TOWARDS A BIOREMEDIATION BUILDING ENVELOPE SYSTEM FOR IMPROVED AIR QUALITY

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According to the World Health Organization and the European Environment Agency, air pollution is the biggest environmental health risk today (European Environment Agency n.d.; Neslen 2018; United Nations Economic Commission for Europe, n.d.). Although general pollutant levels have improved in the last few decades, it is only recently that certain types of highly toxic human-made pollutants have been emitted in unprecedented quantities, primarily in developing regions. Moreover, within these geographic regions, the global population is estimated to double by 2050. The climatic context in most of these predominantly unindustrialized economic territories favors natural ventilation and the seamless interaction between indoor and outdoor space. Still, these areas mainly rely on mechanical systems to homogenize atmospheric living standards. Air conditioning systems produce wasted heat that alters the microclimate of buildings' surroundings, while creating additional air pollution exhausted by the running cycles of equipment. To disrupt this vicious cycle of energy expenditure and air pollution replenishment, this research proposes a hybrid air purification modular ceramic system for building envelopes in regions where fiscal means are limited, and natural ventilation is a viable option, to regulate both exterior and interior atmospheric pollution. The objective is to create a low-tech, high-value system, conceptualized as a combination of mechanical components, with the effectiveness and sensitivity of biological organisms. This infrastructural strategy serves as a site of inquiry towards the potential amelioration of local urban pollution airstreams in the developing world. Through an extensive analysis of air pollution bioremediative systems' attributes and a series of research initiatives, several variables of the proposed system were substantiated. The probable impact factor of the system on the projected global population was also investigated with qualitative and quantitative work, defining the potential regions complying with the system's hypothesis criteria. Air pollution levels and urban air velocity thresholds were further characterized for specific cities inside the boundaries of these regions. Computational Fluid Dynamics parametric experimental work investigated air velocity-related issues that would be evaluated under established air exchange rates to further streamline the design features of the core modular system's ceramic plant host component. While with this work, the technical applicability of the proposed system is established, the intention was not only to provide an explicit technical solution, but also to suggest an encounter with cultural settings based on the premise that when people lose their relationship with the environment due to air pollution, they also lose their societal cohabitation and cohesion patterns.

Keywords: Air pollution, air quality/inequality, bioremediation, envelope-system.

1. THE NEED FOR VIABLE AIR POLLUTION CONTROL BUILDING SYSTEMS IN DEVELOPING REGIONS

In recent years, air pollution has been inextricably linked to the changing physiology of the human body (Schell et al. 2010). Air pollution has already affected the way we have evolved as a species. Although pollutants have been emitted into the atmosphere throughout history, either by biogenic or technogenic origin, it is only recently that new types of highly toxic and noxious human-made pollutants have been emitted in unprecedented quantities. In a 2012 report, the World Health Organization (WHO) estimated that 7 million premature deaths annually are linked to air pollution, characterizing the adverse effects of air quality on the human organism as the world's largest environmental health risk (Jasarevic, and Osseiran 2014; European Environment Agency, n.d.; Neslen, 2018; United Nations Economic Commission for Europe n.d.). According to the United Nations (UN), the world's population, currently numbered around 7.6 billion people, will increase to 9.8 billion by 2050, with nearly 90% of the increase concentrated in Asia and Africa. As the world population continues to grow and urbanize primarily in regions with challenging economies, so are the ambient air pollution-associated problems. The WHO indicates that the majority of air pollution-related deaths

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occur in South-East Asia, Africa and some Western Pacific regions. In fact, nearly 92% of air pollution-related deaths occur in low and middle-income countries (World Health Organization 2016; Katsouyanni 2013).

The intensification of air pollution problems in developing regions is mainly due to the outsourcing of industrialized manufacturing processes from capitalist-oriented markets to economies where the cost of human labor is grossly undervalued. Other contributing factors include the lack of infrastructure that deals with rising levels of air pollution, and the lack of relevant legislative policy that prevents citizens from using alternative fuels, like biomass, for their household needs. Nevertheless, within those geographic regions, the population is estimated to double by 2050 (Mannucci, and Franchini 2017; Shanmugam, and Hertelendy 2011).

2. THE PREMISE OF PHYTOREMEDIATIVE BUILDING ELEMENTS

This research proposes solutions for reducing air pollutant concentrations in the urban airstreams of regions with developing economies and mild climatological conditions by augmenting natural ventilation, contrary to the more popular but energy-intensive mechanical ventilation. Through comparative analysis of phytoremediative systems for indoor and outdoor air pollution, as well as experiments in computational fluid dynamics (CFD) and other studies, the analysis concludes with the design of a low-tech biomechanical phytoremediation envelope system. The proposed vertical hydroponic system is a hybrid in the sense that it combines organic plant life along with mechanical components that are strategically instrumentalized to augment the growth of plant life. It is also hybrid since it is used for both indoor and outdoor phytoremediation, eventually reducing air pollutant concentrations in urban ambient air.

An essential parameter in the realization of the proposed system is the role of an augmented natural ventilation complex, which supports the right volume and velocity of airflow to sustain organic life while also regulating air pollution control. As is well established, there are natural and mechanical ventilation systems, yet the aim in this particular research is to enhance the performance of natural airflow with passive formal means like the use of solar chimneys. This decision is critical as it requires as little external energy as possible to augment and orchestrate airflow for pollution control and indoor climate control and is also easily implemented worldwide at a low cost. The system is primarily focused on performing under natural ventilation conditions, yet under certain environmental conditions, it requires the assistance of low-energy active components, such as room air extraction fans, which can support an adequate air purification and circulation rate. Contrary to the majority of existing systems that perform as extensions of mechanical systems or as fully automated mechanical systems with the addition of biotic components, the proposed approach is redefining the envelope of the building in order to take full advantage of the regional environmental flows while at the same time regulating the indoor and outdoor air streams (Lau 2015; Wang, and Zhang 2011). Consequently, this augmented natural ventilation system is designed and developed under the premise that it will use materials in the most environmentally sustainable way, which could be locally sourced. It takes full advantage of its envelope integration in reducing watering and artificial lighting needs. At the same time, its acquisition and maintenance cost would be feasible for less financially affluent people since it could perform in multiple levels from air biofilter to thermal regulator to building enclosure. Overall, this line of research investigates the following two questions and related subjects around them:

1. Can we envision an integrated building system that would be feasible to construct and function in the naturally ventilated environment of an emerging

economy; a system comparable to existing indoor phytoremediative systems in terms of air pollution control but more interactive in terms of its exchange with outside environmental flows? Additionally, could we control the microclimate around such systems through a design approach incorporating plant evapotranspiration and solar heat regulations through plant shading?

