Creating Holistic Architecture

Unifying Natural Ecology with Technology Through Design

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[redacted]

A thesis submitted to the Faculty of Graduate and Postdoctoral Affairs in partial fulfillment of the requirements for the degree of Masters of Architecture

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x. Abstract:

The current mentality towards sustainable architecture is incomplete. As architects, we are rightfully concerned with energy conservation, material life cycles, recycling and footprint. However, we tend to overlook the deeper psychological implications contributing to ecological degradation and climate change. In order for architecture to become truly sustainable, our buildings must actively work to reduce local environmental pollution and must also work to repair the dissonance between human habitation and natural ecosystems.

This Master's Thesis seeks to determine which aspect of an ecological setting will promote occupant health, productivity and ecological awareness through a detailed study. In conjunction with this familiarity study, research will be conducted into emerging technologies which can remedy the effects of urban air pollution. The most promising system will be selected, and will be redesigned to be incorporated into an architectural composition. The final project for this thesis will involve combining the data accumulated from the survey along with the remediation technology into an architectural design. This project will actively reduce surrounding pollution while fostering a greater relationship between local ecology and the building's occupants, creating the first truly holistic architectural design.

xi. Preface:

"To be capable of transforming a forest into packaging for cheeseburgers, man must see the forest not as a display of the miracle of life, but as raw material, pure and simple"[1].

Martin Heidegger is commenting on how we have come to view and treat our planet; for millions of years we evolved and lived in and alongside nature. Natural ecology housed us, sheltered us, and provided us with sustenance. Yet as our intelligence grew and our understanding of our environment advanced, we began to separate ourselves from nature; we created our own shelters, developed agriculture, and eventually settled into towns and cities. In the last few thousand years we have come to view ecology not as life or home, but as a resource to fuel our consumption and personal enterprise; something separate that can be visited but must not be allowed into our personal spaces.

Architecture plays a key role in this relationship with our planet, fulfilling a dichotomy of creation and destruction. Our constructions sustain our daily lives, but for us to create architecture, we need to destroy surrounding habitats and natural ecology, transforming forests, plains and pastures into concrete jungles. The act of building is one of the main contributors to environmental degradation and climate change, two issues that today pose the

[1] Zimmerman, M. (1977). Heidegger: The Man and the Thinker: Beyond Humanism: Heidegger's understanding of technology, Listening. P. 79

biggest challenge to human existence. In Canada the construction process contributes to over 48% of all energy consumption and greenhouse gas emissions, larger than the transportation and industrial industries combined[2].

Organizations such as LEED (Leadership in Energy and Environmental Design), National Green Building Standard (NGBS), BREEAM (Building Research Establishment's Environmental Assessment Method), etc, seek to encourage the development of “sustainable” architecture, which look to reduce the level of environmental destruction in architectural design. These certification programs are intended to outline and confirm that architectural designs and constructions meet a particular set of environmental standards which go beyond the basic building codes. This includes standards in energy use, recycled content, air quality control, and water consumption that directly impact environment quality[3]. The goal behind these parameters is to reduce the overall effect of construction on the environment, creating zero footprint buildings that do not place a larger burden on our environmental and energy systems.

However, where these programs succeed in promoting more environmentally neutral buildings, they are ultimately failing to foster the kind of action needed to combat issues such as climate change, rising population density, behavioral reform and environmental remediation. If we are to make a lasting difference in these areas and attain a truly holistic solution to these environmental issues, our understanding of architectural design needs to change. Buildings can no longer remain vessels for our activities, but must actively take part in molding our physical and psychological relationships between the built world and the natural world. Architecture must be designed in a way that can engage its occupants, promoting healthy living and interaction with natural ecology, while also utilizing new technologies to actively reverse the detrimental effects we exert on our environment.

[2]Climate Change and Architecture, The Royal Architectural Institute of Canada - https://www.raic.org/sites/default/files/involvement/documents/2030factsheet_e.pdf

[3]Guide to green building rating systems: understanding LEED, Green Globes, Energy Star, The National Green Building Standard, and more - by Reeder, L. Hoboken, NJ: John Wiley & Sons, Inc., 2010.

1. Introduction:

1.10 Identifying the Effects of Air Pollution, and the Shortfalls of Current Environmental Solutions:

According to a report released by the World Health Organization in 2014, 7 million people died in 2012 as a result of exposure to air pollution. Of those deaths, 4.3 million were attributed to household air pollution and the remaining 3.7 million occurred due to ambient air pollution[4].

While North America does not reach the same level of mortality as nations such as China and India, we are not immune from the effects of air pollution. According to The Canadian Medical Association it is estimated that Canada's air pollution is responsible for 21,000 premature deaths, 92,000 emergency-room visits and 620,000 visits to a doctor's office in a year, resulting in an economic cost of air pollution-related illness and death in Canada topping $8 billion a year[5]. In comparison, the estimated cost of air pollution-related illness and death in Europe is $1.7 trillion, while the numbers in the United States range from $187 billion to $500 billion annually[6].

Looking at such staggering statistics poses the question as to why such pollution exists, what are the causes, and how do we remediate our most affected areas? Much research has been done to try and answer these seemingly straight forward questions, especially from the views of sustainable architecture and technology. However, the research that has been conducted only presents stand-alone solutions – solutions that address one small aspect of the greater issue at a time – rather than presenting a holistic approach.

Architects play an integral role in finding a lasting solution to the growing issues of environmental pollution and degradation. With the populations of cities projected to grow exponentially, it will be up to careful urban planning and architectural design to accommodate this rising population. Buildings will need to be more efficient, more productive, cleaner, and must also present a psychological solution towards correcting our pollution-creating behavior if we are to support such growth in a responsible way.

The following proposal will outline a research approach into two key aspects of such a responsible design.

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[4]Smith K, Bruce N et al. "7 million premature deaths annually linked to air pollution" - Public Health, Social and Environmental Determinants of Health Department, World Health Organization, 1211 Geneva 27, Switzerland © World Health Organization 2014

[5]Rennie, Steve. "CMA Sees Sharp Rise in Air Pollution Deaths | Toronto Star." Thestar.com. August 13, 2008. Accessed November 9, 2015. http://www.thestar.com/news/canada/2008/08/13/cma_sees_sharp_rise_in_air_pollution_deaths.html.

[6]Brickman, Stephanie. "Air Pollution Costs European Economies US$ 1.6 Trillion a Year in Diseases and Deaths, New WHO Study Says." WHO/Europe. April 28, 2015. Accessed November 9, 2015. http://www.euro.who.int/en/media-centre/sections/press-releases/2015/04/air-pollution-costs-european-economies-us$-1.6-trillion-a-year-in-diseases-and-deaths,-new-who-study-says.

1.11 Identifying the General Focus of the Research Project

This Master's Thesis Project, which was developed at Carleton University's School of Architecture, will examine two aspects of an architectural design solution to urban air pollution. The first will investigate the psychological influence of an ecological setting on potential occupants of a space. This research will build off of existing research by Mangone (2013), Verderber (1986) and Ulrich (1984) which concluded that people in spaces with vegetation compared to those lacking vegetation are more likely to experience stress reduction, better overall health, more positive moods, increased attention and productivity, and reduced mental fatigue[7,8,9].

The research will be conducted in the form of a familiarity study with the purpose of identifying the type of ecological setting in which people would be the most comfortable/productive. The results from the study would then be incorporated into a new architectural design proposal for an urban location.

The second aspect of the Master's thesis identifies front-running technologies which combat the effects of climate change and more specifically urban air pollution. Research will attempt to investigate the validity of these emerging technologies and will compare each system based on common performance metrics. The most effective technology will be re-designed for architectural integration and incorporated into a final project along with the results of the familiarity study, thus creating an example of holistic sustainable architecture.

1.12 Research Objective

The intent of the research is to establish a potential building occupants' familiarity with an ecological setting, and to translate that into a sustainable architectural design focused on reducing urban air pollution and on fostering a positive relationship between the occupant and natural ecology.

1.13 Research Questions

The study questions will be structured so as to ascertain the impressions a subject experience's as they are presented with an image of a type of ecological setting. These questions will be identical for each new image presented in the study, and will be answered through a rating

[7] Rachel Kaplan, and Stephen Kaplan, *The Experience of Nature : A Psychological Perspective* (Cambridge; New York: Cambridge University Press, 1989)

[8] T. Fjeld, B Veiersted, L Sandvik, G. Riise, and F. Levy, 1998. The Effect of Indoor Foliage Plants on Health and Discomfort Symptoms among Office Workers. Indoor Built Environment, 7:204-209.

[9] Heshong-Mahone Group, 2003. Windows and offices: A Study of Worker Performance and the Indoor Environment. California Energy Commission: PIER program.

system of 1 to 7. This will allow for a more accurate measurement and comparison of the reactions to each of the images presented to the subject.

The research questions investigating the potential of air pollution remediation technology will be much more direct and specific. Their purpose will be to acquire precise data on the function, operation and design of the individual systems in order to evaluate and compare one against the other. The system deemed to be the most feasible in terms of architectural potential will then be incorporated into a comprehensive project illustrating the concepts of holistic sustainable architecture.

1.14 Primary Research Questions

What ecological settings do people most associate with, and how can that translate into a more holistic architectural design?

What emerging sustainable technology is the most effective as a solution to urban air pollution, and can it be adapted into an architectural design?

1.15 Sub Research Questions

Familiarity Study:

1. What characteristics of a particular ecological setting appeals most to the subject in terms of mental/physical restoration?
2. What are the spacial qualities of an ecological setting that inspire the feeling of being away?
3. What are the spacial qualities of an ecological setting that inspire comfort/compatibility?
4. What are the spacial qualities of an ecological setting that inspire fascination?
5. Can an architectural design reconnect its occupant with an ecological space?
6. Can an architectural design that is based on an ecological setting foster a stronger bond between the building occupant and other natural ecological settings?

Emerging Technology Analysis:

1. Which emerging technology is most versatile, which will allow for a greater architectural re-imagining?
2. Which emerging technology is economically viable?
3. Which emerging technology offers the greatest performance in terms of air pollution remediation?
4. Which technology will successfully tie into the research collected from the familiarity study in a final design project?

1.16 Research Methodology

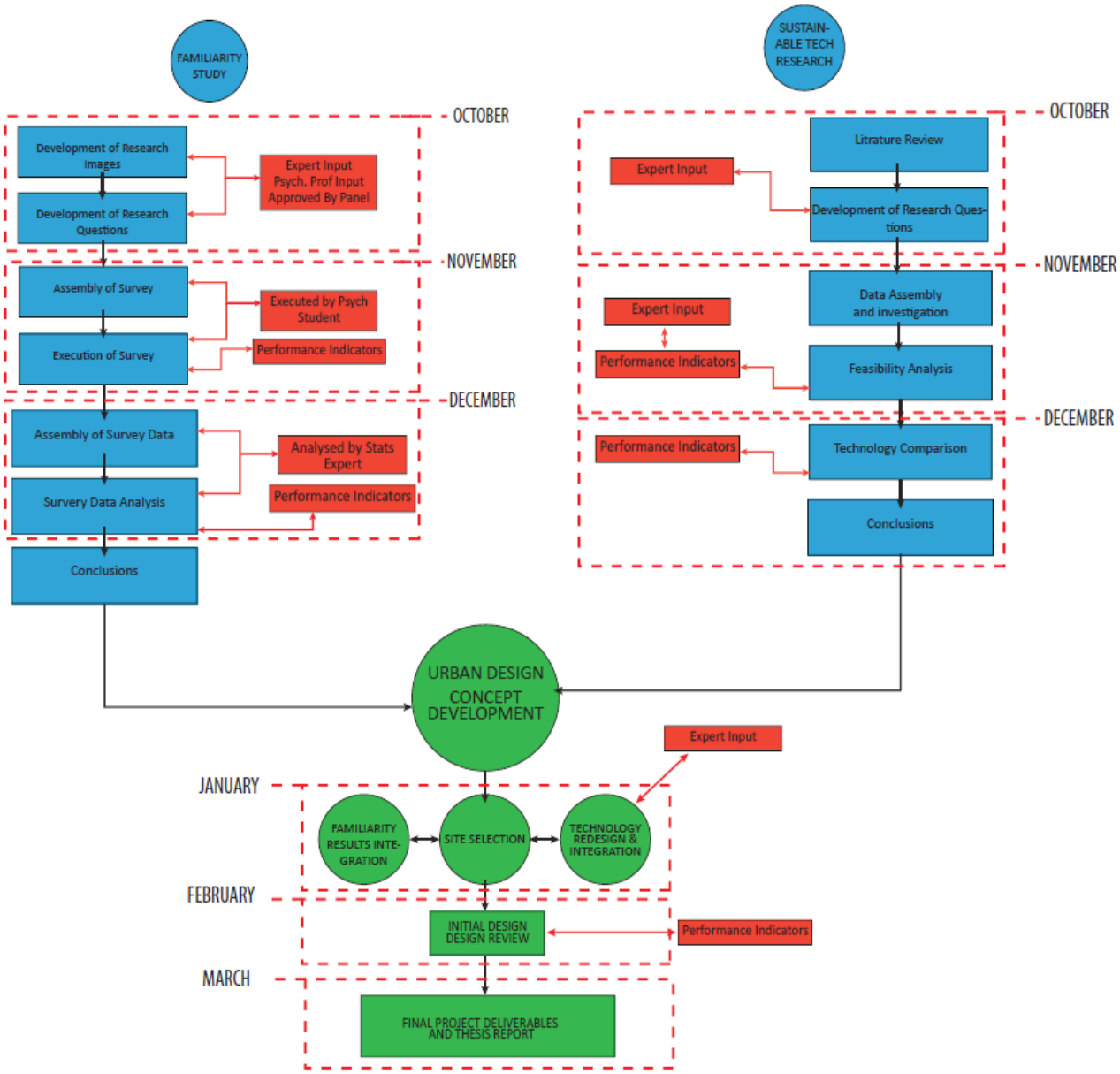

Figure 1.1: Research Methodology Framework

1.9 Specific Application of Research Methodology

The development of the familiarity study and the research into air pollution remediation technology was conducted using a Design Research Methodology framework. This framework ensured accurate accumulation and execution of non-biased material, precise measuring of responses, and the proper processing of high quality data. Design Research Methodology framework is composed of four research phases: Research Clarification, Descriptive Study 1, Prescriptive Study, and Descriptive Study 2[10]. This methodology allows for diverse research

question development, various exploration, observation and experimentation methods, and structures the resulting research into a focused and rigorous framework.

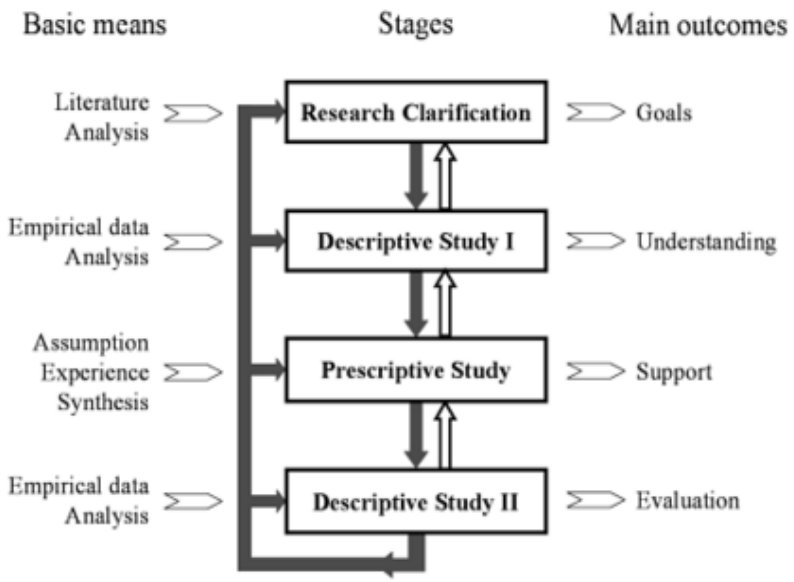

Figure 1.2 DRM Framework[10]

For the purpose of this masters' thesis, greater emphasis was given to the phases of Research Clarification and Descriptive Study 2. The reason for this was because the requirements of the Master's thesis places greater value on the development of a final design project, and so the main focus of this research will be to provide the necessary empirical data and analysis so as to complete this project. That being said, the 4 research stages were completed as followed:

1.9.1 Research Clarification Phase:

The research clarification phase is characterized by the establishment of quality research objectives, and is comprised of a detailed literature reviews[11]. The results of this review was the basis point for structuring our familiarity survey.

A literature review was also conducted to identify emerging technologies which actively combat the effects of air born pollution and carbon emissions. This involved sourcing scientific journal articles which identified current projects undergoing by university researchers, various start-ups companies, and several architectural and engineering firms. These potential projects were then researched in more detail through academic papers, patent design applications, spec sheets and online publications.

[10]T.M. Blessing, Lucienne, and Chakrabarti, Amaresh . "DRM, a Design Research Methodology." Springer-Verlag London Limited 2009.

[11]Lucienne T. M. Blessing, and Amaresh Chakrabarti, Drm*, a Design Research Methodology (*Dordrecht; New York: Springer, 2009)

1.9.2 Descriptive Study 1

The Descriptive Study 1 phase is meant to foster a deeper understanding of the literature gathered in the previous phase. Here the performance parameters were identified and analyzed by the researcher. Experts were consulted at this point, and feedback was provided on research methods, performance parameters and accumulated data[11]. This analytic research processes helped to determine which performance parameters were important to consider to attain the research objectives. For example, while existent research does support the assertion that interaction with ecology has numerous benefits to our health and productivity, the research does not identify which specific environmental setting has a greater effect[12]. This recognition will direct our familiarity study towards comparing not only how a subject interacts with different spacial qualities, but also different types of ecological settings.

The analysis of the literature review and research provided us with the criteria for developing a specific set of research questions and survey images that were used for the familiarity study. These questions and images were examined and approved with the aid of Professor John Zelenski from the department of Psychology at Carleton University, and Raelyne Dopko, a student also from the department of psychology at Carleton University.

The data collected from the research into air pollution remediation technologies was grouped, compared and analyzed in this phase as well. A set of specifications were identified in each of the most promising new technologies which allowed for a comparison of each systems' level of efficiency, effectiveness and feasibility in terms of its' ability to remediate high levels of air pollution. A single system was then chosen based on its performance criteria and architectural potential to be further analyzed and later incorporated into the final architectural design.

1.9.3 Prescriptive Study Phase

The Prescriptive Study phase is focused on determining if alterations need to be made to the existing situation to generate the desired results[11]. At this point the existing research was more comprehensively understood, and so the definition of the research was refined and corrected depending on the altered research goals moving forward.

