URBAN FOOD GROWTH:

DESIGNING FOR VERTICAL BUILDING SURFACES

by
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A THESIS

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THESIS ABSTRACT

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Title: Urban Food Growth: Designing for Vertical Building Surfaces

This thesis attempts to determine if food-producing plant growth can be incorporated within a building envelope to create an ideal plant growth environment while simultaneously enhancing the thermal properties of the building envelope. A window system was designed as a means of bringing food production into the built environment in an easily accessible fashion from the interior of a high-rise apartment complex. The Ya-Po-Ah Terrace in Eugene, Oregon, was chosen as a case study site for research on how a window could promote health, provide nutrition, and enhance the thermal comfort of the inhabitants. The design of the window unit is founded in precedent research on methods of plant growth in urban environments and systems for growing food in small and efficient ways. The design found that it is possible to create an ideal plant growth environment within a building assembly for use as a food production method for building inhabitants.

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CHAPTER I

INTRODUCTION

Urban gardening has the potential to lessen food insecurity for seniors who do not have sufficient access to fresh produce and garden space can be difficult to find in dense urban environments. In response, I am proposing a window system for food -producing plant growth to be installed on the south side of senior high rise apartment buildings. The Ya-Po-Ah Terrace in downtown Eugene, Oregon, will be a case study site for research on how such a window system could work to promote health, by providing produce and a higher quality of life, while enhancing thermal comfort. The case study is meant to develop a design that could be applied in similar building typologies. The design includes a precedent study, a retrofit design proposal intended for building designers, and a users' manual for the inhabitants of the building.

Plants grown in a window can begin to bring nature back into the city, promote urban gardening, and enhance the thermal function of the building facade. Allowing urban dwellers to grow food in an apartment has the potential to promote healthy living and a better quality of life. Food security is also a problem in dense urban environments within the United States and this project has the potential to alleviate a small portion of this problem by allowing more food to be grown by individuals who do not have access to traditional garden space. Access to nutritional produce can be hard for mobility impaired segments of the population such as seniors. Seniors are a vulnerable demographic because often they are unable to get to healthy stores or to pay for the more expensive fresh produce. This project proposes the adaptation of current building envelopes into food producing building components, focusing specifically on the window assembly.

Thesis Objectives

The primary objective of this thesis is to explore the potential of growing plants in a window by designing an ideal environment for food plant production that also enhances the indoor thermal comfort of the inhabitants of an apartment.

The second objective of this thesis is to provide information on how to use this product for various types of food producing plants.

It is not the intention of this thesis to suggest that everyone wants to garden or that this project will solve food security problems. Nor is the intention to prove what has been established as current gardening and building façade methods as being wrong. This thesis will not cover design options for all climate zones of the U.S. or all plant varieties. It is also recognized that this product is dependent on the construction type used in the case study and cannot be applied universally.

Research Questions

1. What are current methods of growing plants in urban environments and combining plant growth with the built environment?
2. What are compact and efficient methods of growing food?
3. Can an ideal environment for food growth be created in conjunction with an inhabited space?
4. Can the thermal properties of plants be incorporated into the thermal function of a building façade to enhance interior comfort?
5. What plants are well suited for merging an inhabited space with a building assembly?

Hypotheses

This thesis predicts that an ideal environment for growing food producing plants can be created in a building assembly and that, secondly, the thermal properties of the plants and their growing environment can be used to enhance the thermal comfort of an inhabited space. This thesis also hypothesizes that these food producing plants can be easily maintained and harvested by the occupants from the interior of the inhabited space.

Thesis Approach

This study focuses on the creation of gardening space for the production of food. People of all ages and backgrounds are interested in gardening but do not all have the available land to maintain a garden, especially in dense urban living situations. This thesis looks at the various methods of bringing plant growth into living units of the built environment.

Gardening is climate and weather dependent, affecting the growing conditions of the plants. Therefore this project looks to ameliorate those conditions to provide a gardening environment with less annual fluctuation to provide for more consistent food production. Because of the variety of living spaces and building assemblies currently in use within the U.S., this study is limited to a specific case study of a high-rise senior apartment building in Eugene, OR.

Organization of Thesis

This document is organized into seven chapters, including the introduction. Chapter two is the context to and reasoning for the project. This provides a foundation of knowledge supporting the dominant driving forces of this project and the associated benefits. Chapter three is the background information necessary to understand the context of the project and the methods of solving the problem. The main area of research is plant production in urban environments and methods of efficient food production. Chapter four is a case study of a building typology used to focus the design process. Chapter five explains the design process and the overall outcome of the process. This provides a look at the performance specifications for the project and the various methods of reaching those goals. Chapter six explains the results from the design process and analyzes the outcome. Chapter seven concludes and summarizes the thesis with a discussion of the findings and thoughts on further research. An appendix is included as a user's manual explaining how to use the product.

CHAPTER II

CONTEXT AND REASONING

Introduction

The following chapter outlines the context within which this project is focused and establishes the reasons for this project and associated benefits. Psychological, emotional, and physical health benefits for individuals using the product will be presented along with information about adapting and enhancing the indoor thermal properties associated with the building façade.