2. If a low-tech, high-value phytoremediation system is a viable option for the region, how might this affect the public life of the built environment? Additionally, what kinds of transformative effects might such a system have on existing building typologies, specifically how they relate to and accommodate their inhabitants?

The underlying assumption behind both these questions is that such a system would require direct exposure of buildings to external environmental flows designed to perform within the framework of economic constraints in developing regions. Additionally, there are multiple factors to consider in terms of the embodied energy of the system, the life cycle of its components, or the source-origin of its raw materials. More importantly, one would need to evaluate its significance within a broader socio-political value structure particular to the geographic region under consideration in order to limit to an absolute minimum, the necessary use of mechanical apparatuses in the built environment.

3. MECHANICAL VERSUS BIOLOGICAL VENTILATION SYSTEMS

Although a big part of this work is data-driven and scientifically substantiated, the assumption suggests an alternative building system as a response to air pollution but also critiques a larger context: the establishment of building practices abiding exclusively by Western capitalist-oriented market modes and the logic of uniformity and expedient optimization that in most cases disregards the environmental patterns of specific geopolitical territories (Bachman 2003).

Around the globe, oversized mechanical air conditioning systems are used unilaterally to homogenize atmospheric standards of living. Other than the obvious high embodied energy usage of these mechanical systems, the byproducts of their provided services come in a multitude of forms; from excessively produced, wasted heat that alters the microclimate of the building's surroundings to additional air pollution that is exhausted by the running cycles of the equipment. As a response to this vicious circle of energy expenditure and air pollution replenishment, this research work proposes a hybrid air purification system (EPA 1991; Raji et al. 2015; Sung 2016).

Architecture has not always been as heavily dependent on mechanical systems as it is today. Less than a century ago, natural ventilation was the prevailing method for revitalizing stale air in interior spaces. Advancements in building systems and materials, along with energy conservation requirements, have radically reshaped the building industry throughout the last few decades. With the assumption that buildings can be completely isolated from the outside, the industry invested in and promoted envelope systems as artificial barriers of separation, heavily equipped with and dependent on mechanical ventilation systems. With the rise of atmospherically-controlled buildings, universal typologies of physiological living standards related to building codes emerged assuming that they would support and accommodate a universal inhabitant (De Dear, and Brager 2002; Heating et al. 2004; Larsen et al. 2020; Simonson et al. 2002).

Within this mechanical paradigm, the capital invested in environmental control systems, as a percentage of the total cost of construction, has increased more than five-fold in the past 100 years, from 5% to 27% (Kieran and Timberlake 2004). Regarding energy consumption, Heating, Ventilation, and Air Conditioning (HVAC) systems account for circa 40% of the total energy used for the building sector (U.S. Department of Energy 2015; Westphalen, and Koszalinski 2001). Furthermore, when we consider the functional life cycle analysis of buildings within the context of increasing concerns regarding toxic and non-renewable material consumption, it becomes evident that research on systems for environmental control and how they interact with the building envelope has become today more relevant than ever, especially for their deployment in the suggested regions.

Traditionally, in biomes where natural ventilation is permitted, for example, the Mediterranean basin, the distinction of indoor/outdoor air that characterizes the built environments of many Western cultures is inconceivable (Klepeis et al. 2001). Instead, natural ventilation is the prevailing mode of air conditioning, whether conducted passively or actively using fans. In the western world, air pollution has become detrimental, to an extent, in the way buildings are designed; it has also greatly affected patterns of urban habitation. My objective is thus to create a phytoremediative building system that could potentially provide an effective countermeasure to air pollution, allowing for natural ventilation and, ultimately, positively affecting modes of living in an urban setting.

4. BIOGEOGRAPHICAL CONTENT AND SOCIO-ENVIRONMENTAL AMBIENT AIR POLLUTION TRENDS

If we make a close empirical examination between the regions that the UN predicts to witness the most extensive urbanization and population growth, with the regions that demonstrate high levels of air pollution, we will see that these are the same regions that have traditionally developed architectural/habitational typologies that favor the seamless interaction between indoor space and the exterior environment (The Global Health Observatory, n.d.; United Nations & Department of Economic and Social Affairs, Population Division, 2015 2017). In other words, areas that are predicted to urbanize rapidly and are, in most cases, climatically suitable for natural ventilation; however, due to rising levels of air pollution, these areas will most likely have to rely on mechanical ventilation systems if there is no alternative proposal provided (Arnfield 2016; Petersen et al. 2021). The cost of such implementations would be high, leading to partially unpolluted, or over-sterilized air supplies through the Heating, ventilation, and Air Conditioning (HVAC) filters, but most importantly to a significant alteration of urban living isolation that would negatively impact the culturally traditional habitation patterns.

Beyond this empirical overview, three research initiatives were developed to accurately establish variables that geographically define the regions mentioned and the projected number of people that could benefit from implementing the proposed natural ventilation bioremediation system.

The first initiative is a visual mapping of parameters analyzing the human health impact of air pollutants, their primary origin, relative concentration space around a building, and the corresponding normalized air quality standards provided by several governmental and non-governmental regulatory agencies worldwide (Figure 1). In addition, an HVAC systems filter analysis was also established for these pollutants. The findings indicated that even the higher efficiency filters like an Ultra-Low Penetration Air filter (ULPA) have limited removal efficiency when the particle size of non-biological pollutants is smaller than 0.1μm. Another important piece of information from this study was the discovery that air pollution standards were often significantly different among various agencies, with many of the pollutants not having established standards, while the ambient air pollution guidelines for human health from the United Nations—World Health Organization (UN-WHO) proposing the lowest concentration levels of air contaminants per time of exposure overall.