1.9.4 Descriptive Study 2 Phase

In the Descriptive Study 2 phase, the results of the research that are developed in the previous phases are evaluated. This evaluation is conducted in order to determine the effectiveness of the research methods, the successes and shortfalls of the evaluation strategies, whether the research addresses the intended research objectives, and whether the resulting research has delivered expected and/or unexpected results.

- [12]Terry Hartig, Florian G. Kaiser and Peter A. Bowler. “Psychological Restoration in Nature as a Positive Motivation for Ecological Behavior” 2001 Sage Publications. Pg 593

For this thesis, the results of the Descriptive Study 2 phase are discussed in later chapters. These results were then refined and appropriated into a new architectural design also to be discussed in later chapters.

2. Familiarity Study

2.1 Understanding Human Evolution:

Why is it that people enjoy activities such as camping, or hiking? How come we get such enjoyment out of sitting in or walking through a forest, or lounging on a beach, or canoeing down a river? Is it simply because this takes us away from our everyday routine and places us in a new, stimulating environment? If this were the only reason, then wouldn't traveling to any new setting achieve the same results?

These questions imply that our relationship with nature isn't as superficial as we tend to imagine. In the early 1950s, the German office landscape movement headed by Eberhard and Wolfgang Schnelle, sought to promote a more private and intimate spaces for working (thus inventing the cubicle)[13]. During their research they had the idea to enrich these work spaces with indoor plants, assuming that the presence of ecology would make an environment more collaborative and humane[14]. Their instincts weren't wrong, and they began to notice that workers with plants in their work space were more productive than those without. Though they didn't take this research much further, others took interest. A later study by Dr Chris Knight from Exeter University and his colleagues at the American Psychological Association found that employees were 15% more productive when workplaces were filled with just a few houseplants[15]. Another study by the University of Sydney found that plant presence resulted in a 37% reduction in tension/anxiety, 58% reduction in depression, 44% reduction in aggression/hostility, 38% reduction in fatigue, and a 28% increase in vigor/feeling of energy[16].

These studies indicate that our relationship and interaction with natural ecology has greater psychological implications on our health and behavior than simply for recreation. In order to understand why this is, we have to first understand how human psychology evolved and how that affects our daily lives.

The human story begins over 55 million years ago with a creature called Smilodectes, one of the first true primates to evolve near the beginning of the Eocene Epoch. They were still somewhat squirrel-like in size and appearance, but they had grasping hands and feet that were increasingly more efficient in manipulating objects and climbing trees[17]. These “Prosimians” flourished in the treetops, and evolved into many different species of primates.

Monkeys evolved during the early Oligocene/end of the Eocene (roughly 35 million years ago)[18]. By 16-14 million years ago, in the middle of the Miocene Epoch, Apes had evolved and were much larger and more intelligent than their other simian counterparts. They began to

[13] Saval, Nikil (2014). *Cubed: A Secret History of the Workplace*. Published by Knopf Doubleday Publishing Group, New York.

[14] Sundstrom, E., & Sundstrom, M. G. (1986). *Work places: The psychology of the physical environment in offices and factories (environment and behavior)*. Cambridge, UK: Cambridge University Press

[15] Nieuwenhuis, Marlon; Knight, Craig; Postmes, Tom; Haslam, S. Alexander (2014). *The relative benefits of green versus lean office space: Three field experiments.* Journal of Experimental Psychology: Applied, Vol 20(3), Sep 2014, 199-214.

[16] A. Craig, F. Torpy, J Brennan & MD Burchett (2010). *The positive effects of office plants*. University of Technology Sydney © NGIA Ltd 2010

[17] O'Neil, Denis (2012). *The First Primates*. http://anthro.palomar.edu/earlyprimates/early_2.htm

adapt to life at the edge of the forest, moving into the savannas and tall grasses which had begun to encroach on the forests due to shifting climates[18].

As these species moved down from the trees and began to travel greater distances to locate food, bipedalism began to emerge as a more energy efficient and practical mode of travel. They were able to go longer and further for food, and carry supplies back with them[19]. These primarily bipedal species were the first of the "Homo" genus, with Homo Habilis being the first of its kind to create tools 2.4 million years ago. They were followed by (among others) Homo Erectus 1.8 million years ago, and Homo Neanderthalensis and Homo Sapiens roughly 230,000 years ago[20].

What is important to take from this story are two key points:

1. We are here because our ancestors were able to successfully pass down their survival genes to us, which means that we are the embodiment of millions of years of instinct, habit and behaviors. It is these common genetic traits and how they affect our daily lives and behaviors that form the basis for human psychology. A fact that must be considered if human kind is to make any lasting change to our current environmental behavior.
2. The common thread throughout this story, is that we have lived and evolved in nature for over 55 million years. Forests, fields, lakes and rivers have provided us with shelter, resources and comfort over this entire time. In fact, it is only in the last 10,000 years that we have begun to build our own shelters, and to separate ourselves from the natural world.

Our connection with natural ecology runs deep within our DNA, and can have a profound influence upon our psychological and physiological wellbeing. Yet when it comes to designing our built environment, our cities, our workplaces and our homes, we still come to view nature as something that must be separate from us, simply resources for our consumption. Can we change our unnatural view of nature? As architects can we draw elements from natural ecology and incorporate them into our designs so as to improve our relationship with the environment, not to mention our own personal health and happiness? What would that look like?

The initiation of a familiarity study will attempt to answer these questions, the results of which will be integrated into an architectural urban design project.

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[18] Roger Lewin, Principles of Human Evolution: A Core Textbook (Malden, MA: Blackwell Science, 1998), 219-22.

[19] Robert Martin, "Walking on Two Legs," The Cambridge Encyclopedia of Human Evolution, paperback edition, ed. Steve Jones, Robert Martin, and David Pilbeam (New York: Cambridge University Press, 1994), 78; Fred Spoor et al., "Implications of Early Hominid Labyrinithine Morphology for Evolution of Human Bipedal Locomotion,"Nature369 (1994), 645-49.

[20] Hill, Kyle (2009), "The Timeline of Human Evolution". https://sciencebasedlife.wordpress.com/2011/05/10/the-timeline-of-human-evolution/

2.2 Attention Restoration Theory

Attention Restoration Theory, developed by Stephen and Rachel Kaplan, and builds on similar assumptions about human psychology and cognitive abilities in natural environments. The Kaplans assert that our environments exact pressures and demands upon our capacities for directed attention, either serving to weaken or strengthen them depending on various qualities. Directed attention fatigue can result in negative emotions, a sense of physical fatigue, irritation, a drop in performance and productivity, and even an increase in stress[21]. Terry Hartig and his colleagues found that a relocation to a more natural or stimulating environment was particularly effective at mitigating directed attention fatigue[22].

Further research has yielded a set of measurements evaluating the level of direct attention restoration referred to as the "Perceived Restorativeness Scale". The PRS was designed to measure an individual's perception of 4 restorative components assumed to be present to a greater or lesser extent in the environment[23,24]:

1. Being Away:

The Kaplans describe being away as attaining a sense of distance from the ordinary or routine aspects of one's life[22]. This sense of distance does not necessarily have to be physical in order to have restorative effects, but can also be attained through a psychological distancing, or even a combination of the two.

2.Extent, or Coherence and Scope:

Extent involves the influence of connectedness (or coherence) and scope upon an individual. Connectedness describes the relationship between perceived elements or features of an environment and the individual experiencing said environment, for example, a past memory of walking through a forest with a relative might elicit a fond connection with greenery.

Scope recognizes that scale also plays an important role in affecting the response to an environment. Scope not only involves our immediate surroundings, but also applies to areas that are out of sight but can still be imagined. For example, even if a person walking through the woods can only see trees in their immediate vicinity, their senses and imagination still tells them that the environmental scale is greater than what they can see[22].

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[21]Hartig, T., A. Book, J. Garvill, T. Olson & T. Gärling, (1996). "Environmental Influences on Psychological Restoration", Scandinavian Journal of Psychology 37: 378-393

[22]Terry Hartig, Kalevi Korpela, Gary W. Evans & Tommy Gärling, (2007) "A Measure of Restorative Quality in Environments", Scandinavian Housing & Planning Research 14: 175-194

[23]Kaplan, S. (1995). The restorative benefits of nature: Toward an integrative framework. Journal of Environmental Psychology, 15, 169-182

[24]Hartig, T., Kaiser, F.G., & Bowler, P.A. (1997a). Further development of a measure of perceived environmental restorativeness. Working Paper No. 5. Institute for Housing Research, Uppsala Universitet.

3.Fascination

Fascination in different contexts can be a double edged sword; people can be fascinated by events that may not benefit them mentally, or that might alter their emotional states in ways that are not constructive (ex the game "Candy Crush", which has captured the fascination of millions of users, yet does very little to positively influence their cognitive abilities or sense of restoration). Other examples are violent events or dangerous distractions (texting and driving, office conflicts, etc).

Other sources of fascination can be very constructive and beneficial to an individual's mental and emotional states. Art for example, offers us a stimulating medium that triggers our intrigue, encouraging us to exercise our cognition and improving our experience without negatively impacting our routine. The Kaplans thus introduced the term "soft fascination" in order to distinguish between nonconstructive and constructive experiences[25].

4.Compatibility

The final area associated with a restorative environment is the compatibility between the environment and the occupant of said environment. This refers to the match between the person's demands for the use and occupation of the space, and the ability of the space to provide the support for the execution of these activities. A high level of compatibility is thought to permit interaction and reflection, resulting in a more profound and lasting relationship between the occupant and the environment[26].

2.3 Structuring the Familiarity Study

The familiarity study will expand on the qualities stated above by identifying specific visual and experiential aspects of an ecological setting by testing for the following:

1. Connection to nature – level of comfort/relaxation experienced in natural settings **(Extent)**
2. Sense of public/private space – Evaluating the social aspects of a natural setting **(Compatibility)**
3. Level of engagement **(fascination)**
4. The sense of **being away**

In order to properly test for the above attributes, the familiarity study questions and images have been carefully scrutinized for any undesired biases that might skew the resulting data.

2.3.1. Participants

[25]Herzog, T.R., A. M. Black, K. A. Fountaine and D. J. Knotts (1997) "Reflection and Attention Recovery as Distinctive Benefits or Restorative Environments", Journal of Environmental Psychology 17: 165-170

This study involved 273 participants, 188 from Ottawa Ontario Canada. The mean age was 23.5 years (from 18 to 45), and 51.3% were female. This gave us the widest demographic possible of adults most suited towards regular interactions and experiences with natural ecological settings.

2.3.2. Materials

Based on the literature review, 10 ecological settings were chosen to be evaluated in the Familiarity Study. Four color photographs representing each outdoor environment were then carefully selected based on their visual components. The images had to properly convey each setting without demonstrating any bias towards stimulation that might distract from the environment being evaluated. For example, a forest setting could not contain any bright colors (such as fall leaves) as this would not properly represent the forest setting, but would create bias due to the increased stimulation through color. The ecological settings and images chosen are as follows:

1. Beaches



2. Lakes




3. Marshes

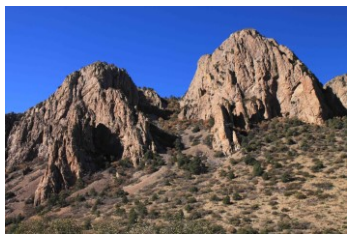



4. Meadows




5. Mountains



6. Parks




7. Rivers




8. Swamps




9. Temperate Forests




10. Tropical Forests




2.3.3 <u>Method</u>

For each ecological setting, the test subject will view 4 different images of each setting and will answer the following 13 questions:

1. How much do you like this environment, for whatever reason? (*1= do not like it at all, 7= like it very much)* – ***Cohesion/Compatibility***
2. How much would you like to live permanently adjacent to this environment? *Please ignore any social, economic, and cultural factors when making your decision.*

   (1= would not like to live adjacent to this environment at all, 7 = would very much like to live adjacent to this environment) - ***Extent***
3. How familiar is the environment? *(1=not familiar at all, 7 = very familiar)* - **Extent**
4. How safe would you feel in this environment? *(1=not at all, 7 = very much)* - **Cohesion**
5. How public is this environment? (1=not at all, 7 = very much) **public/private**
6. How beautiful is this environment? *(1=not at all, 7 = very much)* - **Extent**
7. *How pleasant is this environment? (1=not at all, 7 = very much)* ***Pleasant/unpleasant***
8. How relaxing is this environment? *(1=not at all, 7 = very much)* ***Relaxed/stressed***

Please rate how much you agree with the following statements, on a scale of 1 to 7 (1=not at all, 7=very much)

9. Places like this are fascinating - **fascination**
10. In places like this my attention is drawn to many interesting things **fascination**
11. In places like this it is hard to be bored - **fascination**
12. Places like this are a refuge from nuisances - **being away**
13. To get away from things that usually demand my attention, I like to go to places like this - **being away**

2.4 Results

Although we are currently awaiting a more detailed analysis of the final results, the current indication of the data shows that the preferences of the survey subjects were towards rivers and parks.

It is our belief that these settings offer reasonable contrast to the subject's typical place of residence (ie. Home, school or work), yet are familiar enough to generate a sense of cohesion/compatibility with the subject. These settings were different and stimulating enough to score higher in terms of inspiring the feeling of “being away”, yet were not overly stimulating to the point of creating unease. Fascination likely scored higher in these settings due to the wider range of possible activities that could take place within them, but fell short of a setting such as a tropical rain forest, which might have been viewed as more intriguing but also overwhelming.

People's preferences for familiar/regular relaxation spots may also have played a large role in determining their ecological preferences. Parks and river activities (such as camping or hiking) are readily available in Northern Ontario, and are very popular destinations for locals and tourists alike. This fact may have skewed the subjects’ preferences, as they have become more accustom to these settings due to the frequency of their visits.

2.5 Conclusion

The resulting data has indicated that the ecological settings preferred by the test subjects are parks and rivers. This information was used to form the guidelines for the architectural project discussed later in this paper, with the intent of creating a new design order that psychologically restores the occupant's mental capacities and reconnects them with natural ecology.

3. The Reality of Air Pollution

3.1 Introduction to Air Pollution

Chapter 1 of this Master's thesis cited disturbing numbers regarding the health impacts and economic cost of air pollution worldwide. Air pollution poses a major problem in our modern society, and is the driving force behind climate change as well as directly causing over 7 million premature deaths worldwide[26]. Due to the effects of climate change, The World Health Organization and the IPCC are projecting droughts, famine, arduous weather, flooding and a dramatic loss of fertile soil over the next 50 to 100 years.

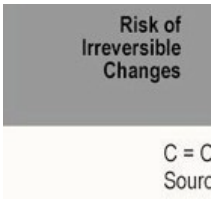


Figure 3.3: Projected Impacts of Climate Change – Stern Review on the Economics of Climate Change

In addition to this, statistical trends by W.H.O. are showing a growing percentage of the population choosing to reside in urban centers vs suburban towns.

[26]Smith K, Bruce N et al. "7 million premature deaths annually linked to air pollution" - Public Health, Social and Environmental Determinants of Health Department, World Health Organization, 1211 Geneva 27, Switzerland © World Health Organization 2014

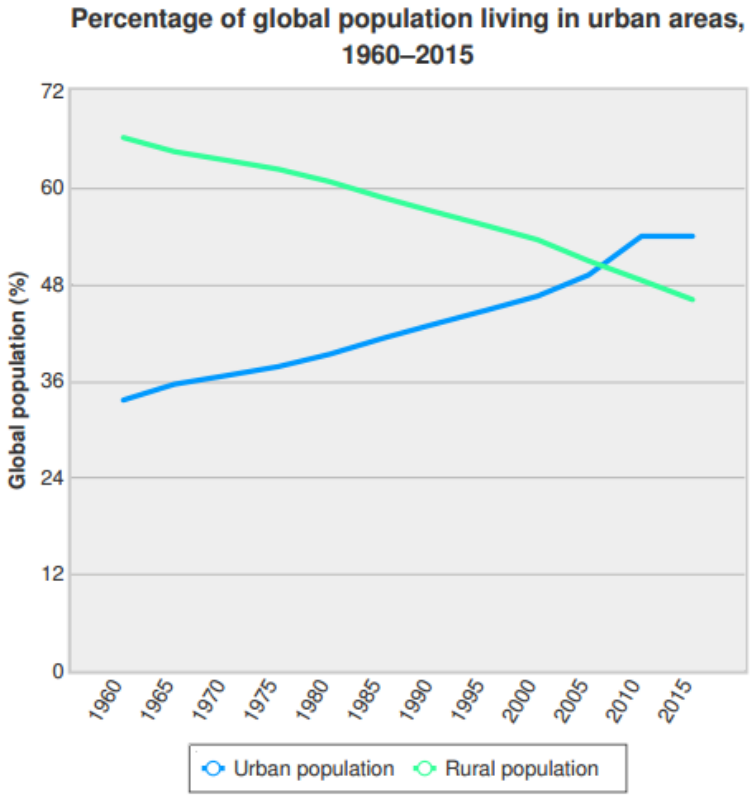


Figure 3: Percentage of global population living in urban areas 1960-2015[28]

While this trend is ultimately positive as it reduces urban sprawl, it sparks issues from the economic impact of rising population density to an increasing demand on social programs and institutions (ex. larger police/fire fighting forces, access to health care, and educational institutions), as well as worsening environmental implications. Air pollution in some cities in China, for example, has gotten so bad that the government regularly issues Red Alters, which temporarily shuts down schools and factories, and bans cars from the road until the severity of the smog has abated[27].

[27] You, Tracy. "Over 100 MILLION Chinese Residents Are Warned to Stay Indoors as More Cities Issue Red Alerts for Hazardous Air Pollution." Mail Online. December 24, 2015. Accessed December 25, 2015. http://www.dailymail.co.uk/news/peoplesdaily/article-3373049/Even-dog-needs-mask-100-MILLION-Chinese-residents-warned-stay-indoors-cities-issue-red-alerts-hazardous-air-pollution.html.

Figure 3.1: Heavy Smog in China - ChinaFoloPress via Getty Images

Outdoor air pollution is a major environmental health problem affecting a broad population in developed and developing countries alike. The World Health Organization estimates that some 80% of outdoor air pollution-related premature deaths were due to ischemic heart disease and strokes (Ischemia is the restriction in blood supply due to a shortage of oxygen caused by damaged blood vessels, a common effect of regular exposure to high levels of air pollution), while 14% of deaths resulted from chronic obstructive pulmonary disease or acute lower respiratory infections, and 6% of deaths were due to lung cancer[28]. Other health effects are as follows:

[28]"Ambient (outdoor) Air Quality and Health." WHO Media Centre. March 1, 2014. Accessed December 25, 2015. http://www.who.int/mediacentre/factsheets/fs313/en/.

