water, nitrogen, carbon, and other minerals. It breaks down organic materials and makes their raw materials available for circular and metabolic use in new envisioned infrastructural self-sufficient high-rise communities. Figure 7 shows a proposal for a Mycorrhizal Network Design Sequence for the Miami Harbor. The outcome of the interdisciplinary research foresees benefits from synthetic biological coding of the organism’s mycelium in the local
environment. At the same time, indoor and outdoor urban horticulture and agriculture provide food for building occupants.

2.2.3 Results of Method 2. The work resulted in a series of highly efficient connected circulation sequences and transportation networks for the new grown islands along the I95 freeway of Biscayne Bay between Miami and Miami Beach. The study utilized the networking capabilities of the organism. Possible performance behaviors in the material properties were disregarded at this stage. Figure 6 illustrates the network growth to and between a series of high-rise buildings. The distance between the structures derives from benchmarking against micro-climatic open data, such as sunlight and wind direction. Figure 7 illustrates a dynamically flexible structure that worked in symbiotic networks, including living systems to transform the flooded Port of Miami. The design utilized Mycorrhizal Networks with multiple fungi that encapsulate long thread-like structural sound roots that reinforce over time caused by dynamic environmental load conditions. For example, mycelium is a long thread-like geometry and is an entirely biodegradable material with extraordinary properties. Using mycelium with synthetic biological coding could benefit the local environment, while indoor and outdoor urban gardens and agriculture provide food for building occupants. These embedded mycorrhizal networks connect individual plants to carry water, nitrogen, carbon, and other minerals. It breaks down organic materials and makes their raw materials available for circular and metabolic use in the new envisioned infrastructural self-sufficient high-rise communities.

Figure 6. Source and Images by FIU CRUNCH Studio Spiegelhalter-Theodoros, Spring 2021.

Figure 7. Images of the Midterm designs by Gianna Martinez, Maria Pardilla, Soroya Friedwald. Source: CRUNCH Miami Research Studio Thomas Spiegelhalter, Fall 2021.

A new port of growing tectonics with built-in solar systems to collect and produce energy in the form of liquid fuels, just like the green leaves of plants, is an alternative to burning fossil fuels. Both methods described above were envisaged to be tested in other locations such as Berlin, Germany for its global relevance as a metropolis with a rapidly increasing population.
2.3 Berlin – Proposal of a trans-localational Application
According to Sea level Monitor Data collected and analyzed by the North-German Coastal, and Climate office of the Helmholtz-Zentrum sea levels on German coasts have risen 15-20 cm within the last 100 years [27]. Despite national water management measurements utilizing dams and Locks in the northern and eastern German states, the country has been increasingly affected by floods; most recently in Bad Neuenahr-Ahrweiler with more than 100 dead and the partial destruction of a whole region. Additionally, the climate models developed by the Climate Service Center Germany (GERICS) show that the temperature in Germany could potentially rise by 5.3°C by 2100. Therefore, extreme changes in the groundwater level, temperature increase, and unstable, vulnerable climate conditions must be tackled as urgent and primary parameters for an adapted urban planning strategy, formally, infrastructurally, and socially. The proposed study aims at adapting the system/method developed throughout the 4-year CRUNCH Miami period to the city of Berlin. Geographically Berlin is flat and offers an unique water system approximately 180km south of the Baltic Sea. Its population grows by approximately 1% annually. The Berlin government is planning densification and thus enlarging the already 34% of sealed surface [28] throughout the city. DFG researchers state, “As the need for more sustainable approaches to managing urban waters grows, such an understanding of how natural and engineered hydrological systems combine in cities is crucial to the evidence-base for rational decision making […]” [28]. Thus, Berlin presents a number of pre-requisites to stand-out as a case-study location to analyze and react to future scenarios. The goal is to test and evaluate the primary system architecture developed through CRUNCH for the Miami area in a case study in Europe. The Objective is to learn which categories and parameters need to be adapted to the European/German location and which can remain global ones. Outcomes include rising awareness of complex factors such as the source and choice of datasets and scenario solutions, planning laws, zoning regulations, and sensitivity to building forms and culture.

3. Conclusion
The paper introduced In-Silico Environmental Resilience to better understand possible future urban scenarios resulting from increased Sea-Level-Rise, Storm Surges and Heat Impacts. It developed the Integrated Decision Support System (IDSS), a digital platform based on geographic information for carbon-neutral city scenarios enabling decision-makers and citizens of various levels of knowledge to provide coordinated support to multiple users in making individual decisions [1]. The research illustrated two methods of computational simulation to assist urban design strategies. Both methods had multiple scenarios that resulted in a compound effect. It responded to the global goal of Carbon-Neutrality. It suggested steps, tools, and a strategy of designing, which may add to the many ways to simultaneously slow down, and to adapt to climate change. The outlook of the research integrates the above-presented methods and tools. Questions resulting from the bio-computational design method include if further research in this area of synthetic biology can help protect low-lying urban communities in Miami and other areas from the impacts? Further, how can molecular modeling, cloud computing, biophoton imaging, and bioengineering nodes and scripts programmed for synthetic biology be studied and integrated to develop growing adaptive structures between today and 2100? Our research, analysis, and results validated the IDSS as a necessary tool to respond to climate change and address all stakeholders. It offered a highly adaptive, carbon-positive design strategy for blue-green and resilient, zero-emission, AI-powered infrastructure for coastal cities in 25, 50, and 80 years

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The International 21st Conference of Parties (COP 21), so called Paris Agreement to the United Nations Framework Convention on Climate Change (UNFCCC), so called Paris Agreement, was created to generally support professional and municipal architecture and urban design practice emphasizing greenhouse gas reductions and carbon-neutral city planning and operations.

In this respect, Miami benefits through multiple large-scale grants focusing on strategic solutions to combat and adapt to the effects of global warming, sea-level rise, flooding, hurricane impacts, and salt-water intrusion.

This paper critically presents research findings of the funded four-year transdisciplinary, research project CRUNCH by EU agencies and the US-National Science Foundation in partnership with nineteen partners from six countries (the UK, the Netherlands, Sweden, Poland, USA, and China).

It illustrates how transdisciplinary, -infrastructural outcome scenarios for the period from 2019 to 2100 can be produced digitally, in silico, and material, in a laboratory. The first method is based on parametric-algorithmic, generative design research workflows, combined with cloud-based artificial intelligence and machine learning simulation engines, the second on material through bio-scripting.

These bio-inspired scenarios of architectural and urban scale are generated by the Miami in collaboration ….. research team at the Urban Living Lab (ULL) in Miami ….. Florida International University (FIU).

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Goals of the research are firstly, to support international governments regarding sustainability master plans, and secondly, to raise and increase awareness towards an urgent and societal relevant topic for the future of human habitats.

The ULL’s research sectors include green-blue infrastructures to combat sea-level rise, synthetic biology scripting, robotic urban farming, local food production and hydroponics, mixed renewable energy design, and carbon-neutral power generation with adaptive infrastructure projects that support the local and regional Food-Energy-Water Nexus.