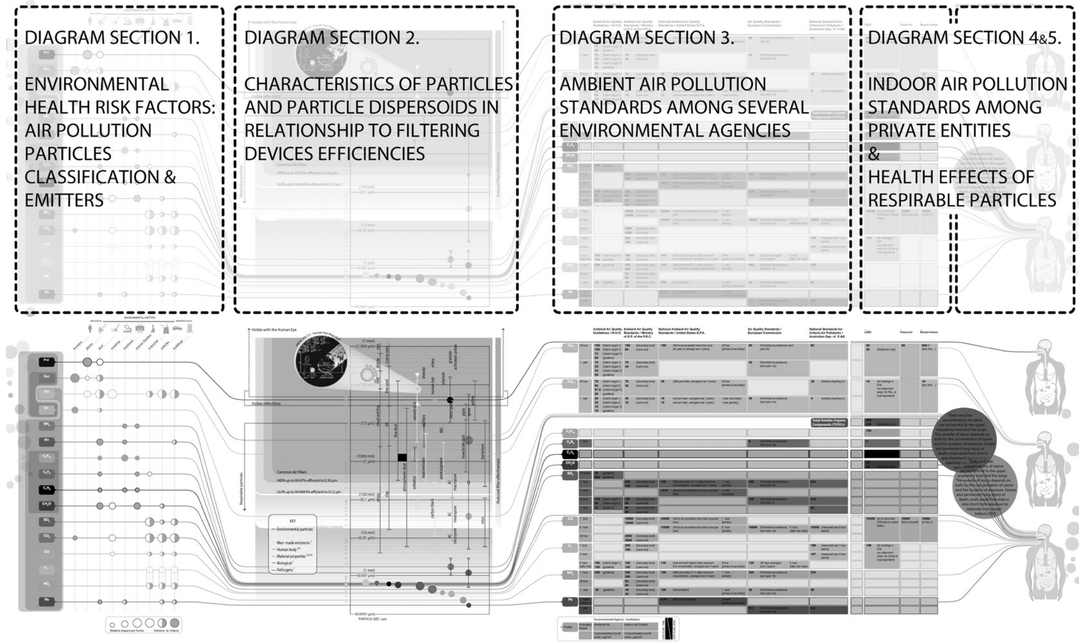

Figure 1: Multivariable diagram associating air pollution sources and standards, health severity of individual pollutants, and HVAC filters efficiencies. Source: Author 2018 in collaboration with: CASE students Anna Dyson et al.

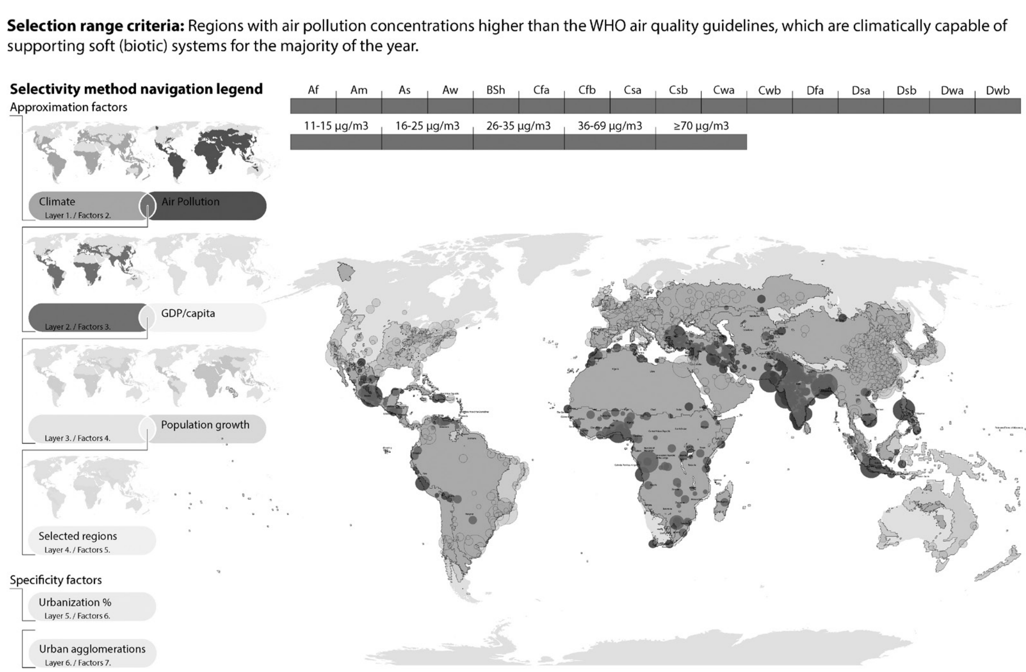

Figure 2: Global map of regions under selection criteria for the proposed system applicability and impact factor to projected population growth. Source: Author 2021.

Based on these findings, a second initiative was formed that used quantitative and qualitative data in the form of several maps with resolution at 0.5° (or ~50 km) (Figure 2). For the first section of this initiative, four main maps were used in a geospatial Venn diagrammatic study, where the final selected map area resulted from the exclusion of the non-mutual areas. The four global maps used for this stage of the initiative were a climate map based on the Köppen-Geiger climate and ecosystems condition classification, an air pollution map of annual median concentrations of fine Particulate Matter (PM2.5) above the UN-WHO standards guideline, a Gross Domestic Product (GDP) per capita map and finally a natural population growth map of countries (Kottek et al. 2006; The World Bank Group, n.d.; United Nations, and Department of Economic and Social Affairs, Population Division 2017). The criteria used in each map for the appropriate selection of the geospatial data sets represented were based on the research's hypothesis that the hydroponic planted system proposed would require climatic conditions that would not prohibit a plant from growing in the envelope of a building in terms of regional annual temperature and air-water content. As for the GDP/Capita, thresholds were set below the poverty thresholds set by the U.S. Department of Health & Human Services for individuals for 2019 (U.S. Department of Health and Human Services n.d.).

The sequence of the maps used was marginally altered from the research's hypothesis for a hybrid bioremediative envelope system that could be implemented in developing regions with mild climatological conditions and air pollution problems and where the local population is projected to increase. The main reason behind this sequence inconsistency was the assumption that a low-tech system like the one proposed does not necessarily mean that it is also a low-value system only for developing regions. Although unpopular in many financially affluent areas, natural ventilation has many benefits in terms of energy reduction. In fact, an almost 60% total primary energy reduction could be saved if offices in the commercial building sector apply natural ventilation strategies (Baker & Steemers 2000) (Figure 3).