Table 1. Health Impacts of Industrial Fossil Fuel Pollution		
Pollutant	**Health Effects**	**Environmental Effects**
Acid Gases (Hydrogen chloride & Hydrogen fluoride)	Eye, skin, nose, and throat irritation; respiratory problems.	Contribute acid rain; damage to crops and forests.
Benzene & Other Aromatics	Known carcinogens; irritation to eyes, skin, and respiratory tract; central nervous system effects (e.g., drowsiness, dizziness, headaches, depression, nausea, irregular heartbeat); reproductive (spontaneous abortion), developmental, and immune effects.	Contribute to ozone-smog formation.
Dioxins	Known/probable carcinogens (soft-tissue sarcomas, lymphomas, stomach carcinomas); developmental and immune effects; reproductive problems; interference with hormones.	Deposit in ecosystems; taken up by fish and wildlife; accumulated in the food chain.
Formaldehyde & Other Aldehydes	Known carcinogen (lung and nasopharyngeal cancer); eye, skin, nose and throat irritation; respiratory symptoms.	Contribute to ozone-smog formation.
Heavy Metals (Arsenic, beryllium, cadmium, chromium, manganese, nickel)	Carcinogens (lung, bladder, kidney, skin); affects the nervous, cardiovascular, dermal, gastro-intestinal, immune, respiratory and reproductive systems.	Accumulate in soil and sediment; can contaminate water.
Lead	Anemia; high blood pressure; brain and kidney damage; neurological disorders; cancer; lowered IQ; behavioral problems; immune effects; reproductive hazards (lower sperm count, spontaneous abortion).	Affects animals, plants, and aquatic ecosystems.
Mercury	Damage to brain, nervous system, kidneys and liver; causes neurological and developmental birth defects (including lower IQ), behavioral problems such as attention deficit hyperactivity disorder, and cardiovascular effects (heart attacks, increased blood pressure and thickening of arteries).	Carried around the globe; taken up by fish and wildlife; accumulates in sediment and the food chain.
Nitrogen Oxides (NO_x)	Increased susceptibility to respiratory infections; irritation of the lung and respiratory symptoms (e.g., cough, chest pain, difficulty breathing).	Contributes to the formation of smog, acid rain, water quality deterioration, global warming, and visibility impairment.
Ozone (O_3) (Secondary Formation Of)	Eye and throat irritation; coughing; respiratory tract problems; asthma; bronchitis; lung damage; premature death.	Damage to crops, vegetation, and ecosystems.
Particulate Matter (PM)	Asthma; bronchitis; lung damage; cancer; heavy metal poisoning; cardiovascular effects including heart attack and premature death.	Visibility impairment; atmospheric deposition; aesthetic damage.
Polycyclic Aromatic Hydrocarbons (PAH)	Known and probable carcinogens (lung); developmental toxicants; birth defects; associated with lower IQs; affects the immune system and skin.	Can accumulate in soil and sediment and potentially contaminate water.
Sulfur Dioxide (SO_2)	Eye irritation; wheezing; chest tightness, shortness of breath; lung damage.	Contributes to the formation of acid rain; visibility impairment; plant and water damage; aesthetic damage.

Sources:
1. Agency of Toxic Substances and Disease Registry. ToxFAQs, http://www.atsdr.cdc.gov/toxfaqs/index.asp (accessed June 2011).
2. Environmental Health & Engineering Inc., 2011.
3. U.S. Environmental Protection Agency. Health Effects Summary, http://www.epa.gov/apti/course422/ap7a.html (accessed June 2011).

Figure 3.2: Health Impacts of Industrial Fossil Fuel Pollution- © Natural Resources Defense Council July 2011

3.2 The Physical Properties of Air Pollution

Air pollution is a very general term used to describe the various gases, particles and contaminants that reside in unnatural quantities in our atmosphere.

3.2.1. Criteria Air Contaminants:

These pollutants are designated by the EPA as "criteria" air pollutants because they are regulated in response to human health-based and/or environmentally-based criteria for setting permissible levels. Criteria Air Contaminants are the main pollutants found in smog, and are composed of Sulfur Oxides (SOx), Nitrogen Oxides (NOx), Particulate Matter (PM), Volatile Organic Compounds (VOC), Carbon Monoxide (CO), Ammonia (NH3) and Ground-level Ozone (O3 – Ozone is a secondary pollutant, created when VOCs and NOx combine in the lower atmosphere).

3.3 Pollution Remediation

With the concentration of airborne pollutants continuing to rise despite global efforts to curb emissions, it is clear that drastic technological changes must be made in order to avoid disastrous and irreversible consequences.

Companies around the world are developing new sustainable technologies that can actively filter out the toxic and warming chemicals found in the atmosphere. Most of these solutions are still in the prototypical phase, but a select few are reaching a point in development of becoming economically viable in the next couple years. Their design and functionality not only present new avenues for engineering, but also offer intriguing new architectural possibilities.

4. Investigating Emerging Sustainable Technologies

4.1 Overview

The new remediation technologies being developed will play an important role in the fight against urban air pollution and climate change. This thesis has identified four emerging technologies that seem to be the leaders in terms of feasibility and effectiveness in air pollution remediation; Titanium Dioxide coatings, Biofiltration, Direct Carbon Capture, and Algae Photobioreactors. Each of these systems are unique in their approach to air filtration, and as a result they all have distinct benefits and draw-backs to their designs.

The main purpose of this Masters' Thesis is to create a holistically sustainable architectural design by combining the results from the familiarity study described in chapter 2 with one of these remediation technologies. In theory any or all of these systems could be incorporated into an architectural design project, but for our purposes it is far more prudent to use the system that will accomplish the following:

a) The chosen system will prove to be versatile, meaning that it is capable of being physically manipulated to allow for a stimulating architectural re-design.

b) The system will be economically viable, meaning that its' cost of construction and operations won't deter developers from investing in the technology.

c) The chosen system will prove itself to be superior to the other remediation technologies in terms of its ability to filter pollutants from the atmosphere.

d) The system used will best reflect the visual and experiential qualities most conducive to a restorative ecological setting according to the familiarity study.

The following chapter will weigh each of the four systems abilities to meet the above criteria, and will select the system that best suits the next stage of the master's thesis. In order to clearly discern the best technology, each system evaluation criteria (versatility, economic viability, system performance and experiential qualities) will be ranked on a scale of 1 to 7, with 1 being the least desirable and 7 being very desirable. Once all of the criteria has been evaluated for each system, the total scores will be summed and the system with the highest score will be selected for the final design project.

4.2 Titanium Dioxide

Titanium dioxide (TiO2) is a photocatalytic substance that when stimulated by sunlight, converts air pollutants such as nitrogen oxides (NOx), volatile organic compounds (VOCs), carbon monoxide (CO), and ozone to more environmentally acceptable products such as

calcium nitrate and carbon dioxide. TiO2 can either be mixed into concrete or asphalt as an aggregate, or be applied to most building surfaces as a paint or clear coat[29].

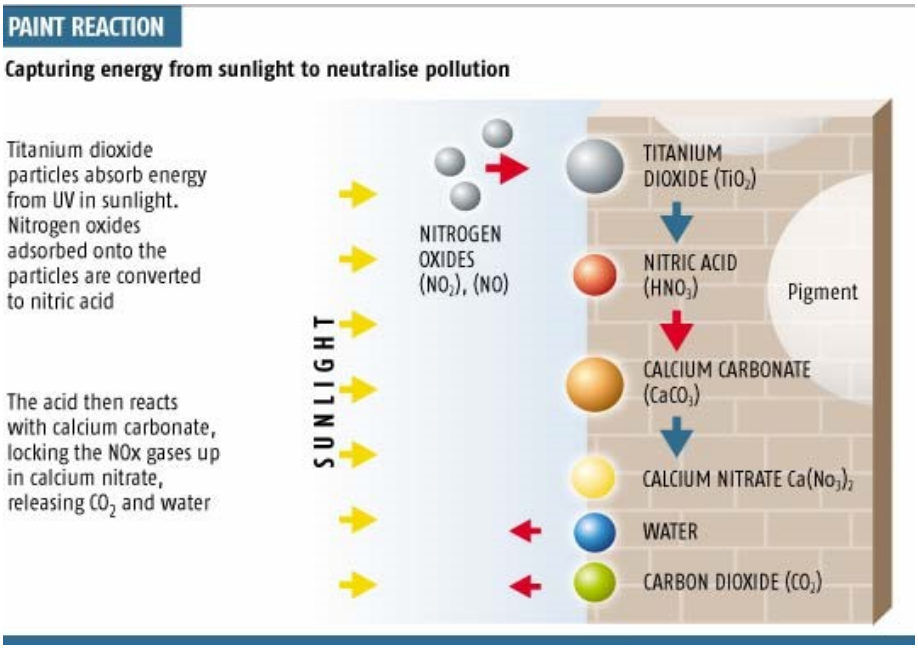


Figure 3.4: Outline of the pollutant-removal chemical reactions for a TiO2 coating. (Courtesy of Hogan, New Scientist, February 4, 2004, http://www.newscientist.com/article.ns?id=dn4636.)

The innovative technique has recently been applied at the Manuel Gea González Hospital in Mexico City, one of the most polluted cities in the world. The hospital facade was constructed using a new system of interconnected thermoformed plastic shells (heated plastic molded into specific shapes) coated in TiO2. The designers used Rhino to fabricate five different modules, each shaped to maximize surface area, light reception, and wind resistance, increasing the effectiveness of the Titanium Dioxide treatment[30]. The system developed by Elegant Embellishments noticeably cleans the surrounding atmosphere, giving the hospital visitors a much needed breath of fresh air.

[29]P. Berdahl, and H. Akbari. 2008. Evaluation of Titanium Dioxide as a Photocatalyst for Removing Air Pollutants. California Energy Commission, PIER Energy-Related Environmental Research Program. CEC-500-2007-112.

[30]Shaw, Matt. "Smog-Eating Façades and the Future of Air Quality." Architizer. March 13, 2014. Accessed December 29, 2015. http://architizer.com/blog/smog-eating-facades-and-the-future-of-our-air-quality/.

Figure 3.5 & 3.6: The Manuel Gea González Hospital in Mexico City Titanium Dioxide coated facade.[32]

4.2.1 Versatility of Titanium Dioxide Coatings

Due to the fact that titanium dioxide can either be applied to a surface as a paint, or mixed into concrete as an additive, the number of architectural possibilities for this product are vast. The only restrictions are that the titanium dioxide needs to have direct access to sunlight in order for the binding reactions to take place, and the design must also maximize the exposed surface area so as to clean as much air as possible.

Versatility Score: 6

4.2.2 Titanium Dioxide Costs

In terms of the product costs alone, titanium dioxide is very economical. According to existing literature, the average market price of this technology is roughly $20/kg, which translates to a cost of $2.20 per m^2 of surface application[33]. A conservative estimate for additional labor costs would be $8.33 per m^2 of surface ($50 per hour/6 m^2 coverage per hour). If the titanium dioxide is to be used as an additive to concrete or asphalt mix, then the overall cost of the mix is increased by roughly 4% per m^2 of installed concrete[31]. In terms of energy consumption, there is effectively a negative consumption rate as the reflective properties of a titanium dioxide coating help to reduce a building's level of solar heat gain. The measured reduction in electricity use for summertime cooling due to the reflected sunlight from a titanium dioxide coating has been documented as a net annual energy savings of 10%–20%[35].

Economic Score: 5

4.2.3 Titanium Dioxide Air Remediation Performance

[31]Marwa M. Hassan, Heather Dylla, Louay N. Mohammad, and Tyson Rupnow ISSN 1997 "Methods for the Application of Titanium Dioxide Coatings to Concrete Pavement" Int. J. Pavement Res. Technol.5(1):12-20 Copyright @ Chinese Society of Pavement Engineering

Studies by the California Energy Commission testing the effectiveness of Titanium Dioxide's ability to remove pollutants from the local environment determined that if on average 1 m^2 of catalytic film can clean 100 m^3 of air per day, it has an activity of 100 m/day. Laboratory data shows that a high-quality TiO2 catalyst has an activity of about 200 m/day for NOx (ie 1m^2 of TiO2 cleans 200 m^3 of air per day, or 2.3 kilograms per m^2 per year[32]), and about 60 m/day for typical VOCs[33].

Unfortunately, titanium dioxide does not filter CO2, so it's impact on climate change is negligible, however it is fairly effective for filtering smog and air pollutants in dense urban environments when it is applied over a large surface area.

System Performance Score: 4

4.2.4 Titanium Dioxide Experiential Qualities

While titanium dioxide is architecturally quite versatile, it offers almost no tangible experiential qualities to the architecture on which it is applied. This is because it is either applied to a surface as a clear-coat or paint, or it is mixed in with concrete or asphalt. In either case, an occupant would not have any indication that the titanium dioxide is present, and so this system will not be ideal for integration with the results of the familiarity study in a design.

System Experiential Score: 0

4.2.5 Compatibility Score

Titanium Dioxide Scores:
Versatility - 6
Economic Viability - 5
Remediation Performance - 4
Experiential Qualities – 0
Total = 15

To conclude, titanium dioxide has intriguing architectural implications, and also offers a viable and economically feasible solution to highly localized urban smog. Unfortunately, titanium dioxide would require very widespread application throughout a city in order to achieve a greater level of remediation[35], and it cannot process CO_2, making it an unviable solution to

[32] Burton, Adrian. "Titanium Dioxide Photocleans Polluted Air." Environmental Health Perspectives. June 1, 2012. Accessed December 29, 2015. http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3385448/#r6.

[33] Berdahl, P., and H. Akbari. 2008. Evaluation of Titanium Dioxide as a Photocatalyst for Removing Air Pollutants. California Energy Commission, PIER Energy-Related Environmental Research Program. CEC-500-2007-112

climate change. Finally, it also lacks any distinguishing experiential qualities, meaning it is not suitable for integration with the results from the familiarity study into a final design project.

4.3 Direct Air Carbon Capture

Direct air capture refers to technologies that can capture and sequester industrial-scale quantities of CO2 and other pollutants from the atmosphere.

Carbon Engineering was founded in 2009 by Harvard professor David Keith, based in Calgary, Alberta and is backed with over $3.5 million in private investments from high profile names such as Bill Gates and Murray Edwards. They are currently developing a DACC system and have been conducting tests on their project since 2014[34].

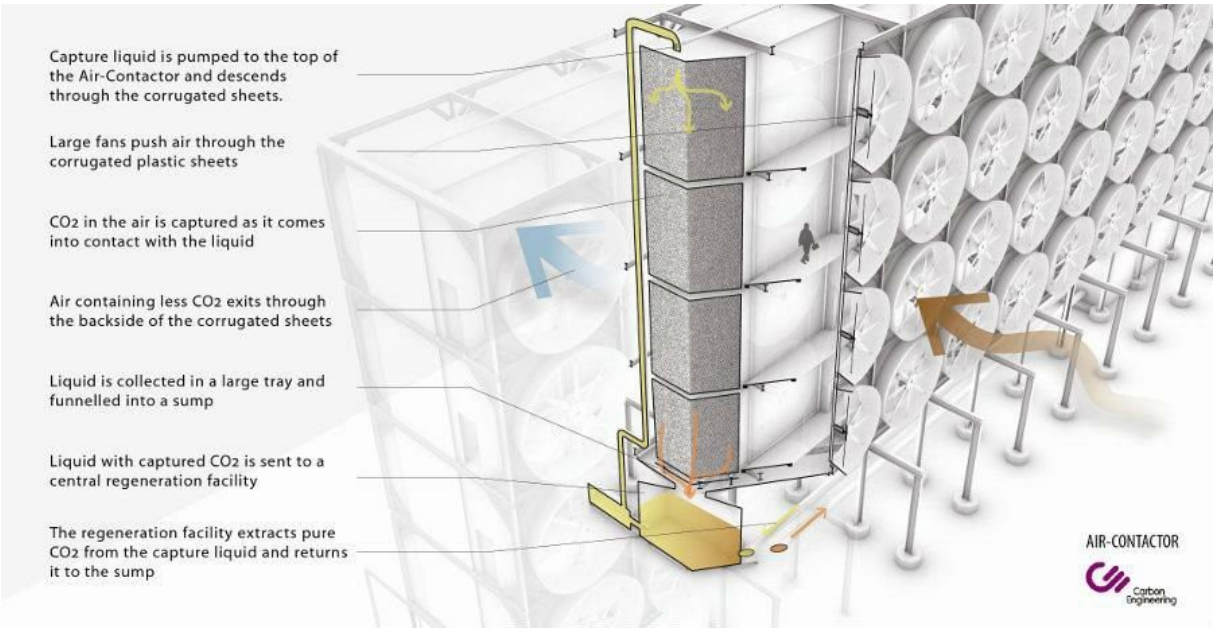


Figure 3.7: CE's Air Contactor Diagram - http://carbonengineering.com/our-technology/

CE's design draws local atmosphere into an air contactor with a fan, which blows the air horizontally through a chamber filled with structured packing material coated with a strong hydroxide solution. This solution is pumped to the top of the system and is trickled down the structured packing. The solution forms a film on the packing that captures CO2 from the air passing through the packing channels. This solution, now containing the captured CO2, is then sent to a regeneration cycle that simultaneously extracts the CO2 while regenerating the original chemical solution for re-use in the contactor. The extracted CO2 is compressed into pellets and can be reused as fuel. These two processes work together to enable continuous

[34]Eisenberg, Anne. "Pulling Carbon Dioxide Out of Thin Air." The New York Times. January 5, 2013. Accessed 2016. http://www.nytimes.com/2013/01/06/business/pilot-plant-in-the-works-for-carbon-dioxide-cleansing.html?_r=2&.

capture of CO2 from atmospheric air, with energy (and small amounts of make-up chemicals) as an input, and pure CO2 as an output. The stream of pure CO2 can be permanently sequestered deep underground, or sold and used in industrial applications.