Finally, after the graphical representation of the global regions under compliance with the selected criteria, two additional maps are imposed over the selected regions as factors of specificity to define the impact factor of the system further. Evaluation of numbers of the projected population increase in the next 78 years until 2100 are established through population growth projection studies from the UN.

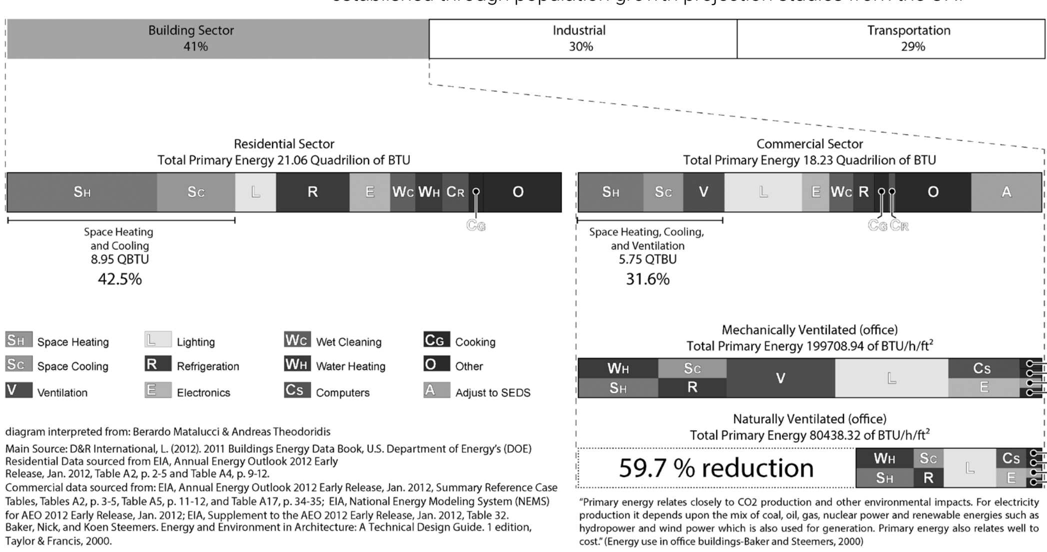

Figure 3: Potential primary energy reduction of naturally ventilated buildings for the commercial building sector of U.S. Source: Berardo Matalucci & Author 2020.

Following the outcomes of the previous initiatives, the third one was conducted to investigate diagrammatically and numerically the climate and air pollution concentration trends in the atmosphere of cities inside the boundaries of the previously designated global areas (Figure 4). The main scope of the inquiry was to verify the relative urban air velocities required to disperse air pollution concentrations below the UN-WHO recommendation guidelines for Particulate Matter (PM10). Particulate Matter was selected for this initiative as a baseline pollution indicator since it is considered by most environmental agencies, including the U.S. Environmental Protection Agency (EPA) and the E.U. European Environment Agency (EEA), as one of the most common criteria pollutants for setting ambient air quality standards.

Three cities from three different continents were selected to be studied, which are Mexico City from North America, Athens from Europe, and Delhi from Asia. Annual detailed data archives of 2018 were used from the corresponding national agencies for weather and air pollution. For instance, in the case of Athens, air data were used from the Hellenic National Meteorological Service with a resolution of three hours, 2920 data points in total, and 8736 hourly data points were obtained from the European Environment Agency for air pollution. After the required post-processing of the data to the necessary form for diagrammatic analysis and display, a series of timeline and bar chart diagrams of several resolutions were developed for each city. For this line of work, the wind direction was not as important of a factor to consider, especially considering it can vary significantly across the scale of an urban setting. Some of the anticipated trends, such as the lower air pollution concentrations as the wind speeds got higher, were the first ones depicted by the graphs. After an extensive analysis of the charts, a more detailed and appropriate conclusion would be that the graphs generally show a negative correlation between wind speed, temperature, and air pollution concentrations and a positive correlation between relative humidity and air pollution concentrations. These results suggest that while wind speed might predominate general pollution levels on a day-to-day basis, temperature and humidity are better indicators of pollution trends within the daily cycle

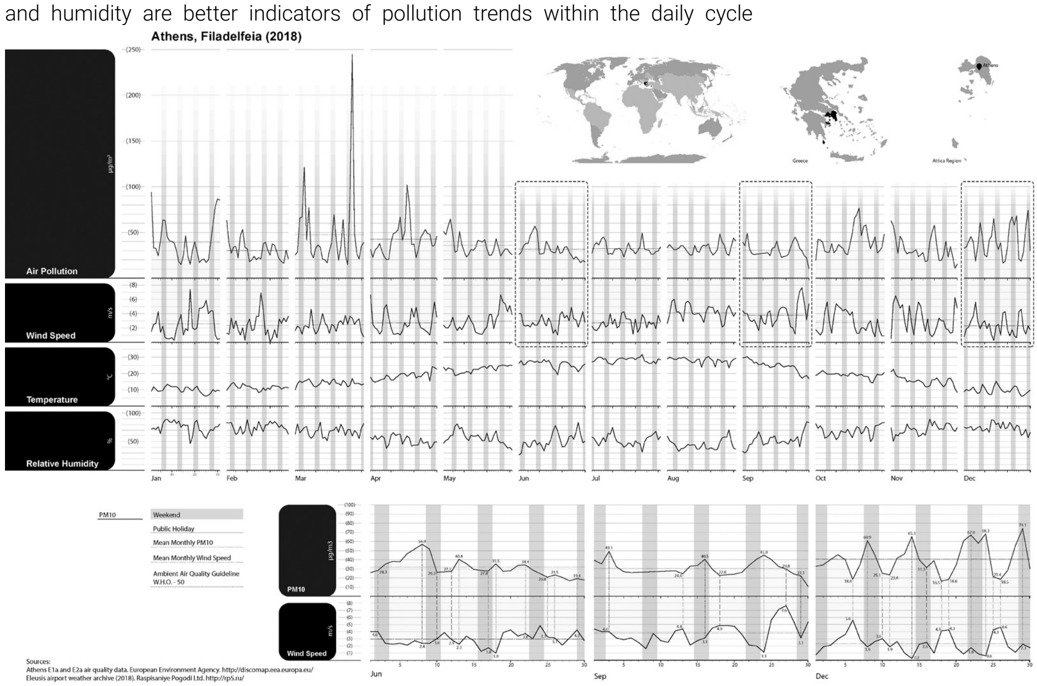

Figure 4: Urban air pollution to environmental variables association diagram for Athens. Source: Author 2021 in collaboration with: Daniel Ruan.

and that the concentration of pollutants generally follows the cycles of human activity; however, meteorological factors have a significant impact on air quality. For instance, during the weekends in Athens or during the national holidays in the winter days, since people spent time inside their homes burning solid fuels to warm their spaces, pollution levels were spiking. Nevertheless, these studies numerically suggested that above wind speeds of 3.5-4m/s, air pollution levels are getting below the 50 μg/m3 concentration for PM10, indicated as the lower interim target level for daily average time exposure by the WHO (The Global Health Observatory n.d.).

5. LITERATURE REVIEW OF PHYTOREMEDIATIVE BUILDING SYSTEMS

The current systems in the market or those still in development for experimental purposes are primarily divided into two main categories for indoor and outdoor space systems (Figure 5). Besides this classification, they come in different sizes and manifestations, from small portable to the scale of a plant pot, to a whole wall installation with a partially indoor systems integration to entirely independent standalone exterior space installations.

Indoor space systems come in various physical sizes following entirely different approaches, from standalone structures to fully integrated, and manually regulated to fully automated. Two typical examples of standalone systems are the first version of the Active Phytoremediation Wall System (AMPS) experimental prototype created at the Center for Architecture Science and Ecology (CASE) and the commercial N-series systems that NAVVA produces (Aydogan 2012; CIAT 2019; Kallipoliti 2018; Naava n.d.; NAAVA 2020; Polidori 2010). These systems are portable, not attached to the floor or the walls, and they have inherent modularity that allows them to take different sizes and volumes. At the same time, everything required for the system to perform is provided from the apparatus itself. Both systems have their own structural components, lighting and watering system, and subsystems with pumps, air fans, sensors, and actuators regulating the circulation of air, fluids, and humidity. Unless the specific device version is not equipped with manually refilled fluid tanks and rechargeable batteries, then the device's container room should be provided with a regular electricity socket required to plugin, and a water installation with drainage pipes for the circulation of fluids.

On the other side of the spectrum, the integrated systems coexist with the building's mechanical systems installations. The most recognizable systems of this typology are the ones of Dr. Alan Darlington of NEDLAW with the indicative commercial name "Living Walls," which have been installed in building lobbies worldwide (A. Darlington 2015; A. B. Darlington et al. 2001; Nedlaw 2016). Also, the latest instantiation of the AMPS prototype, has been installed in the Public Safety Answering Center II in the Bronx, NY (PSAC II) and mounted on the ground floor main lobby wall (SOM n.d.). The system's front side is directly interacting with the long side of the lobby main transitioning corridor as a typical passive green wall commonly used in interior spaces. However, its unseen mechanical side is expanded in a dedicated space on the back of the wall. This space is used to monitor and maintain the wall, which is transformed into a fully functional automated, active wall dragging air through its plants' rhizosphere for regulating and conditioning air quality levels of the space for one of the crisis decision-making rooms. Although the lighting source for the PSAC II AMPS system is still individualized to each plant and attached in each interchangeable module, the system's water and air handling components are directly controlled and integrated into a continuous mechanism with the more conventional mechanical systems of the building's HVAC. Installations like the one briefly described above are mainly possible to reach this level of interconnectivity in new constructions

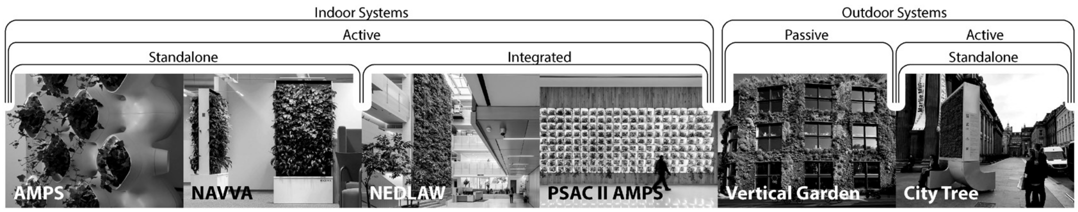

Figure 5: Categorization of phytoremidiative systems. Source: Author 2022.

or extensive retrofits that will plan the necessary requirements in the early design and construction building phases. In less extensive renovations and existing spaces, standalone systems would probably adapt better with less disruption in the fundamental building systems.

Current outdoor systems are mainly divided into two categories, passive and active. Although passive outdoor phytoremediation systems are not considered as air purification systems alone, contrary to the active ones, which force the air through specific routes, we will include them for the purposes of this review. They are the only ones currently described as outdoor biotic systems in the related literature, except for a singular active outdoor air-forcing standalone system. The most renowned representative of exterior phytoremediation systems is the botanist Patric Blank whose work with passive green walls named "Vertical Garden - Mur Végétal" and green spaces attached to building walls' exterior (Bianchini n.d.; Blanc et al. 2008; Blank n.d.; Kmieć 2014; Nurnberg n.d.). Blank's "vertical gardens" are primarily felt-based additions to existing building facades interacting with the surrounding building environment more directly but always with the supplement of an envelope component that acts as the substrate for the plants to grow. Since these types of "green walls" are placed outdoors, their mechanical lighting and watering requirements are minimized almost entirely. Depending on the region's climatic conditions, it may require additional water that is usually a dripping irrigation system on the top of the wall, with a gutter on the lower part for collection and recirculation of the excess water. "City tree" is the only outdoor active system in existence so far and, as its name suggests, is a standalone vertical fully automated greening system (Mok 2020; Patel 2018; Splittgerber & Saenger 2015; urbanNext 2018). "City tree" is a ground-placed system equipped with its own irrigation and air-handling system, while solar panels provide its energy. The system uses moss as its primary plant-growing substrate and an abundance of sensors for