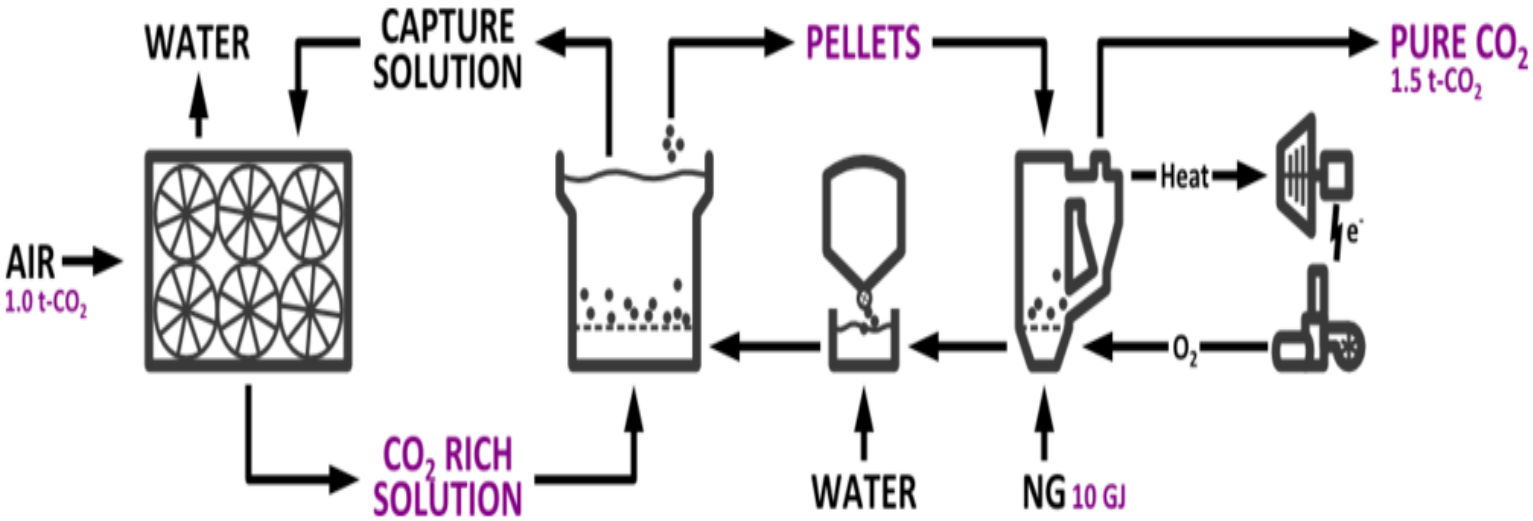


Figure 3.8: Carbon Engineering's air capture process.[37]

4.3.1 Versatility of Direct Carbon Capture

The design of Carbon Engineering's direct air capture machine cannot be altered without compromising it's functioning, and so at this stage in the projects' development there is little room for architectural re-imagining. Some creative possibilities exist for the air intake and exhaust valves, but apart from that the system cannot really be altered. Carbon Engineering is still in the prototype phase, which means that they are experimenting and testing for the design that generates the best performance possible. Perhaps once they have reached their desired efficiency levels then the system may be more open to architectural interpretation, but until then designers are limited in terms of artistic expression.

Versatility Score: 2

4.3.2 Direct Air Carbon Capture Costs

Current cost projections for the construction and operations of a planned $200 million plant (which CE is preparing to build in the coming future) estimate a capital cost of operations to be $180/ton of CO2, plus another $80/ton of CO2 for fixed costs. This brings the total cost of carbon capture to $260/ton of CO2 captured[35]. This is primarily due to the high energy demands exhibited by the system. According to a report released by Carbon Engineering, the calculated work for liquid pumping, once converted to a per-ton-CO2 captured basis, is <11

[35]Lassiter, Joseph B., III, and Sid Misra. "Carbon Engineering." Harvard Business School Case 814-040, October 2013. (Revised November 2014.)

kWh/tonCO2. Fan energy requirements also present a significant portion of the air contactor energy demands, running approximately <100 kWh/ton-CO2[36]. Carbon Engineering believes that they can reduce these costs through optimization of their current designs and the integration of renewable power sources, along with the resale of captured carbon. They anticipate that this would bring the cost down to $60/Ton of Carbon captured[37].

The American Physical Society (APS) and Professor Kurt Zenz House at the Massachusetts Institute of Technology (MIT) examined the potential of DACC and estimated the overall cost of sequestration to be $600–1000 per tonne CO2[38,39]. CE's $260/ton of CO2 is significantly cheaper; however the cost is still too high for this technology to be economically viable (i.e. to remove 1 gigaton of carbon would be $260 billion – the world produces 32.3 gigatons per year from energy production alone[40]). If Carbon Engineering are able to reduce the energy loads of their system, establish a market for their captured carbon pellets, and attain an overall cost of $60/ton of CO2 or less, then this technology could become very successful. Unfortunately, it is currently too costly to be considered for an architectural project.

Economic Score: 1

4.3.3 Direct Carbon Capture Air Remediation Performance

Carbon Engineering's system currently achieves a CO2 capture rate of 80% and is able to capture an average of 1.3 tons of carbon per day per air contactor unit[39]. This seems like an impressive figure until energy demands and costs are factored in, which seriously impact the feasibility of the project. In addition to this, there is currently no data or information indicating CE's DACC system's ability to capture other airborne contaminants either, such as NOx, Sox or VOCs.

System Performance Score: 7

4.3.4 Direct Air Carbon Capture Experiential Qualities

Carbon Engineering's direct air carbon capture machine is very similar in quality and design to a typical industrial HVAC unit. Unfortunately this means that the system is also very limited in

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[36] Geoffrey Holmes, Kevin Nold, Tylor Walsh , Kenton Heidel, Matthew A. Henderson, Jane Ritchie, Paul Klavins, Arvinder Singh, and David W. Keith (2013) "Outdoor prototype results for direct atmospheric capture of carbon dioxide" Carbon Engineering, Calgary AB, School of Engineering and Applied Sciences and Kennedy School of Government, Harvard University, Cambridge, MA, USA

[37] Geoffrey Holmes and David W. Keith (2012) "An air–liquid contactor for large-scale capture of CO2 from air " Carbon Engineering, Calgary AB, School of Engineering and Applied Sciences and Kennedy School of Government, Harvard University, Cambridge, MA, USA

[38] American Physical Society 2011 Direct air capture of CO2 with chemicals. New York, NY: American Physical Society

[39] House, K. Z., Baclig, A. C., Ranjan, M., van Nierop, E. A., Wilcox, J. & Herzog, H. J. 2011 Economic and energetic analysis of capturing CO2 from ambient air. Proc. Natl Acad. Sci. USA 108, 20 428–20 433. (doi:10.1073/pnas.1012253108)

[40] Mooney Chris Mooney, Chris. "The Magic Number: Holding Warming under Two Degrees Celsius Is the Goal. But Is It Still Attainable?" Washington Post. November 29, 2015. Accessed March 30, 2016. http://www.washingtonpost.com/sf/national/2015/11/29/carbon/.

terms of its ability to convey the kind of ecological experiential qualities yielded from the familiarity study. The system's bulkiness and the noise level of its operation makes it undesirable for any direct interaction with a building occupant, and so it doesn't meet our criteria for architectural integration.

System Experiential Score: 1

4.3.5 Compatibility Score

Direct Air Carbon Capture Scores:
Versatility - 2
Economic Viability - 1
Remediation Performance - 7
Experiential Qualities – 1
Total = 13

Carbon Engineering's technological system shows itself to be a promising future solution to climate change through its ability to directly extract CO2 from the atmosphere. However, its inability to filter out other air particles, its high cost, and its limited architectural potential means that it is not suited for our design project.

4.4 Closed System Biofiltration

Engineered Biofiltration systems have been used extensively for over 40 years in the U.S. and Europe for odor and VOC control in waste water treatment facilities, animal farming facilities, composting facilities, and other low concentration pollution producing operations. During the past few years, it has been used increasingly in the North America for treating high-volume, low-concentration air pollution streams. Studies are currently being conducted to investigating biofiltration's suitability for a wide variety of air emission control applications[41].

Biofilters use beds of organic material found on most farms, such as peat, wood chips and compost coupled with sand, gravel, geotextiles, and shredded plastic or glass to filter out air pollutants. These materials are layered and form a biological film composed of microorganisms. Contaminated air is moistened by a humidifier and is pumped into the biofilter through a chamber below the filter medium. While the air slowly flows upward through the filter media, the contaminants in the air stream are absorbed and metabolized by

[41] F. Adler, Stephen. "Biofiltration — a Primer." Environmental Protection. Center for Waste Reduction Technologies, April 1, 2001. Accessed January 2, 2016. http://www.d.umn.edu/~rdavis/courses/che4601/notes/biofiltration.pdf.

the microorganisms, which then expel clean oxygen as a byproduct. The purified air passes out of the top of the biofilter and into the atmosphere[42].

Open biofiltration systems are effective at filtering low concentrations of pollutants (< 25 ppm), however they begin to experience problems as the concentration increases. Closed biofiltration systems however offer much higher efficiency rates, occupy less space and are very cost effective. These systems are composed of large vertical containers which house the media beds. The multi-layered system prevents the compaction of the filter media and helps eliminate the risk of channeling by the contaminated air stream (channeling is when gaps form in the biofilm allowing contaminants to pass through unfiltered). In addition, the stacked media beds allow for easy maintenance when it comes time to change the filter media.

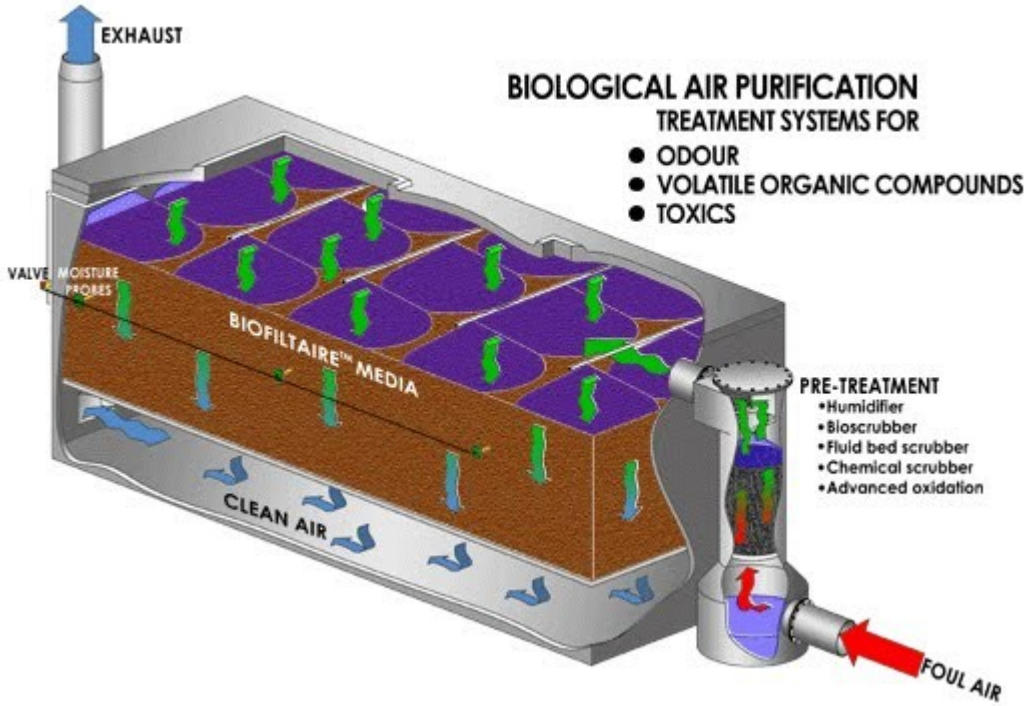

Figure 3.10: Example of a closed biofitration system[43]

In a closed biofiltration system, the contaminants present in the air diffuse perpendicular to the direction of flow, and biodegrade in the supported biofilms. Since the process of filtration is controlled through gradual diffusion, designing a large distance between the supported biofilms reduces the overall degradation rate in the filter. However, larger distances also mean that the biofilms in a biotrckling filter have to be kept moist to maintain bioactivity. Air flowing

[42]Schmidt, David, Larry Jacobson, and Richard Nicolai. "Biofilter Design Information." : Manure Management and Air Quality : University of Minnesota Extension. 2015. Accessed January 2, 2016. http://www.extension.umn.edu/agriculture/manure-management-and-air-quality/air-quality/biofilter-design-information/.

through the biotrickling filter draws moisture away from the biofilms, and so the air entering the system must be humidified so as to maintain a trickling flow of moisture and nutrients to the active bacteria in the biofilms.

4.4.1 Versatility of Closed Biofiltration Systems

Figure 4.3 (left): Ottawa Public Library Interior atrium biofilter design - by Samuel Herschorn

The bulk of a closed biofiltration system is composed of the tanks containing the filtration media, and the fan/humidification system feeding the media with polluted air. These two components also do not necessarily have to be designed near each other, which would allow an architect to play with the systems' design and orientation. For example, the media beds could be held within containers that can be made to resemble rocks, making them into a landscape feature. The tops of the media beds (from which the cleaned air would be exhausted) could be topped with soil and plants, creating a garden and further adding to the efficiency of the air filtration. The Biofiltration units can be designed to physically fit into any shape or size, making them fairly adaptable, and open to architectural re-interpretation.

Versatility Score: 4

4.4.2 Closed System Biofiltration Cost

Biofilters offer a fairly unique set of advantages over other air filtration technologies, the primary of which is cost. The costs involved include materials, fans, energy consumption, media, ductwork and plenum, and labor to construct. The typical cost for building a biofilter and tying it into a mechanical system is roughly $275 per 1000 cfm (cubic feet per minute) of designed flow rate[45]. This roughly equates to $16.60 per kilogram of processed air. Ultimately the cost of building and maintaining a biofilter will vary on the desired quantities of air to be

filtered (and as a result the size of the filtration system), but when compared to other air filtration technologies, biofilters are very economical[43].

Economic Score: 6

4.4.3 Bioflitration Air Remediation Performance

In addition to cost benefits, Biofiltration is versatile in its ability to treat odors, toxic compounds, and VOCs at efficiencies between 70-90%[43]. VOCs produced by vehicle emissions are typically filtered at a rate of 16 grams per cubic foot per hour, or 13.6 kilograms per m^3 per day. Toluene, Ethanol, Ammonia and other emissions are filtered at roughly 24,000 m^3 per day. Bioflitration is able to filter out NOx and SOx pollutants, however in a series of tests run by the California Environmental Protection Agency, it was found that the efficiency was only around 20%, extracting approximately 0.012g per m^3 per minute, or 6.3 kg/year/m^3. When researchers introduced a denitrifying fungal organism to the biofilter, there was a dramatic increase in NOx consumption to close to 90%. This resulted in an increase in the consumption of NOx to 8786 kg/m^3/year, or 24.1 kg/m^3/day[44].

Biofiltration demonstrates itself to be very effective in industrial settings and at filtering out VOCs. However, it is ineffective at controlling CO2, and requires special denitrifying fungal organisms in order to filter out NOx. Thus making biofiltration less qualified for air pollution and climate change remediation than other systems[45].

System Performance Score: 3

[43] Bohn, Jared. "AMBIO Biofiltration Ltd.—Comparison to Alternatives." Biofiltration Comparison to Alternatives. 1992. Accessed January 2, 2016. http://www.ambio.ca/comparison.php.

[44] Nate J. Hudepohl, Yulya Davidova, Chris A. Duplessis, Edward D. Schroeder, Daniel P.Y. Chang. (Feb 1999) “Biofliter Technology For NOx Control”. Department of Civil & Environmental Engineering, University of California. http://www.arb.ca.gov/research/apr/past/96-304.pdf

[45] J. Artuz, Robert, and Selvi B. Anit. "BIOFILTRATION OF AIR." Systems Project: Biofiltration. Accessed January 2, 2016. http://www.rpi.edu/dept/chem-eng/Biotech-Environ/MISC/biofilt/biofiltration.htm.

Table 1. Typical biofilter performance data.				
Application (Reference)	**Contaminant(s)**	**Loading**	**Removal**	**Biofilter Type**
Yeast Production Facility *(1)*	Ethanol, Aldehydes	35,000 cfm/500 yd^3 media, 1 g/m^3	Overall VOC reduction of 85%	Media filter
Plastics Plant VOC Emissions Control *(1)*	Toluene, Phenol, Acetone	1,000 m^3/h	80%–95%	Media filter
Pharmaceutical Production *(2)*	Organic carbon	1,000 m^3/h, 2,050 mg/m^3 (5,800 mg/m^3 peak)	>98% first stage, >99.9% overall	Media filter (two-stage)
Artificial Glass Production *(3)*	Monomer methyl methacrylate (MMA), Dichloromethane (DCM)	125–150 m^3/h, 50–250 mg/m^3	Biofilter: 100% MMA, 20% DCM; BTF: 95% DCM	Media filter plus biotrickling filter (BTF) in series
Hydrocarbon Emissions Control *(1)*	Hydrocarbon solvents	140,000 m^3/h, 500 mg/m^3	95%	Media filter
Compost Plant for Garbage *(4)*	Odor	16,000 m^3/h, 264 m^2 (1 m deep) 60 $m^3/m^2 \cdot h$, 230 mg C/m^3	>95%	Media filter
Gasoline VOCs Emissions Control (Pilot Scale) *(5)*	Total VOCs	16 $g/ft^3 \cdot h$	90%	Media filter
Hydrogen Sulfide Emissions Control (Laboratory Scale) *(6)*	H_2S	1.9–8.6 mg/kg•min (25–2,651 ppmv)	93%–100%	Media filter
Styrene Removal (Bench Scale) *(7)*	Styrene	Up to 22 $g/m^3 \cdot h$, 0.5 min retention time	>99%	Biotrickling filter
Styrene Removal (Bench Scale) *(7)*	Styrene	Up to 100 $g/m^3 \cdot h$	>95%	Media filter (peat)
Rendering Plant *(8)*	Odor	1,100 m^3/h (650 cfm), 420 m^2 (4,500 ft^2)	99.9%	Media filter
Fuel-Derived VOC Emissions Control *(9)*	Nonmethane organic carbon (simulated jet fuel)	500 ppm•cfm/ft^2, 500–1,500 ppm•cfm/ft^2	>95% 30%–70%	Media filter

Figure 3.11: Typical biofilter performance data[46]

4.4.5 Bioflitration Experiential Qualities

The experiential potential for biofiltration systems is intriguing. Because of the system's versatility as discussed in section 4.4.1, a designer is able to play with different tank mediums, either exposing the biofiltration media beds, or hiding them. Biofilters also offer great opportunities to incorporate ecology, enhance or diminish various odors, or create different layouts and spaces that can stimulate a building occupant. This makes biofiltration a viable

1. [46]F. Adler, Stephen. "Biofiltration — a Primer." Environmental Protection. Center for Waste Reduction Technologies, April 1, 2001. Accessed January 2, 2016. http://www.d.umn.edu/~rdavis/courses/che4601/notes/biofiltration.pdf.

candidate for architectural reinterpretation, and will be able to tie into the results of the familiarity with relative ease.