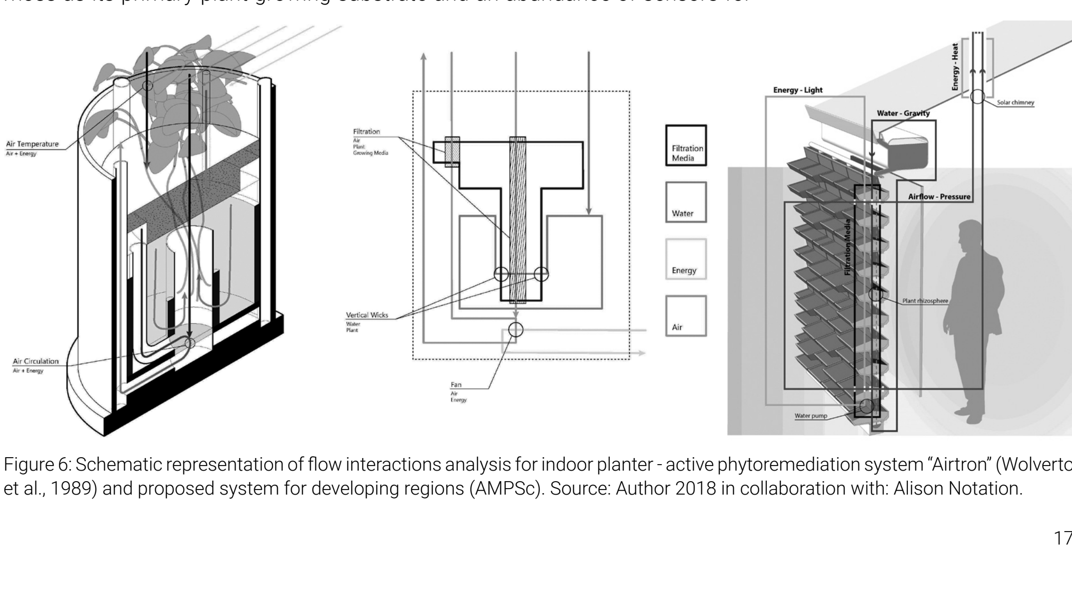

Figure 6: Schematic representation of flow interactions analysis for indoor planter - active phytoremediation system "Airtron" (Wolverton et al., 1989) and proposed system for developing regions (AMPSc). Source: Author 2018 in collaboration with: Alison Notation.

remotely monitoring its performance and maintenance requirements (Kohlstedt 2017; Priday, and Scott 2018).

All these hybrid systems have in common their prescribed services of air quality, sound absorption, space microbial inoculation, and biophilia, among others. The biological organism, most usually a plant and rarely moss or algae, is the acting agent for all the system's services. The organisms, nevertheless, need to be supported literally and figuratively by the mechanical part of the system since their survival depend on the artificial environment's performance. Therefore, in addition to keeping plants in place with structural elements and vessels with growing media—mainly a combination of inert small-size substrates or types of felt and/or other artificially made porous material—such systems require the regulated and consistent provision of light, water, nutrients, treated or untreated air in order to keep plants alive and thriving. Overall, all required system inputs are based on the interaction of three main elements: energy, water, and air (Figure 6). Their combination, manipulation, and treatment with the necessary equipment, such as water pumps, air fans, electricity cables, irrigation tubes, and lighting sources create the conditions to keep the plants alive, effectively illuminated, watered with nutrients liquids, temperature, and air velocity regulated and with a specific volume of air dragged through their rhizosphere.

6. PROPOSAL: THE AMPS BRICK

Following the literature review of phytoremediation systems and their corresponding design attributes, it becomes evident that most systems are based on a logic extracted from the mechanical services era that we live in by prioritizing the mechanization of the system's design and development. There is, therefore, a growing need to reinterpret passive ventilation systems in traditional architectural practice as an adaptation strategy to regionally established architectural typologies. There is also a growing need for the development of a system that does not rely exclusively on technological instrumentation: a system easy to adapt, fabricate, and support in different regions of the world, which lack the financial means not only to install a complex and expensive imported system, but even to service it and maintain it.

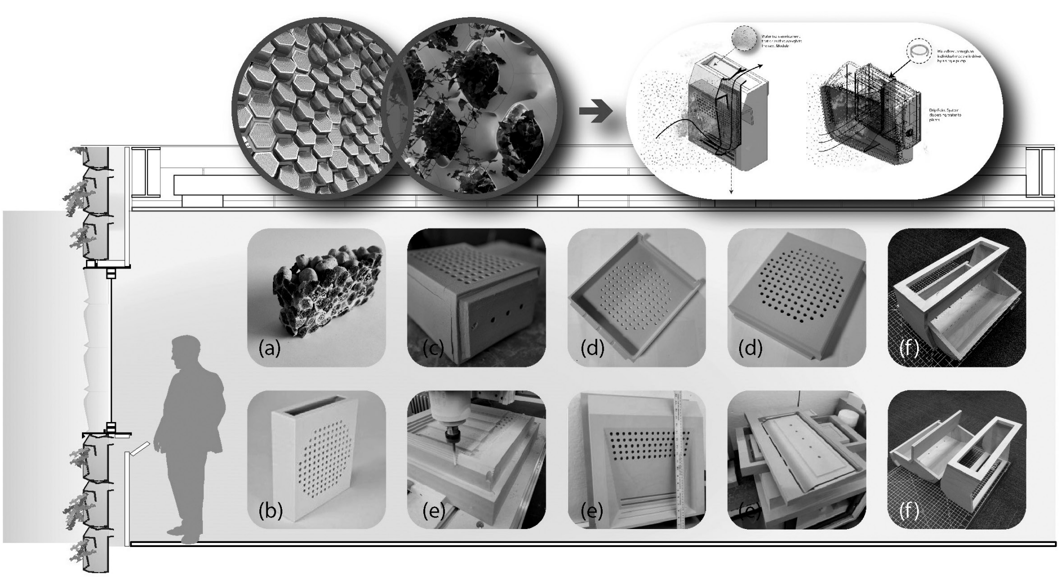

Figure 7: Proposal of materials and systems elements combinatorial development into new core modules under differentiated prototyping procedures. Source: Author 2019 in collaboration with: Abena Bonna & CASE students Anna Dyson et al.

The proposal is thus a low-tech high-value proposition using locally sourced materials, reducing the carbon footprint and saving embodied energy, associated with importing materials from other continents. It is critical to create phytoremediation systems that minimize development costs, unnecessary expansion of expertise needed for assembly, and additional construction assembly components between the several material layers.

In this light, the proposed indoor-outdoor hybrid system, tentatively termed as the "AMPS brick" (Figure 6), uses clay as its primary structural component, which is a material already used in abundance as a wall infill or weight carrying material in more conventional structures (Vollen 2010). Walls composed of AMPS bricks take the shape of interchangeable modules that can be subtracted for maintenance from the indoor side of the wall. AMPS bricks are locally sourced, made from materials abundant in every region of the world, and assembled with easy manufacturing techniques in existence already, familiar with local communities, as in the construction of bricks, roof shingles, plumbing systems, floors, and wall tiles.

The AMPS brick reinterprets the Active Modular Phytoremediation System (AMPS) and the advanced Eco Ceramic envelope system (EcoC), both previously developed at the Center for Architecture Science and Ecology (CASE) (Figure 7). These two prototypes indicate the need for the development of a more reliable method to integrate the material substrate designed to support plant growth. There is a clear need to explore alternative design methods that would minimize excess material in order to amplify the module's capacity to support a wide variety of plants (Figure 8). Further, it would be highly beneficial if the overall system of modules were not designed as a standalone structure, but rather as units capable of maximum integration into the rest of the building system and its site-specific and more ambient environmental flows.

AMPS was specifically conceived as an alternative approach to mechanically dependent building systems that amplify plants' inherent air-cleaning capacity to improve indoor air quality (IAQ), while simultaneously decreasing energy consumption and minimizing the use of conventional air filters

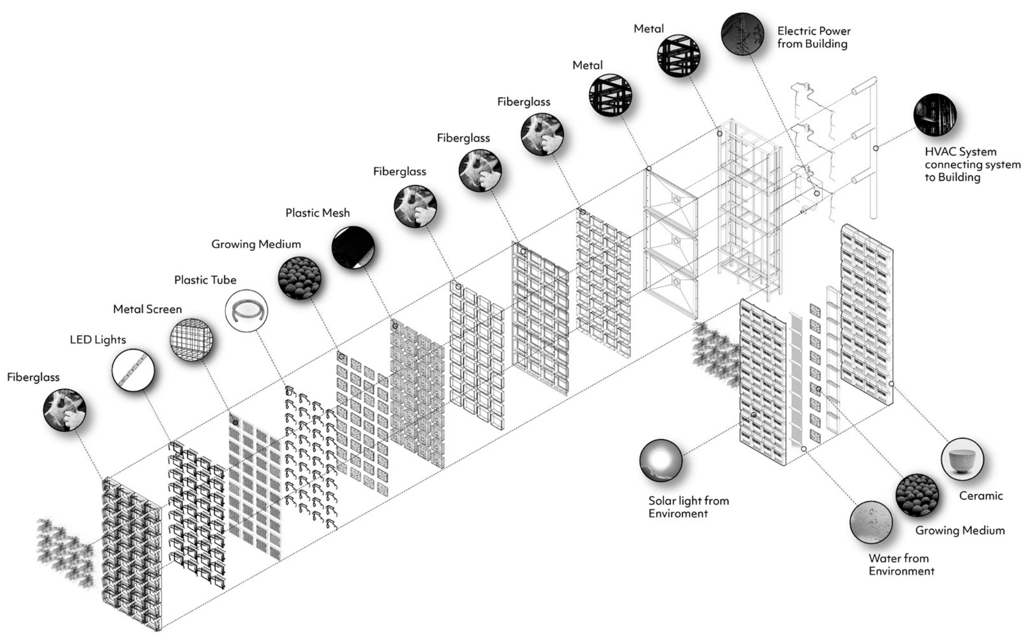

Figure 8: Material and assembly analysis of existing and proposed systems. Source: Author 2018 in collaboration with: Abena Bonna.

for mechanically ventilated buildings (Polidori 2010). Nevertheless, AMPS was designed, constructed, and tested to perform within buildings that have limited interaction with outside environmental flows. It is, therefore, primarily conceived as an extension of a typical mechanical (HVAC) ventilation system (Wang, and Zhang 2011). Although based on the research outcomes of AMPS, this research work primarily focuses on climates that permit natural ventilation, thus making a significant shift in how such a system can be designed and implemented. This approach favors natural ventilation, questioning mechanical systems that completely isolate a building from its environment.

Since the proposed system takes advantage of environmental flows such as rain, the orientation of the growing medium is not vertical, but in inclination with the overall module directing the water collected to the bottom lower center part and then through a series of small water irrigation holes to the one below. Certain precautions should be taken into account in terms of plants' water requirements, depending on the biome intended to perform. Subsequently, the watering system is a drip irrigation gravitational system similar to the ones used by Patric Blank in his green walls; it means that in biomes with a higher content of atmospheric water, plants prone to water should be placed higher in the wall to avoid overwatering. However, for more arid biomes, plants that have higher watering needs should be placed lower in the wall since, in addition to the irrigation system's water, the rainwater collected from the modular bricks in higher parts of the wall would eventually be directed to the lower water collection tank.