System Experiential Score: 6

4.4.6 Compatibility Score

Bioflitration Scores:
Versatility - 4
Economic Viability - 6
Remediation Performance - 3
Experiential Qualities – 6
Total = 19

4.5 Algae Photobioreactor Filtration Systems

Algae are simple photosynthetic organisms that range in size from the microscopic (microalgae), to large seaweeds (macroalgae) such as giant kelp[47]. Algae are oxygenic phototrophs, which means that they use light as their energy source for growth and produce oxygen as a byproduct, like plants. In fact, algae produce over 330 billion tons of oxygen each year[48], or roughly 50% of the earth's oxygen, in the process of photosynthesis, and are far more efficient than terrestrial plants at processing pollutants such as CO2, NO2, SO2[49]. Microalgae utilize atmospheric carbon dioxide and transform it into carbohydrates, proteins and lipids through photosynthesis to use as fuel. They also consume nitrogen (NOx), sulfur (SOx) and metals, such as: nickel (Ni), vanadium (V) and mercury (Hg) which constitute their nutrients. Algae is also very good at capturing VOCs and particulate matter, which adhere to the algae's surfaces and become fixed in what is known as biomass – excess algae that has coalesced into a large mass of living biological organisms. Biomass is currently used for the production of a multitude of products, such as biodiesel and bioethanol fuel (derived from microalgal oils and carbohydrates), high-protein animal feed, food additives, agricultural protein-rich fertilizer, biopolymers/bioplastics, medicines and cosmetics[50].

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[47] "Algae." UXL Encyclopedia of Science. 2002. Encyclopedia.com. (January 5, 2016). http://www.encyclopedia.com/doc/1G2-3438100032.html

[48] Hall, Jack. "The Most Important Organism? | Ecology Global Network." Ecology Global Network. September 12, 2011. Accessed March 30, 2016. http://www.ecology.com/2011/09/12/important-organism/.

[49] Packer, M. (2009). Algal capture of carbon dioxide; biomass generation as a tool for greenhouse gas mitigation with reference to New Zealand energy strategy and policy. Energy Policy, Vol. 37, 3428–3437

[50] Chisti, Y. (2007). Biodiesel from microalgae. Biotechnology Advances, Vol. 25, 294–306

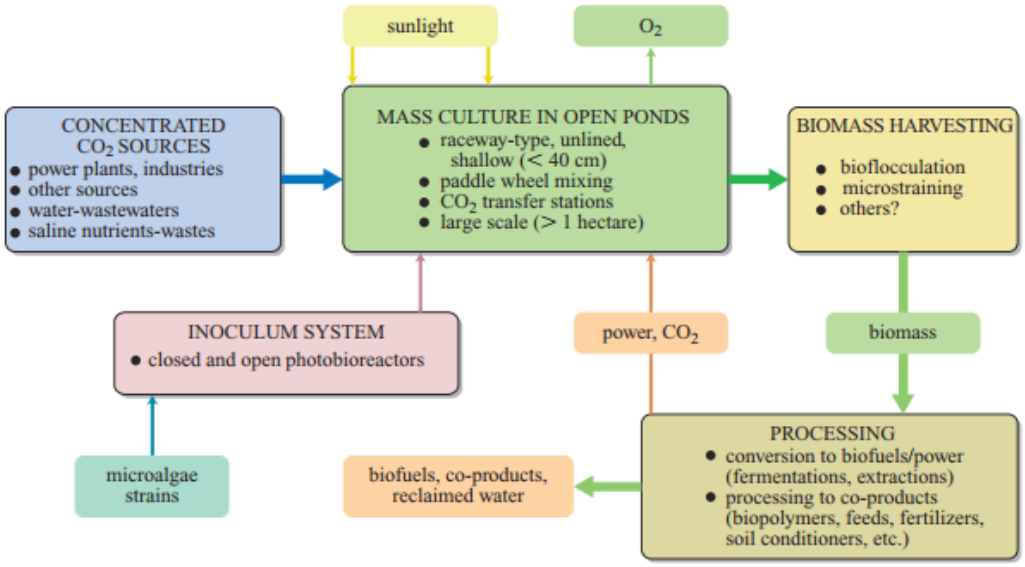

Figure 3.12: Process schematic for biofixation of CO2 and greenhouse gas abatement with microalgae.[51]

There are currently two types of cultivation systems of algae being used to filter airborne pollutants: open ponds and enclosed photobioreactors. Open ponds are large pools of water into which polluted air is fed, and microalgae is bred. These ponds usually have a large mixing propeller that gently circulates the water to keep it from stagnating. This circulation and continuous mixing is also very important for consistent nutrient dispersion, ensuring even thermal distribution, to keep algae cells in suspension, and to enhance light utilization efficiency[52]. A study of open pond algae filters by Caleb Stuart and Mir-Akbar Hessami from Monash University, Clayton, found that that a 4000 m3 pond under natural daily light exposure cycles could sequester up to 2.2 kilotons of CO2 per year[53].

[51]John R. Benemann, Paola Pedroni, "BIOFIXATION OF FOSSIL CO2 BY MICROALGAE FOR GREENHOUSE GAS ABATEMENT" International Network on Biofixation of CO2 and Greenhouse Gas Abatement with Microalgae

[52]Suh, I.S. & Lee, C-G. (2003). Photobioreactor engineering: Design and performance. Biotechnology and Bioprocess Engineering, Vol. 8, 313-321

[53]Stuart C. & Hessami M-A. (2005). A study of methods of carbon dioxide capture and sequestration–the sustainability of a photosynthetic bioreactor approach. Energy Conversion and Management, Vol. 46, 403–420

Figure 3.13: Algae production in open pond. http://www.climatetechwiki.org/technology/co2-mitigation-micro-algae

Closed Photobioreactor systems are structured in a similar way; polluted air is injected into the closed system and is circulated via water pumps. Algae cultures are first grown in a lab setting and are then transferred into the photobioreactor through the culture tank. The algae is distributed throughout the system via the culture liquid, which also acts as the algae's aquatic home (the culture liquid is usually just water). The culture fluid will dissolve the carbon dioxide, nitrogen oxide and sulfur oxide allowing the algae to absorb these elements during photosynthesis. An exhaust outlet must be integrated into the design so that the oxygen generated by the algae can be extracted and expelled back into the atmosphere. A cleaning tank must be factored in as well, so that excess biomass can be removed and packaged for sale/disposal. Finally, a light source, either artificial or natural, is necessary for culture growth and photosynthesis[54].

[54]Tsuruoka, Makoto, Yasumasa Kodo, and Keiun Kodo. "Patent US6083740 - System for Purifying a Polluted Air by Using Algae." July 4, 2000. Accessed January 5, 2016. http://www.google.ca/patents/US6083740.

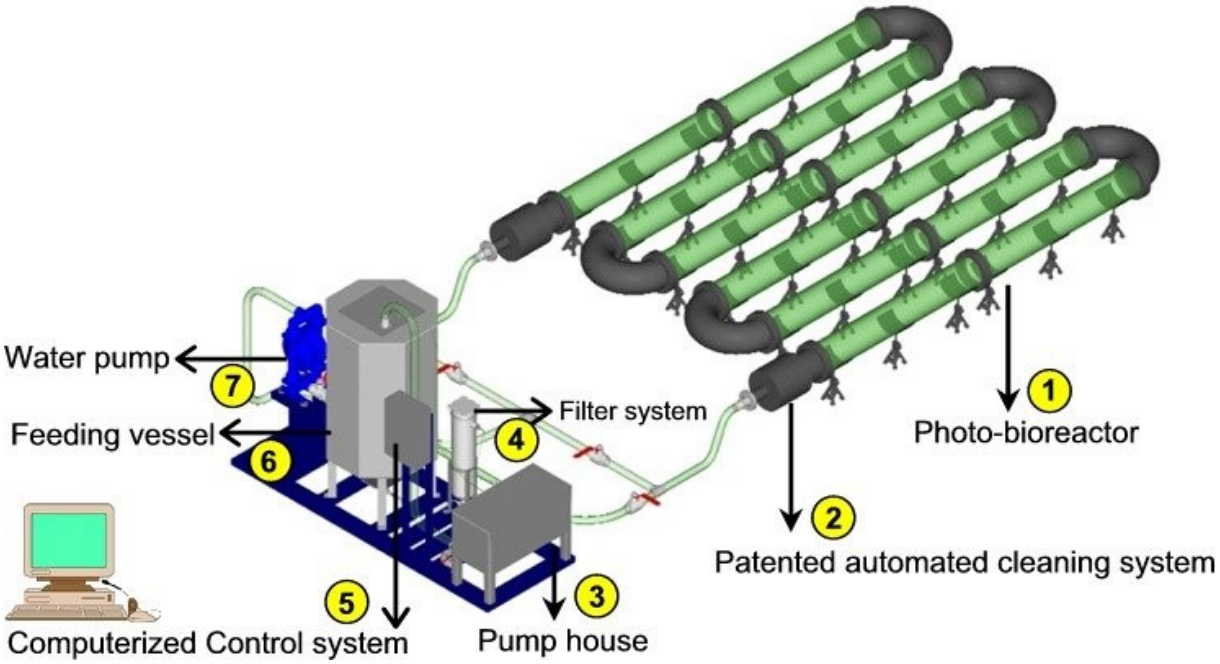

Figure 3.16: Algae Photobioreactor Research - MIT Department of Architecture

Figure 3.14: Horizontal tubular algae reactor – Algae Industry Magazine.com

Enclosed Photobioreactors are designed in a variety of configurations, the most common of which are either flat plate, thin-panel or tubular.

Table 3 Advantages and limitations of different photobioreactors (Brennan and Owende, 2010; Yen and others, 2014)		
Photobioreactors	**Advantages**	**Limitations**
Vertical column (tubular)	Compact, high mass transfer, good mixing with low shear stress, low energy consumption, high potentials for scalability, easy to sterilise, readily tempered, good for immobilisation of algae, reduced photo-inhibition and photo-oxidation	Small illumination surface area, construction requires sophisticated materials, stress to algal cultures, decrease of illumination surface area upon scale-up, expensive compared to open ponds
Flat panel	Large illumination surface area, suitable for outdoor cultures, good for immobilisation of algae, good light path, high biomass productivities, relatively cheap, easy to clean up, readily tempered, low oxygen build-up	Scale-up requires many compartments and support materials, difficulty in controlling culture temperature, some degree of wall growth, possibility of hydrodynamic stress to some algal strains
Horizontal tubular	Large illumination surface area, suitable for outdoor cultures, good biomass productivities, relatively cheap	Gradients of pH, dissolved oxygen and CO_2 along the tubes, fouling, some degree of wall growth, requires large land space

Figure 3.15: Closed photobioreactor confirgurations[55]

[55]Brennan L, Owende P (2010) Biofuels from microalgae - a review of technologies for production, processing, and extractions of biofuels and co-products. Renewable and Sustainable Energy Reviews; 14(2); 557-577 (Feb 2010)

4.5.1 Closed Vs Open Photobioreactor Comparison

Parameter or issue	Open ponds and raceways	Photobioreactors (PBR)
Required space	High	For PBR itself low
Water loss	Very high, may also cause salt precipitation	Low
CO_2-loss	High, depending on pond depth	Low
Oxygen concentration	Usually low enough because of continuous spontaneous outgassing	Build-up in closed system requires gas exchange devices (O_2 must be removed to prevent inhibition of photosynthesis and photo oxidative damage)
Temperature	Highly variable, some control possible by pond depth	Cooling often required (by spraying water on PBR or immersing tubes in cooling baths)
Shear	Usually low (gentle mixing)	Usually high (fast and turbulent flows required for good mixing, pumping through gas exchange devices)
Cleaning	No issue	Required (wall-growth and dirt reduce light intensity), but causes abrasion, limiting PBR life-time
Contamination risk	High (limiting the number of species that can be grown)	Low (Medium to Low)
Biomass quality	Variable	Reproducible
Biomass concentration	Low, between 0.1 and 0.5 g/l	High, generally between 0.5 and 8 g/l
Production flexibility	Only few species possible, difficult to switch	High, switching possible
Process control and reproducibility	Limited (flow speed, mixing, temperature only by pond depth)	Possible within certain tolerances
Weather dependence	High (light intensity, temperature, rainfall)	Medium (light intensity, cooling required)
Start-up	6 – 8 weeks	2 – 4 weeks

Capital costs	High ~ US$100 000 per hectare	Very high ~ US$250 000 to 1 000 000 per hectare (PBR plus supporting systems)
Operating costs	Low (paddle wheel, CO_2 addition)	Higher (CO_2 addition, oxygen removal, cooling, cleaning, maintenance)
Harvesting cost	High, species dependent	Lower due to high biomass concentration and better control over species and conditions
Current commercial applications	5 000 (8 to 10 000) t of algal biomass per year	Limited to processes for high added value compounds or algae used in food and cosmetics

Figure 3.16: Open vs Closed photobioreactor comparison - (Pulz, 2001 adapted in Carlson 2007)[56]

4.5.2 Photobioreactor Case Studies

Numerous studies and projects have been completed on closed system photobioreactors and their abilities to capture carbon dioxide and other pollutants, each one yielding differing results:

HY-TEK Bio is a Maryland based company partnered with University of Maryland's Center for Environmental Sciences. It started a full-scale photobioreactor at Baltimore's Back River Waste Water Treatment Plant in late 2011 and has been capturing flue gas output and mitigating the greenhouse gas emissions from a 3MW methane-fired power plant. The project used three 4' by 20' tanks (holding 6814 Liters) of an algae strain called HTB-1, and was subjected to over 12,000 hours of third party testing. They calculated that one bioreactor was able to attain 85% mitigation of CO2 and nearly 100% mitigation of NOx in just 9 feet of algal culture. They also determined that one bioreactor produced 50 to 75 pounds of algae and 17,000 cubic feet of oxygen per day, and was able to sequester 20 kg of CO2 per day – over 7000 tonnes per year[57].

Other projects boast similarly impressive results. A prototype urban canopy/photobioreactor system constructed by the architectural and urban design firm ecoLogicStudio claims to be

56 Iersel, Sjors Van. "Algae Culture Systems." The Global CCS Institute. October 2008. Accessed April 02, 2016. https://hub.globalccsinstitute.com/publications/algae-based-biofuels-review-challenges-and-opportunities-developing-countries/21-algae-culture-systems.

57 Rosenberger, Paul. "A Game Changing Mitigation Technology." HY-TEK Bio LLC. August 29, 2014. Accessed January 5, 2016. http://www.hytekbio.com/ghg-mitigation.html.

able to produce the oxygen equivalent of four hectares of woodland and up to 150kg of biomass per day[58].

Figure 3.17: Urban Algae Canopy - ecoLogic Studio – Photo courtesy of James Bartolacci

French biochemist Pierre Calleja designed an algae-powered lamp that claims to be able to process CO2 200 times more efficiently than a regular tree[59], with total CO_2 absorption at roughly 9.6 Tons per year.

Algae Tec, an Australian algae producer, designed a high yield enclosed algae growth and harvesting system to consume CO_2 from coal-fired power plants. This system is envisioned to be installed at several venues in Australia and around the world. To date the 4 x 660 MW power plant, called the McConchie-Stroud system, emits about 19 million tons of carbon dioxide annually. Algae Tec plans to use its system to remove 270,000 tCO2 a year from the power station, rising to 1.3 Mt once fully operational[60].

RWE is one of Europe's five leading electricity and gas companies, and its microalgae binding CO_2 system at Niederaussem power station is located in a greenhouse to optimize growing conditions. It was erected with an area of 600 m^2, but can be extended to 1000 m^2.

[58]Bartolacci, James. "Algae Architecture: Bask Beneath This Air-Cleaning Canopy." Architizer. April 17, 2014. Accessed January 5, 2016. http://architizer.com/blog/urban-algae-canopy/.

[59]C. Nguyen, Tuan. "Can an Algae-Powered Lamp Quench Our Thirst For Energy?" Smithsonian. October 22, 2013. Accessed January 5, 2016. http://www.smithsonianmag.com/innovation/can-an-algae-powered-lamp-quench-our-thirst-for-energy-3509307/?no-ist.

[60]Algae Tec (2013) "Algae Tec signs carbon capture biofuels deal with Australia's largest coal-fired power company". Available at: algaetec.com.au/2013/07/algae-tec-signs-carbon-capture-biofuelsdeal-with-australias-largest-coal-fired-power-station, 1 pp (2 July 2013)

Operation started in 2008, and the system can produce up to 6,000 kg dry algae per year, fixing 12 Tons of CO2 [61].

4.5.3 Versatility of Algae Photobioreactors

Algae photobioreactors tend to be delicate systems; they require a great deal of direct sunlight or artificial lighting, they need careful monitoring systems to control pH levels and climate controls to keep a consistent temperature. It would seem at first glance that this type of system is too rigid for any form of architectural re-interpretation, however that is not the case. Open Algae ponds can potentially be designed as water features, and closed algae systems can be oriented to form interesting facades or shading panels. The vibrant green color of the algae presents intriguing design potentials for facades or interior spaces, and the ability of the system to take on different orientations and forms could spark more sculptural architectural elements.

Versatility Score: 5

Figure 4.5: concept image for algae facade – ecoLogic Studio

4.5.4 Closed System Algae Photobioreactor Cost

The glazing materials for commercial closed photobioreactor systems are often only a small part of overall capital costs, with the greater costs resulting from the mixing devices, gas exchangers, nutrient supply, harvesting, control systems, and temperature control. Estimates

[61] RWE Power (2009) RWE's algae project in Bergheim-Niederaussem. Available at: www.rwe.com/web/cms/mediablob/en/247480/data/235578/1/rwe-powerag/lignite/blob.pdf, 9 pp (2009)

place the construction costs at roughly $100/m^2, or about $6.94 per Liter [62]. The costs of operation, transport and maintenance were shown to be an approximate average cost of $16.75 /T of CO2[63,64]. This is very economical in terms of filtration cost; however the cost of construction can be significant. For example, HY-TEK Bio's 6814 Liter photobioreactor tank would cost roughly $47,289.16 to build. Furthermore, the cost of producing a full facade of photobioreactor tubes and algae cultures would be much greater due to the necessary engineering, scope and added materials. A large portion of these costs could be offset through the resale of valuable biomass, either for bio-fuel production or animal feed, etc.

Economic Score: 4

4.5.5 Algae Photobioreactor Air Remediation Performance

After conducting a widespread analysis of existing literature, it is apparent that the CO_2 fixation rates vary extensively depending on the type of algae culture used, the system chemistry, design, and temperature. A study conducted by John Burgess and others (2011) concluded that the potential CO_2 capture rate is estimated at estimated at around 120 g/m^2/d, or 1.3 Tons/m^3/day [65]. This figure when scaled, supports the sequestration rates claimed by companies such as HY-TEK Bio, ecoLogicStudio, and RWE. Another report from the testing firm CK Environmental showed photobioreactors were able to reduced nitrogen oxides by 85.9% (+/-2.1%) and reduced CO_2 by 82.3% (+/-12.5%)[66]. Algae has proven to be adept at capturing other forms of VOCs and particulate matter as well, however efficiencies and quantities are not explicitly stated in existing research as the focus remains primarily on CO_2 and NOx/SOx filtration.

This data indicates that Algae photobioreactors are extremely effective at filtering large amounts of air pollutants, and will also have a significant influence on reducing CO_2 levels.

System Performance Score: 7

4.5.6 Algae Photobioreactor Experiential Qualities

Much like a bioreactor, the algae system's versatility and dynamic nature offers the potential for a stimulating architectural experience. The need to keep the culture liquid flowing gives the system a sense of movement that none of the other systems can provide. The algae's color along with the systems' ability to be structured in varying positions means that a designer can

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[62] Tredici M.R. (1999) Bioreactors, photo, in: Flickinger M.C., Drew S.W. (edited by) Encyclopedia of bioprocess technology: fermentation, biocatalysis, bioseparation, 395- 419, New York, John Wiley, 5v.; v.I, 395-419.

[63] D. J. Bayless, M. E. Prudich, M. L. Vis-Chiasson, K. Cooksey, J. Muhs. (Dec 23, 2003) "Enhanced Practical Photosynthetic CO2 Mitigation". Ohio Coal Research Center Department of Mechanical Engineering Ohio University, Department of Microbiology, LW-113B Montana State University. http://www.netl.doe.gov/publications/proceedings/01/carbon_seq/5a4.pdf

[64] Sean T. McCoy, Edward S. Rubin. "Models of CO2 Transport and Storage Costs and Their Importance in CCS Cost Estimate". Carnegie Mellon University. May 5th 2005. http://www.cmu.edu/epp/iecm/rubin/PDF%20files/2005/2005e%20McCoy%20&%20Rubin,%204th%20Conf%20on%20CCS%20(May).pdf

[65] Burgess J, Jeffery L, Lowe A, Schuck S, Flentje W (2011) Novel CO2 capture task force report. Available at: www.anlecrd.com.au/projects/novel-co-sub-2-sub-capture-storage-task-force, 174 pp (Dec 2011)

[66] Parkavi Kumar, (July 2015)"Capture of CO2 Emissions Using Algae". Oilgae. http://www.oilgae.com/ref/downloads/Analysis_of_CO2_Capture_Using_Algae.pdf

create fascinating spaces that could mimic ecological settings. This makes the algae filtration system a great option to pair with the results of the familiarity study.

System Experiential Score: 6

4.5.7 Final Tally

Algae Photobioreactor Scores:

Versatility - 5

Economic Viability - 4

Remediation Performance - 7

Experiential Qualities – 6

Total = 22

4.6 Conclusion

After conducting a careful and thorough evaluation of each emerging sustainable system, it is clear that the Algae Photobioreactor filtration system is the best option for architectural redesign and integration with the results of the familiarity study.

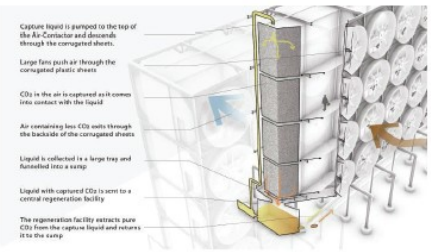
DIRECT AIR CARBON CAPTURE

ENERGY CONSUMPTION: 111kWh/Ton CO^2

COST: $260/Ton CO^2

AVE. CO^2 REMOVAL EFFICIENCY: 80%

CARBON CAPTURED: 1.3 Tons OF CO^2/M^3/DAY



TITANIUM DIOXIDE COATINGS

ENERGY CONSUMPTION: 0.001kWh/Ton CO^2

COST: $1.15/Ton CO^2/M^2

AVE. CO^2 REMOVAL EFFICIENCY: .0001%

CARBON CAPTURED: 0.012 Tons OF CO^2/M^3/DAY

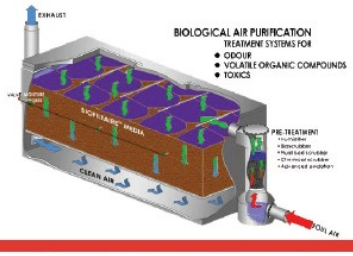
CLOSED SYSTEM BIOFILTRATION

ENERGY CONSUMPTION: 2.5kWh/Ton CO^2

COST: $90/Ton CO^2

AVE. CO^2 REMOVAL EFFICIENCY: 0.7%

CARBON CAPTURED: 0.5 Tons OF CO^2/M^3/DAY



ALGAE PHOTOBIOREACTOR SYSTEM

ENERGY CONSUMPTION: 9.2kWh/Ton CO^2

COST: $16.75/Ton CO^2

AVE. CO^2 REMOVAL EFFICIENCY: 85%

CARBON CAPTURED: 1.4 Tons OF CO^2/M^3/DAY

5. Architectural Design Project

5.1 Site Selection

Canada is a country blessed with vast resources and open spaces, and so doesn't suffer the same effects from air pollution as China, India or even the United States. That being said, Canada is not without its problems. Over 80% of our population lives in urban areas, and our dependence on automobiles as well as coal and gas powered electrical plants means that pollution is still a very real problem. Despite our generally clean air, Canada ranks among the top 10 worst producers of greenhouse emissions in the world, and ranks #1 in per capita emissions (according to 2011 statistics)[67].

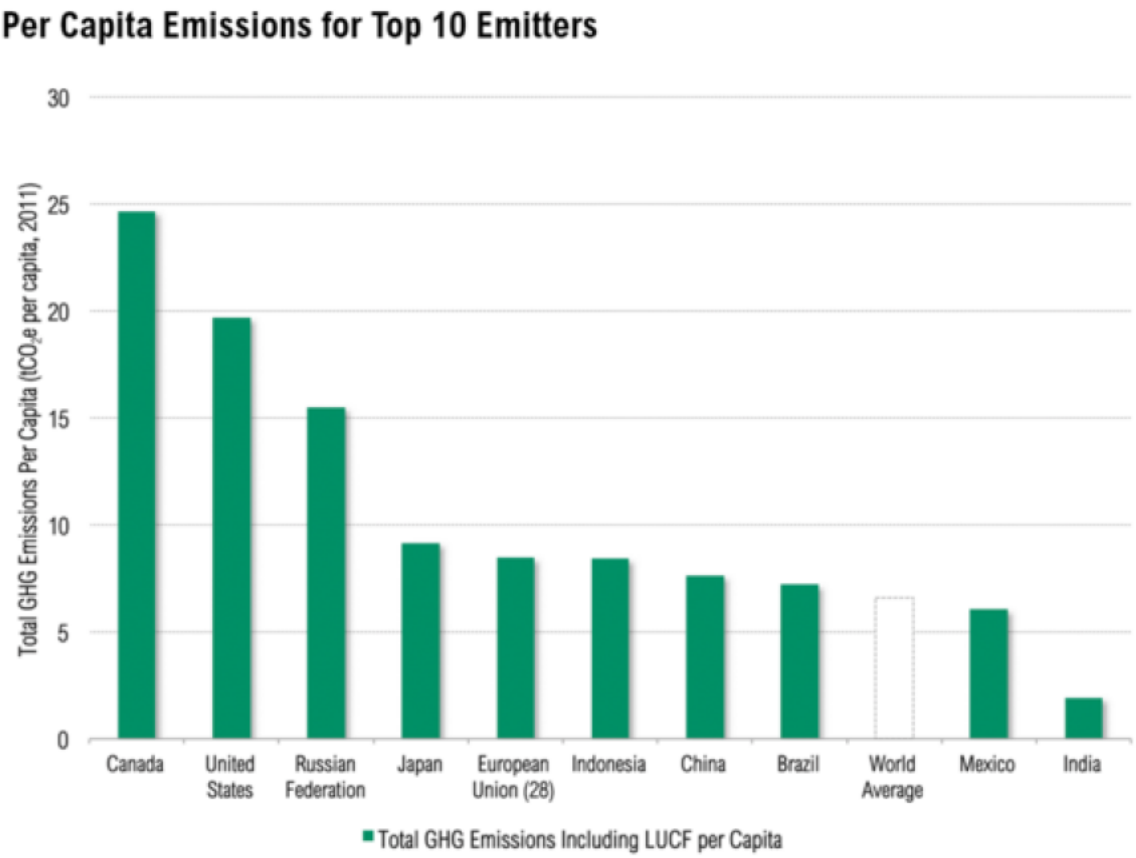


Figure 5.1: Per Capita Emissions for top 10 Emitters[77]

This pollution is released primarily through activities such as transportation, electricity and heat production, industrial processes, and agriculture[68].

[67] Ge, Mengpin, Johannes Friedrich, and Thomas Damassa. "6 Graphs Explain the World's Top 10 Emitters." World Resources Institute. November 6, 2014. Accessed January 7, 2016. http://www.wri.org/blog/2014/11/6-graphs-explain-world's-top-10-emitters.

[68] "Air Pollutant Emissions in Canada." Environment and Climate Change Canada. June 12, 2015. Accessed January 7, 2016. https://www.ec.gc.ca/indicateurs-indicators/default.asp?lang=en&n=E79F4C12-1.

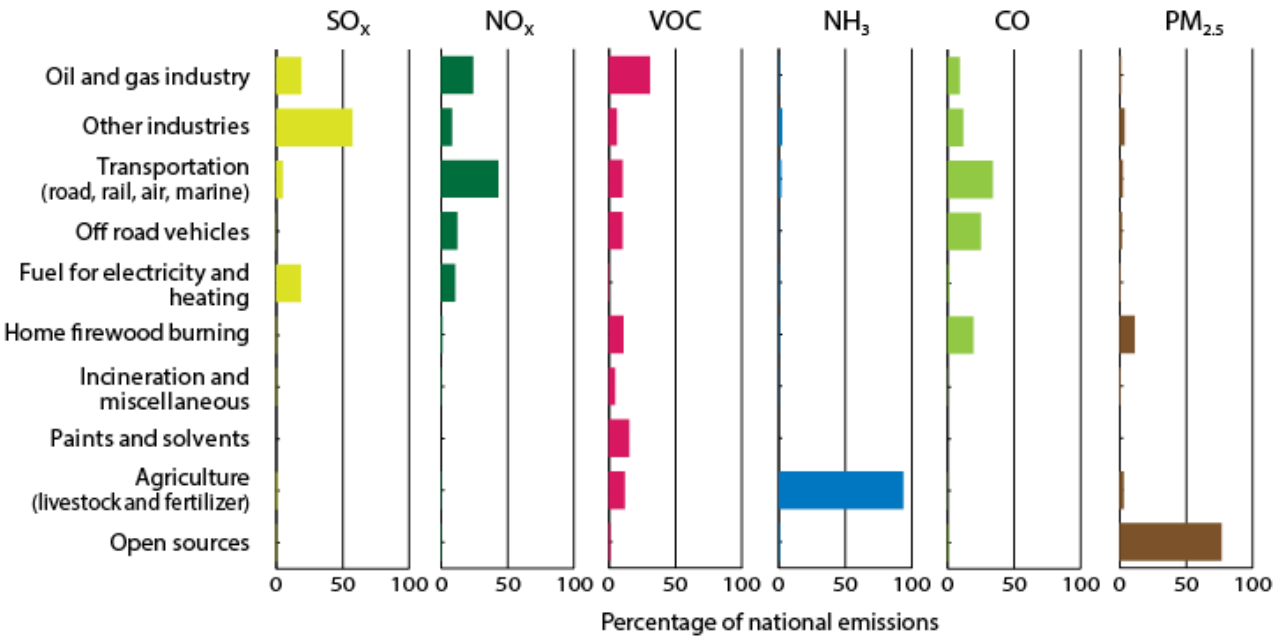


Figure 5.2: Percentage of national emissions sources[78]

The city of Toronto has consistently had one of the highest levels of air pollution in Canada and it is currently estimated to give rise to 1,300 premature deaths and 3,550 hospitalizations in the city each year. Over half of Toronto's air pollution is emitted within the city's boundaries, with the biggest local source being automobile traffic[69].

5.1.1 Mayor's Tower Renewal Project

Toronto is a city of towers. Between the 1950s and the 1980s the high rise became vastly popular, and over 1,000 residential concrete apartment towers were built, giving Toronto the second highest number of towers in North America. Today these concrete slab towers are aging and inefficient, while the open spaces that surround them are underused and poorly maintained. The Mayor's Tower Renewal project is a community reinvestment and green initiative plan that will seek to combine green technology with neighborhood revitalization to make stronger, greener communities across the city.

[69]Stephanie Gower, Ronald Macfarlane, Marco Belmont, Kate Bassil, and Monica Campbell. "Path to Healthier Air: Toronto Air Pollution Burden of Illness Update. Technical Report". Toronto Public Health. April 2014. www.toronto.ca/health/reports

Figure 5.3: Existing Toronto residential high rises – Mayor's Tower Renewal Opportunities Book

5.1.2 Project Site Location

For our project to be successful, it will need to be located near an area in Toronto that receives/emits a high quantity of air pollution, in order to demonstrate the projects' remediation capabilities. In examining a pollution map, we can see that the areas with the highest levels of air pollution (at UFP concentrations of 32,000-36,000. See figure 5.4) are the intersection of Highway 427 and Highway 401, the junctions of the Don Valley Parkway and Highway 401, Steeles Ave. W. and Highway 400, and Steeles Ave. E and Highway 404.

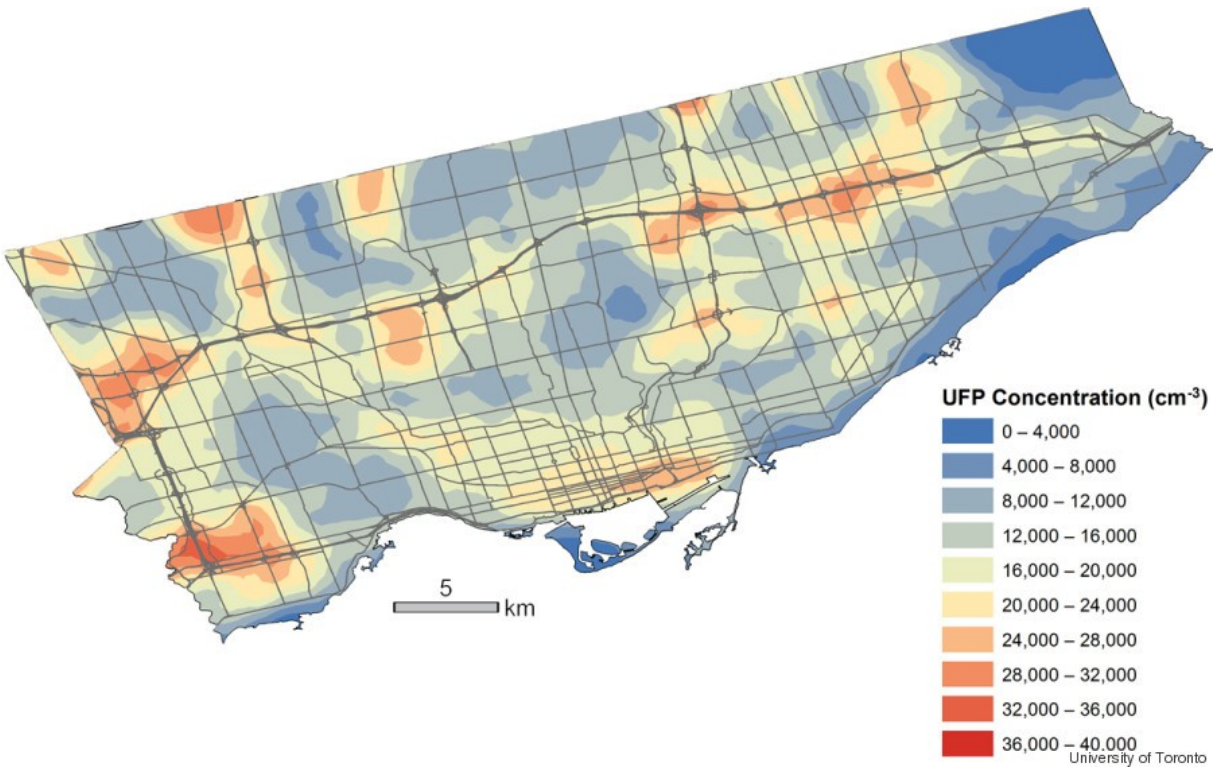


Figure 5.4: Ultra Fine Particle Concentration Map of Toronto - http://www.thestar.com/

Another requirement is that this site must have enough open space to accommodate the design, and must feature some typical local ecology which will be tied into the project's design features. The intersection of the Highway 401 and the 427 meets all of these requirements and so will be chosen as the site for our project.

Figure 5.5: Areal view of Highway 401 and 427 intersection

Figure 5.6: Picture of chosen site from on-ramp – google street view

Figure 5.7: Picture of chosen site from on-ramp – google street view

5.2 Outlining the Design Goals

The overarching focus of this design project was to produce a public space that embodied the experiential qualities of a park and river as determined by the familiarity study, and combine it with the functionality of the Algae system.

5.3 Familiarity Study Characteristics for Design

The following key characteristics were identified in the familiarity study and were chosen to be explored through architectural design:

1. Park Experiential Qualities:

   Public Space – Parks are areas for activities, and so creating a public space that can be used and interpreted by the occupants is a driving characteristic of our project's design. Our design accomplishes this by providing a variety of open areas for recreation, as well as bench seating for more sedentary activities.

   Verticality - while the vertical elements of a park such as trees and bushes are important, the fact that they do not overpower the senses is key to the subject's experience. The design project utilizes scale and imagery in its design so as to convey this sense of verticality. Large spans of glazing are also used to bring in an abundance of natural light, which serves both to power the algae systems and illuminate the space during the day, but also to connect the occupants with the surrounding natural ecology of the site.

   Adaptability – Parks form between urban developments, and so our design is intended to be able to adapt to different urban settings. While the building's form may appear unique, the design elements such as the algae tanks, the tubes and the water systems are all

modular. This allows them to be adapted to fit any site within an urban environment.