Along with the considerations mentioned above, probably the most critical functions of a system primarily focused on air quality were those related to optimizing the module design for ambient and indoor air integration. As a means of addressing this challenge, digital design and fabrication techniques have been employed to expedite the initial testing phase and reduce the cost of production. Additionally, parametric CAD (computer-aided design) models that utilize computational fluid dynamics (CFD) software have been developed to predict the airflow properties and pressure changes characteristic of the new type of typical module. (see fig.9) These wall figures were used to a digitally emulated single pass airflow through-chamber to test the main modular wall component parametrically in a CFD matrix diagram with three different air velocities under four growing media porosities. Each module design was evaluated for its streamlines optimization for maximum pollutants retention in the plant's rhizosphere, while achieving the necessary volumes of air going through the wall according to the established air

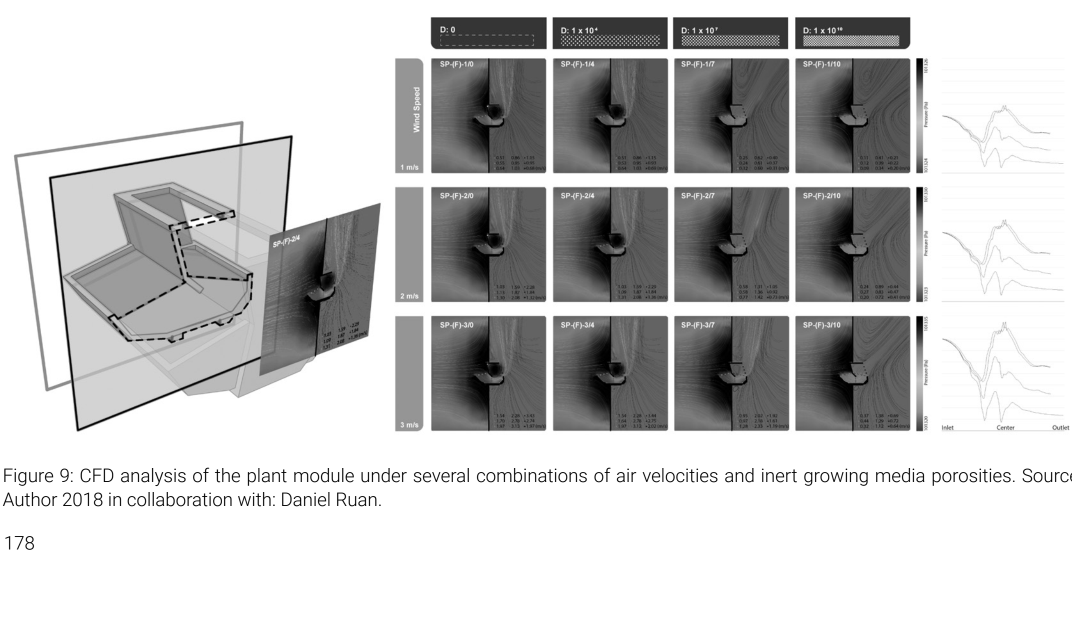

Figure 9: CFD analysis of the plant module under several combinations of air velocities and inert growing media porosities. Source: Author 2018 in collaboration with: Daniel Ruan.

exchange rates under the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) et al. 2013). The three air velocities used were selected based on the previously done studies of urban air velocities to pollution levels in the three cities (Figure 4). All three were under the 3.5-4m/s level recognized as the condition in which urban air pollution levels are not dispersed in safety levels. As for the matrix axis testing the growing media porosities, the first column was the module without a porous material, and then three states of porosities from the equivalent of gravel to the equivalent of dense soil.

In the testing of various module types, five parameters have been used to establish evaluation criteria: a) the geometry of the brick module that contains plant life and a growth medium; b) the porosity of the growing medium of the plant life, in terms of the air volume that may pass through it; c) the air velocity that is channeled in the module for testing; d) the streamlined airflow pathway through the module and virtual chamber; and e) the pressure differential created around the module under different design, growing media porosity, and air velocity conditions. The findings of this analysis will be further evaluated through the production of a physical 1/1 model of the new phytoremediation system proposed previously and assembled from “AMPS bricks” built on a real site in Greece. This full-scale prototype will enable interaction between users and the prototype in a public setting and will further the scope of the research from the laboratory to the field. Finally, it will be evaluated whether or not the system would function effectively for plants to survive in their host module through real life, full-scale application in the context of two locations typical of a natural ventilation biome, those of Chania, Greece, and Limassol, Cyprus. Each location would likely provide significant data, as it relates to different temperature and humidity levels, demonstrating the efficiency and sustainability of this application in terms of plant growth.

CONCLUSION

After substantial research on air quality phytoremediation strategies, it may be asserted that the applicability and the multitude of benefits of a phytoremediation-based building system are strong and can no longer be ignored. The recent iteration of the AMPS system, from the scale of the laboratory to an integrated large-scale building system for the new public safety answering center II (PSAC II) of New York City in the Bronx, is another vote of confidence in the multitude of benefits that the rhizosphere of plants and the related microbial communities could play in the environmental health of building occupants. The possibilities for augmenting the benefits of a natural system that has evolved for thousands of years are limitless. At the same time, our restricted knowledge of the evolutionary mechanisms surrounding microbial communities and plant ecosystems could be a limiting factor for marketing the system to a broader audience, given that it does not currently comply with the established metrics and standards of air pollution strategies established exclusively based on mechanical engineering research.

Work on this specific area of research is currently performed from our research cohort to characterize the microbial communities and to upgrade the metrics used for evaluating complex building systems in the totality of their performance. With two papers accepted in the ASHRAE forthcoming conference—although in its infancy—the results of this research are already too promising.

The Center for Disease Control and Prevention (CDC) estimates the majority of Americans spend approximately 90% of their time indoors. In other parts of the world, this percentage might be smaller, and the indoor space of structures is not as isolated from the exterior environment (Centers for Disease Control and Prevention & U.S. Department of Housing and Urban Development 2006; Klepeis et al. 2001). This does not mean that air quality (AQ) problems are minimized, as in many instances, the absence of viable remediation options could result in the exacerbation of air pollution. There is a need to move beyond the dichotomy of indoor and outdoor air quality and transition to natural ventilation and ambient air quality (AQ) mentality for places where the climate may support it. The suggested interdisciplinary work will attempt to dematerialize this dichotomy with the use of phytoremediation techniques that will impact the quality of users' life in space and reintroduce traditional living patterns in civic space. The breathing envelope solution—under development—has the potential not only to create the conditions necessary to alter the pollution concentrations surrounding air streams, but also to offer a living system that may grow over time into a localized ecosystem that will regulate the quality of life in the environment via the control of local microclimates and their corresponding parameters. Especially in regions with challenging economies, phytoremediation ecosystems could establish a new manufacturing paradigm, building on vernacular systems with exceptional airflow, shading, and civic value. Such systems might transform urban environments into networks of living, breathable buildings rather than accumulations of isolated mechanical building bubbles that exploit the environment for the benefit of temporary IAQ gains.

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