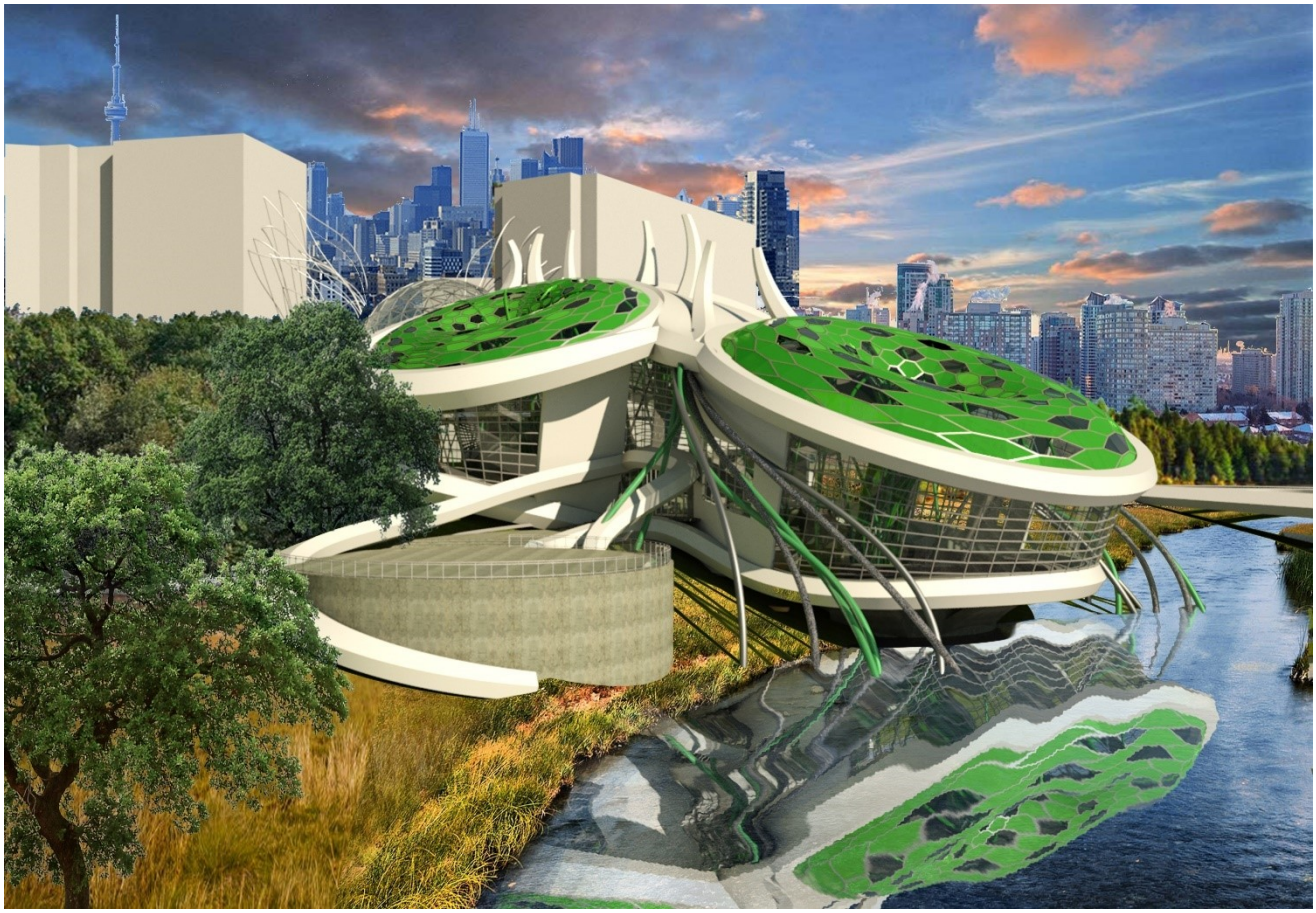


Figure 5.8: Exterior Rendering

Connection to Nature – Large glazing facades on the East, West and South facing ends of the building allow for natural light to flood the building. This glazing will allow for plants to be grown inside of the building, providing the occupants with year round access to greenspace. The large windows also allow for a visual link between the interior space and the exterior ecology surrounding the building. The intent here is to completely immerse the occupants in a vibrant and dynamic space which pairs technological elements with natural ecology.

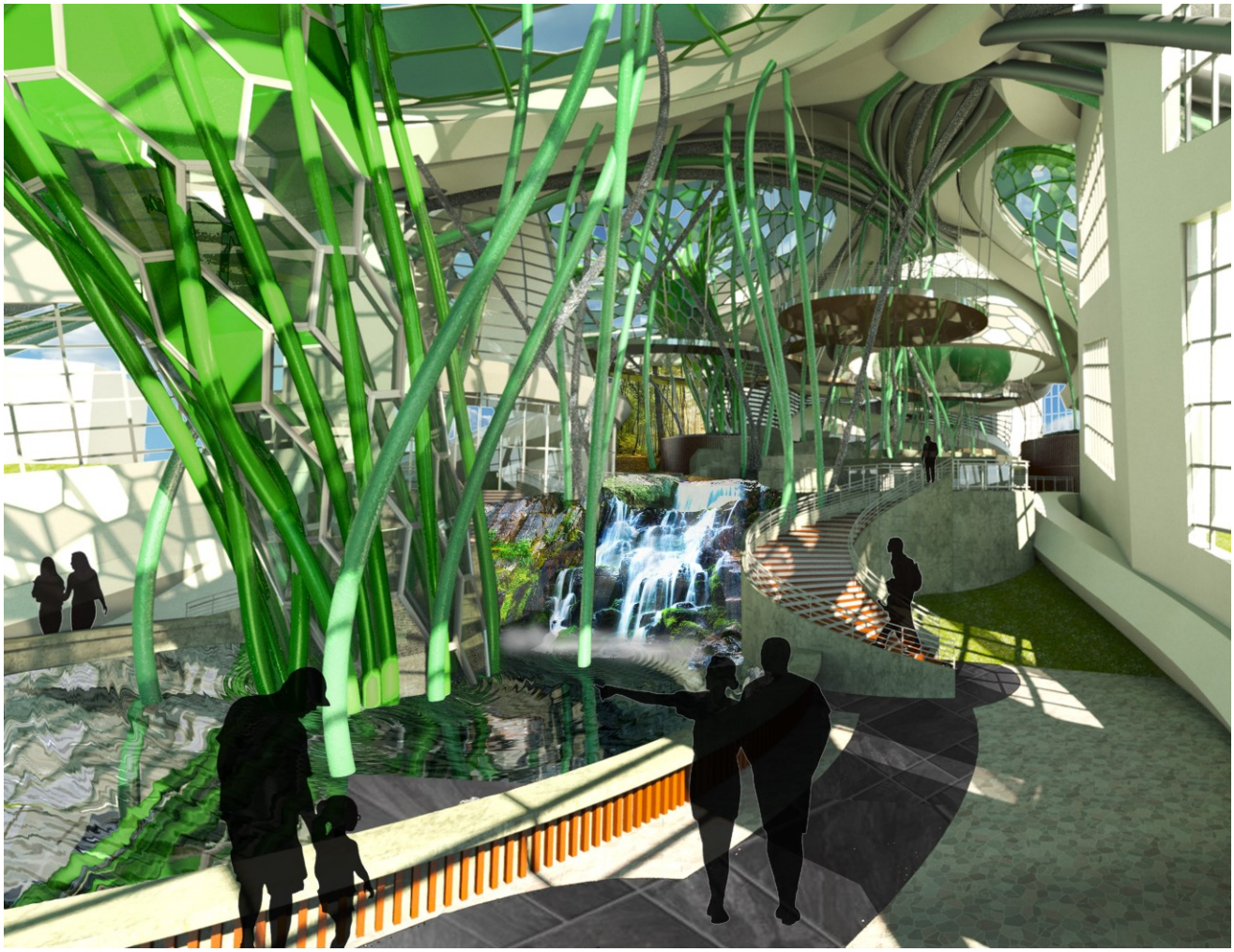


Figure 5.9: Interior Rendering – South most corner with waterfall and pond

2. River Experiential Qualities:

Water – the most essential and defining characteristic of a river is the flowing water. The sight, sounds and smells associated with flowing water create a unique experience, which our project mimics through a combination of open ponds, streams and cascading waterfalls.

Rock – rivers tend to flow over rocky beds and carry sediments with them. Our design integrates the imagery of rocky outcrops around the flowing water in order to convey this characteristic.

Movement – not only is flowing water an important aspect of a rivers' sense of movement, but so is the shape of the river its self. Visually speaking, the curves and flows of a rivers' form enhances the way a subject interacts and relates with the river. Thus our design

creates bends and curves in the flowing water, as well as the paths of travel available to the occupants as they navigate the space. This creates a more dynamic environment promoting a deeper relationship between the space and the occupant.

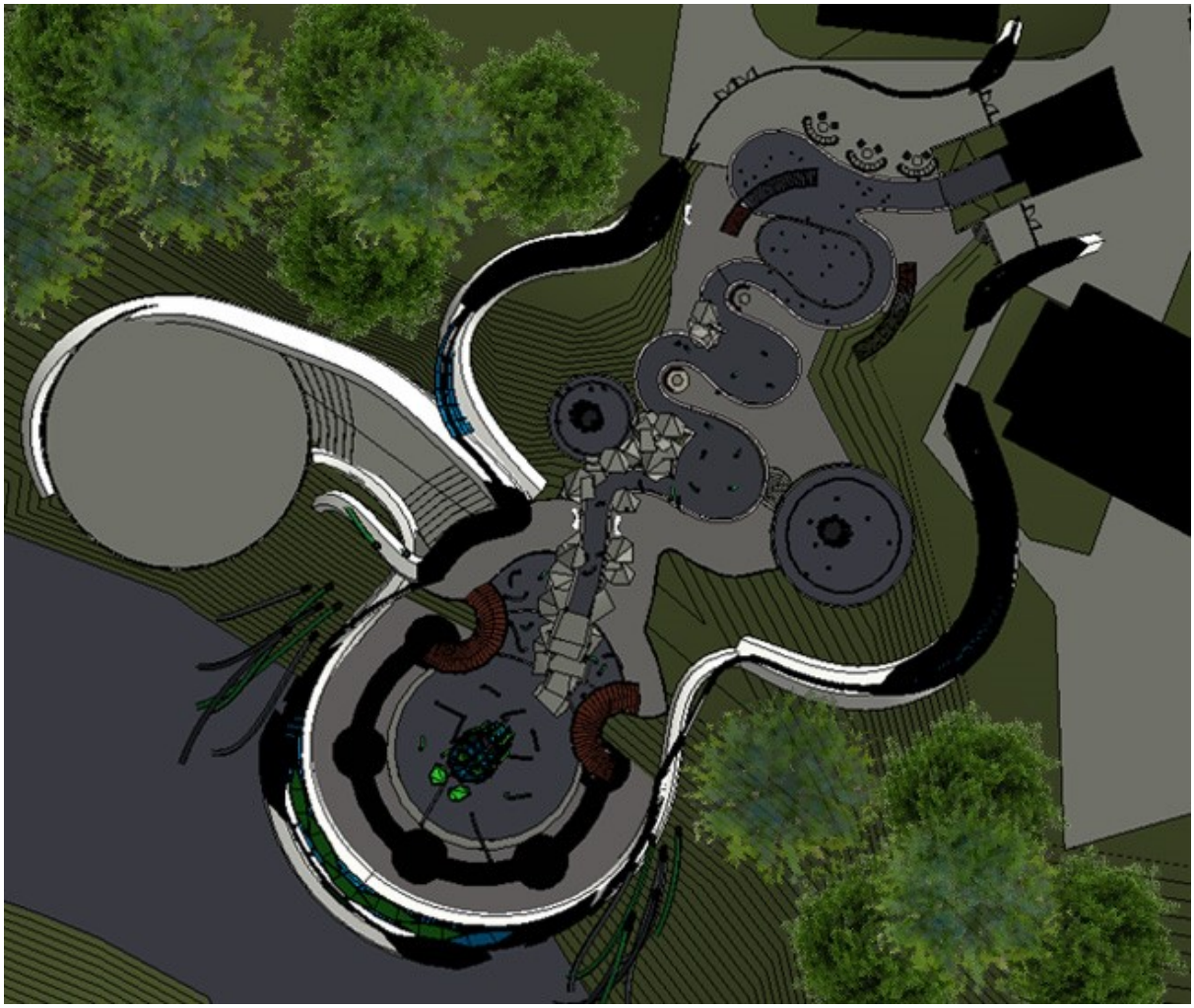


Figure 5.10: Ground Floor Plan

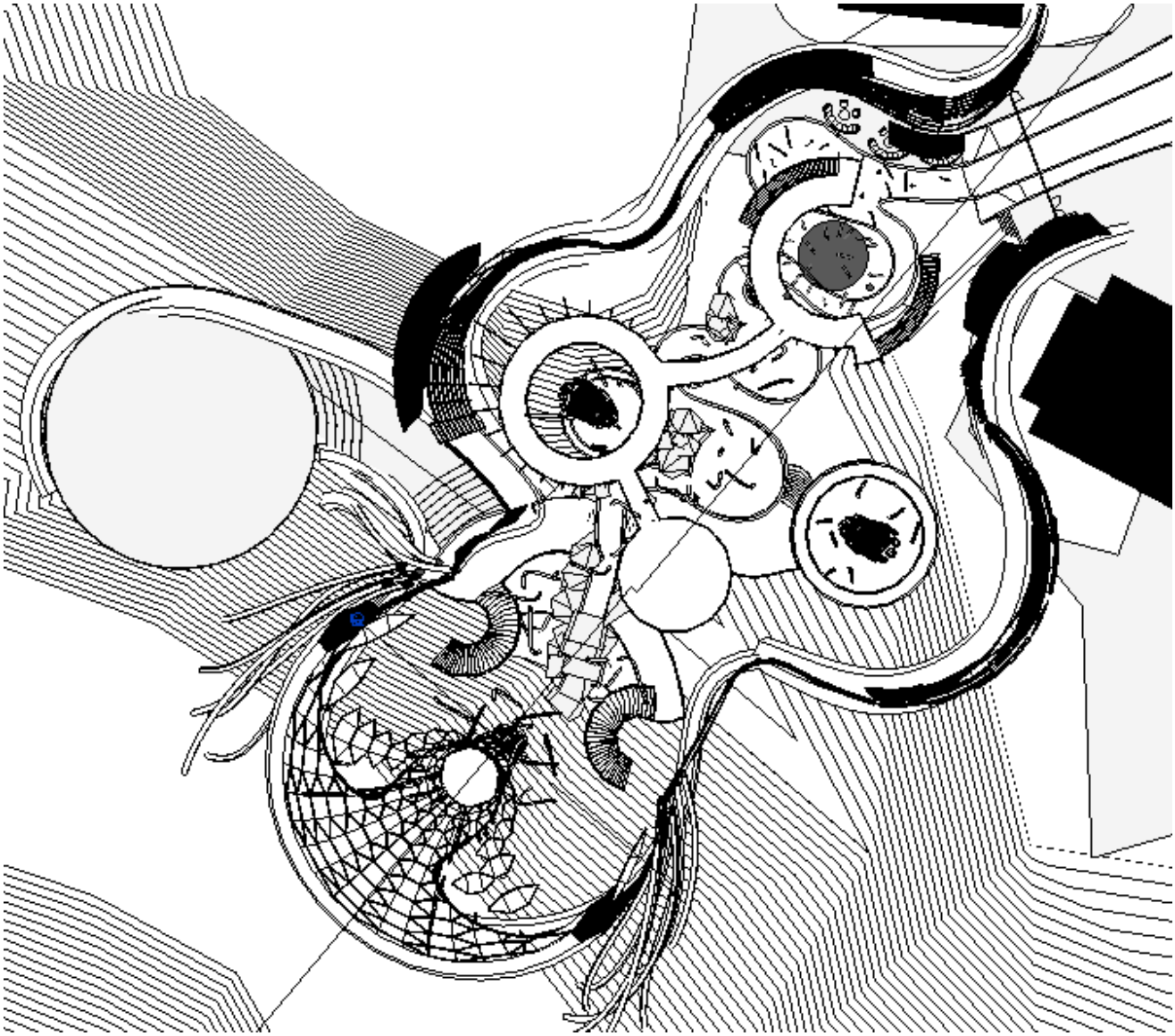


Figure 5.11: Second Floor Plan – Balcony Level

5.4 Algae System Characteristics for Design

The main components of the algae system have been examined in detail, and are illustrated in the proceeding diagram. These elements were then redesigned into new architectural forms and integrated into the final design project as follows:

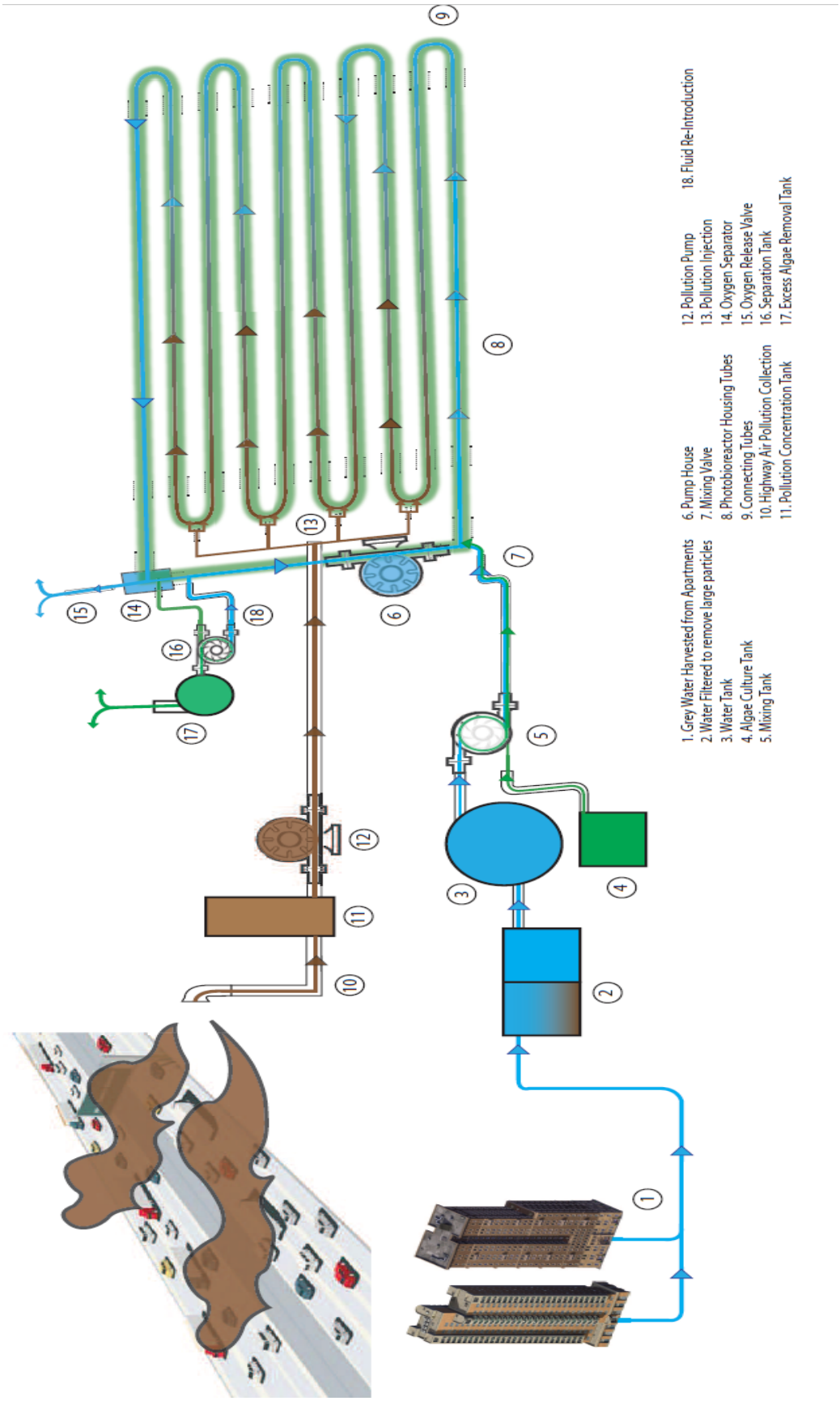

1. Grey Water Harvested from Apartments
2. Water Filtered to remove large particles
3. Water Tank
4. Algae Culture Tank
5. Mixing Tank
6. Pump House
7. Mixing Valve
8. Photobioreactor Housing Tubes
9. Connecting Tubes
10. Highway Air Pollution Collection
11. Pollution Concentration Tank
12. Pollution Pump
13. Pollution Injection
14. Oxygen Separator
15. Oxygen Release Valve
16. Separation Tank
17. Excess Algae Removal Tank
18. Fluid Re-Introduction

Figure 5.12: Algae System Function Diagram

Greywater Harvesting from Apartments (1) – greywater produced by the three apartment buildings adjacent to the project are to be extracted through an array of pipes and fed into the algae filtration system. The algae's ability to filter out contaminants from both water and air make this system ideal for greywater harvesting. However, rather than feeding the water back into the apartments – which would require many more systems for quality control and regulation – the system simply uses the greywater to replenish the water naturally consumed through the operation of the algae photobioreactor.

Open pond (3)– the design project incorporates open algae ponds within the interior space and transforms them into water features. These ponds of open water and algae filter the air within the building and serve as the containing and mixing tanks for the entire algae system. The open water also serves to enhance the space through added sounds and smells, as the water is allowed to evaporate into the atmosphere, and produce algae at the same time. The excess water produced by the system flows into the central "river" of water, which is continually circulated throughout the building.

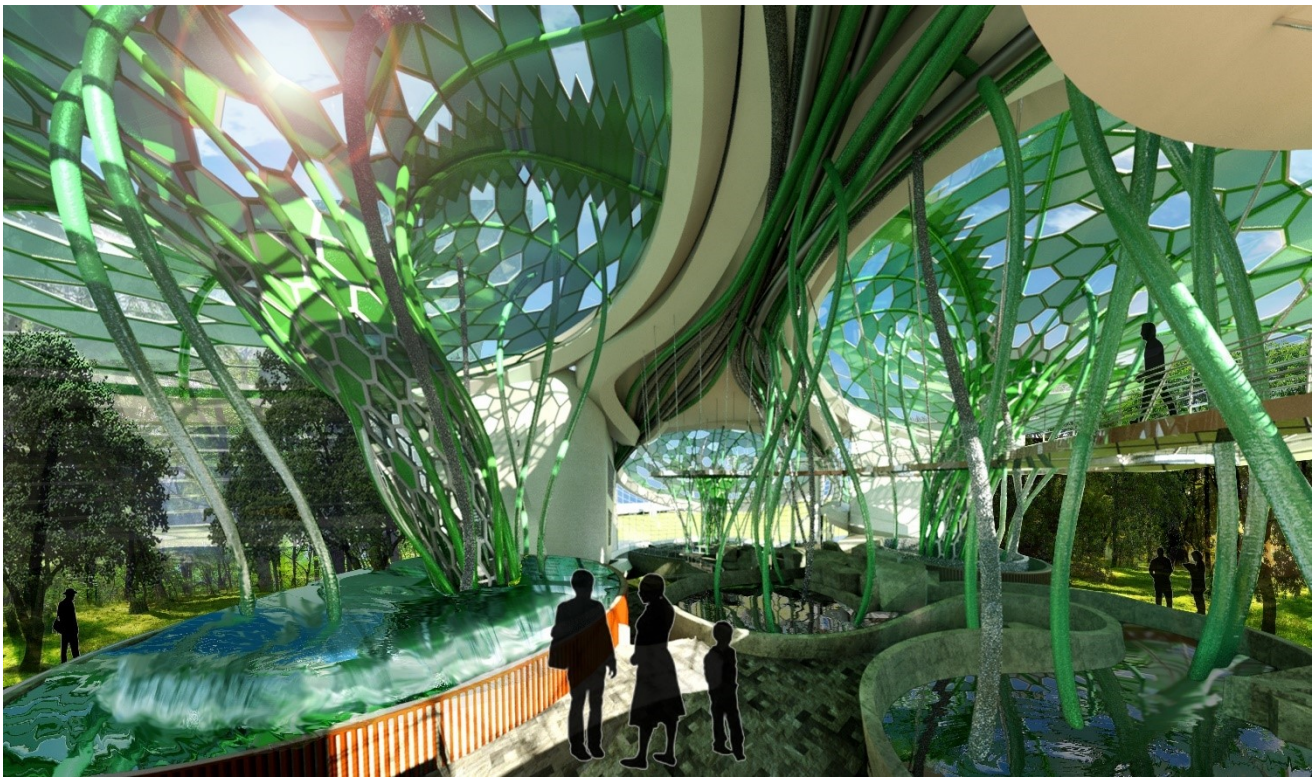


Figure 5.13: Interior Rendering – Main Atrium Space

Algae Tubes (8) – the culture liquid in the panel system still needs to be circulated regularly so that the algae doesn't stagnate and the exposure to sunlight can be maximized. This is done through a series of hanging tubes, which enable the sharing of liquid from the open ponds,

water tanks and algae panels. They are designed to hang from the funnel structure and mimic vines growing up a tree.

Figure 5.14: Interior Rendering – Main Entrance

Closed Algae Panels (9) – as described in section 4.5, the algae can be stored in a variety of different transparent panels or tubular containers. Our design has taken this concept and modified the containers to form several different elements.

Flat hexagonal Plexiglas panels were created and linked together to form a type of funnel shaped canopy which acts as the main components of the algae filtration system. These funnels maximize the algae's exposure to sunlight, and are shaped to harvest rainwater which can be fed into the water tanks and circulated throughout the system. At the main entrance of the building, mouldable clear plastic containers are suspended from the ceiling beneath a large skylight, illustrating a different way the algae can be contained. This creates a cloud-like form and acts as a centerpiece for the entrance. Finally, clear plastic tubes line the walls of the pavillion, functioning to transport the algae and culture fluide from the tanks into the panels and also to create a dynamic experience for the occupants.

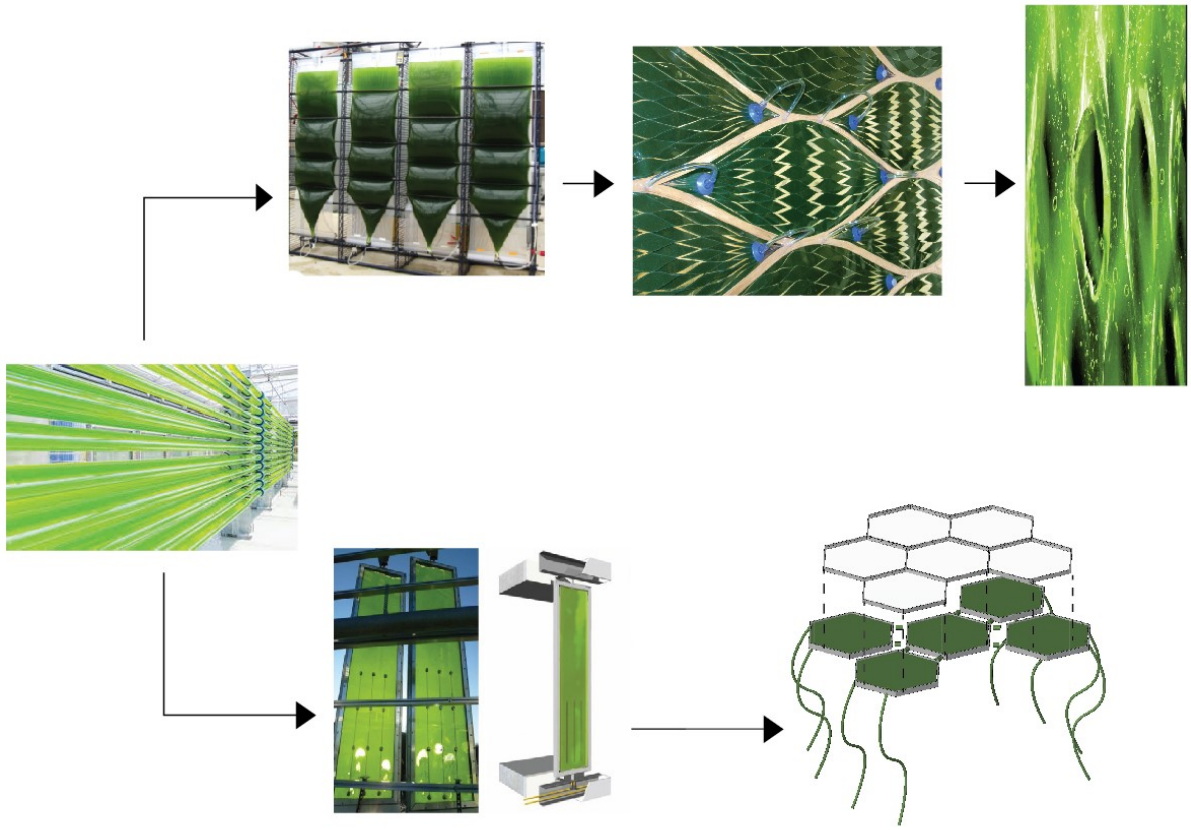


Figure 5.15: Algae Panel Design Progression

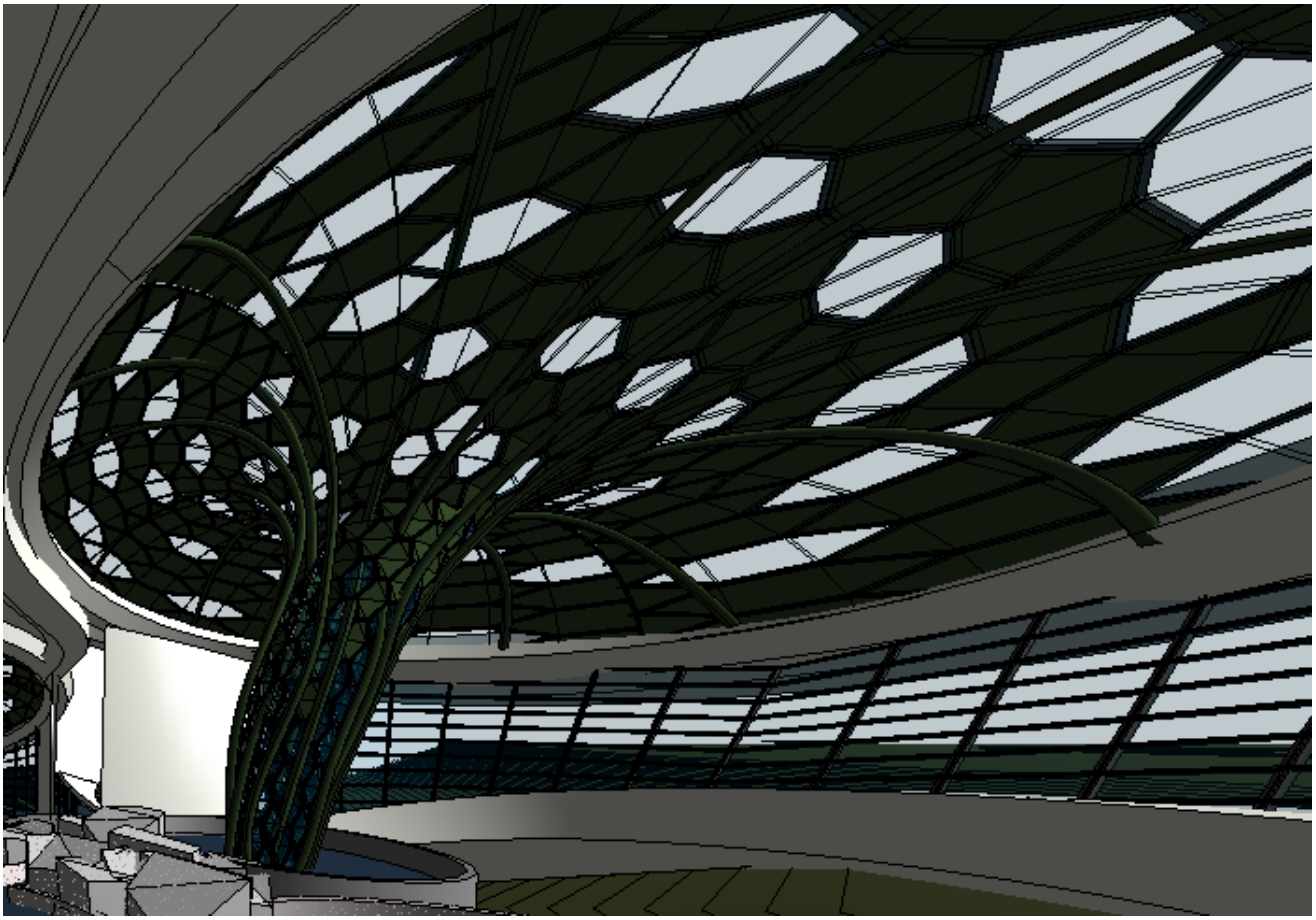


Figure 5.16: Close up view of funnel structure

Air Pollution Harvesting Inlets (10) – in order to capture the air pollution needed to sustain and grow the algae, intake funnels were placed alongside the nearby highway which suck the exhaust fumes and feed them into a collection tank (11). From there the pollution is directed into the building and directly into the algae panels through a series of exposed pipes (13), which add to the sense of movement and machine-like quality of the algae system.

Oxygen Outlet – as the pollutants are processed by the algae, oxygen is produced and must be diverted out from the culture liquid using valves. The oxygen is then released into the atmosphere through chimney-like exhausts located on the roof of the building (15).

Excess Algae Removal – as the algae continuously grows, the excess must be removed from the system to ensure proper functionality and consistent performance. The excess algae is diverted from the system (16) at the base of the flowing "river" of algae, and is fed into the algae removal tank (17) located outside of the building for easy access. This algae can then be harvested and sold to various industries for purposes outlined in section 4.5.

5.5 Algae System Performance Statistics

The full funnel system has a total carrying capacity of 329.62 m^2 and is capable of processing 40 tons of CO_2 per day. With 3 funnels this puts the processing power to 120 tons of CO_2 per day, which is enough to process 43,800 Tons of CO2 per year, or 75% of the total carbon emissions produced from vehicles in the entire city of Toronto (58 Kilotons)[70].

The open ponds within the building have a larger storage capacity of 1698 m^3, but are far less efficient at processing CO_2 at 3.01 tons of CO_2 per day. This is due to the reduced exposure to light (as they are within the building rather than part of the building's façade) and their inherent openness which allows injected air to escape instead of being confined within a vessel, limiting the concentrations of pollutants that they can process. Thus these systems are used primarily for treating the building's indoor air rather than the exhaust harvested from the highway.

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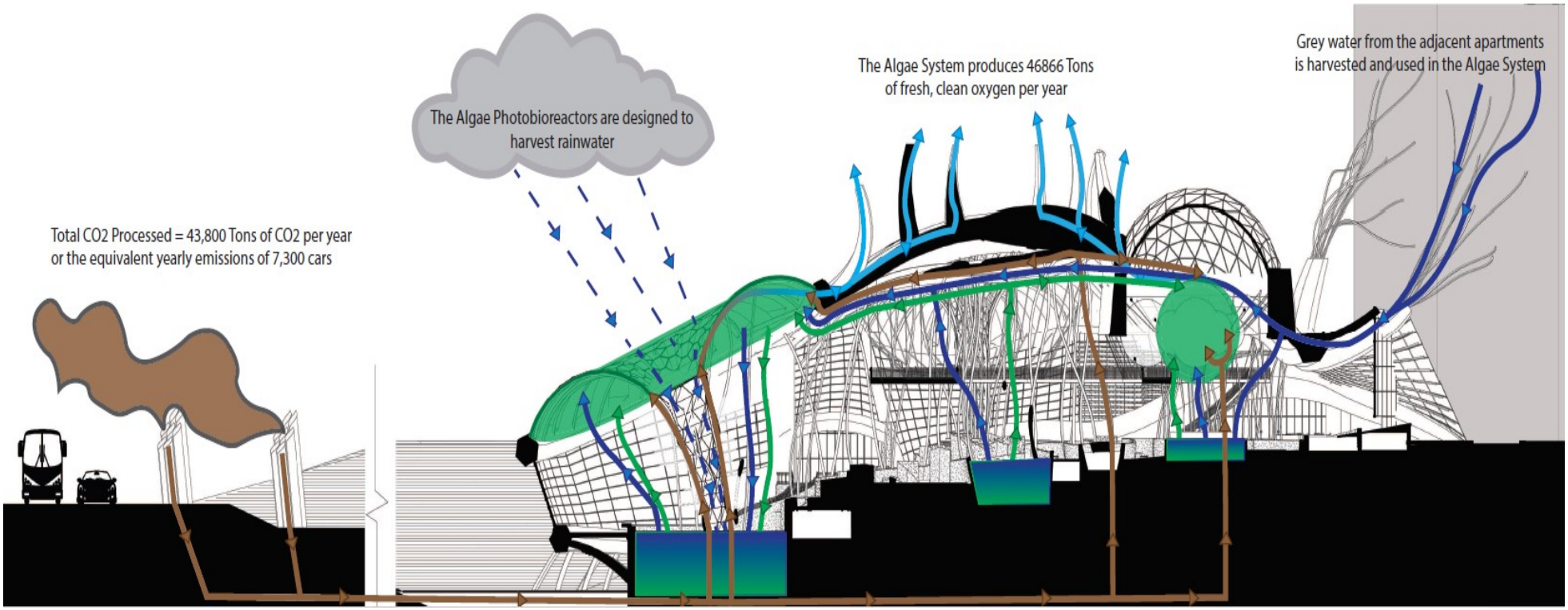
Total CO2 Processed = 43,800 Tons of CO2 per year
or the equivalent yearly emissions of 7,300 cars
The Algae Photobioreactors are designed to
harvest rainwater
The Algae System produces 46866 Tons
of fresh, clean oxygen per year
Grey water from the adjacent apartments
is harvested and used in the Algae System

Figure 5.17: Above - Pavilion Function Diagram

5.6 Conclusion

The final design project was intended as an exploration of the architectural potential in combining highly efficient air pollution remediation technology with a unique experiential aspect of an ecological setting. Our familiarity study helped us to identify two significant ecological settings that became the basis for our architectural design, and we shaped our chosen algae photobioreactor system to become the primary architectural elements in creating the imagery of those preferred settings. Our building merges experiential stimulation with sustainable function, delivering a public space that can both reconnect the occupants with nature and work to remedy the local urban environment. Thus creating an example of a truly holistic architectural design.

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