Individual Benefits

Garden Space

Urban areas are often lacking open space for gardening. One of the benefits associated with this project is the ability for people to have greater access to garden space. Surveys have been done on the amount of available garden space for different living situations and it was found, not surprisingly, that those living in apartments had less access to gardens. Because of this data, the National Trust[1] "called for more green space to be made available through allotments on public land, around offices and through reclaiming derelict land" (Gray) for use as garden space by urban dwellers. The National Trust found the lack of gardens to be a noteworthy problem because this meant a shortage of the associated benefits.

Health & Quality of Life

The American Community Garden Association promotes gardening by listing its many associated benefits[2], the first being "improving the quality of life[3]"(Lewis). Many

[1] UK National Trust is a conservation charity "protecting historic places and green spaces, and opening them up forever, for everyone" (Who).

[2] The other associated benefits listed include encouraging self-reliance, producing nutritious food, reducing family food budgets, conserving resources, and creating opportunities for exercise, therapy, and education.

believe that gardening has a deep impact on life and can boost “pride and self-esteem” in individuals while creating “a benevolent setting in which a person – any person – can take first steps toward confidence” (Lewis). These mentally and emotionally beneficial rewards are felt by many who garden. A study in the UK found that 70 percent of those surveyed think that “spending time in gardens is important for their quality of life” and that, if given a choice, many would “rather spend time in their gardens than in front of the television or shopping” (Gray). This can have an even greater influence on seniors because of their greater risk of disease because of decreased exercise and poor diet. Gardeners tend to make healthier eating choices because of their interaction with fruit and vegetables, and an increased consumption of these has been known to “dramatically reduce an adult's risk for many chronic diseases” (Nauert). Plants can also improve the health of their caretakers by improving their air quality.

Air Quality

Plants play a major role in reducing air pollution and creating better indoor air quality. Urban air pollution is “an international health problem” and, in cities as large as Sydney, air pollution causes approximately 2,400 deaths every year. Urban inhabitants spend approximately 90% of their time indoors, making the case that the air pollutants leading to death are predominately gotten from indoors (Burchett). Professor Margaret Burchett, of the Faculty of Science at UTS, found that air pollution indoors is,

> even higher than outdoors because the outdoor-derived load[4] diffuses indoors and is augmented by indoor-derived contaminants...from other petroleum-based products[5]...The chemical mixtures, even at imperceptible levels, can cause 'building-related illness' and symptoms of headache, sore eyes, nose and throat, or nausea. (Burchett)

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[3] Quality of life is “your personal satisfaction (or dissatisfaction) with the cultural or intellectual conditions under which you live (as distinct from material comfort)” (dictionary.com).

[4] Common outdoor pollutants include: nitrogen, sulfur, carbon oxides, organics, and particulates.

[5] Indoor petroleum based products are problematic because they have volatile organic compounds (VOCs), out-gassing from synthetics in furnishings, detergents, paints, printers, and air fresheners, to name a few.

These contaminants can be offset naturally, with the addition of plants into the indoor environment. Plants in a home will “help to settle out, trap and hold particulate pollutants[6] that can damage human lungs”. Plants also absorb CO2 and “other dangerous gasses” while replenishing the air with oxygen for us to breathe (SCFC). Studies of plant installations in offices over the past couple of decades have shown that in the work environment, “well-being is improved with sick-leave absences reduced by over 60%, presumably as the result of both air-cleansing and aesthetic properties” (Burchett). Studies have been done testing the efficacy of plants and have found that “even the smallest planting regime[7] was enough to kick in and reduce concentrations by up to 75%”, keeping the indoor air healthier in an aesthetically pleasing fashion.

Biophilia[8]

Cities are often starved of the visual benefits of nature. Paula Horrigan of Cornell University suggests that a community without plants is “disconnected from its natural environment and sense of wholeness” (Goldweber). This concept, of nature being an integral part of society, is one felt by many and is tested with visual preference studies. Urban areas are preferred when an increased amount of nature is present because nature enhances the built environment (Cackowski). In one such study, the natural material was so preferred over the urban material that “the least preferred nature slide was favored over the most preferred urban slide” (Kaplan). These natural connections within the city are important aspects to healthy city life because “environments rich in nature views and imagery reduce stress and enhance focus and concentration” (Lidwell). This has been a belief for centuries, with Fredrick Law Olmsted in 1865 writing:

> It is a scientific fact that the occasional contemplation of natural scenes of an impressive character...is favorable to the health and vigor of men...the re-

[6] These include, but are not limited to, dust, ash, pollen and smoke.

[7] A small plant regime is considered to be 6 shelf sized plants.

[8] Biophilia is a hypothesis that there exists “an instinctive bond between human beings and other living systems” (Wilson).

> invigoration which results from such scenes is readily comprehended (Cackowski).

Even from within a building, a view of plants can have a beneficial effect on inhabitants because just the mere “presence of windows appears to increase healing” (Cackowski). Hospital windows have been tested to find the effects on patient health and it was “found that patients with window views of trees used less medication and were discharged, on average, nearly 10% more quickly than patients who had views of a brick wall” (Hull). A test on the amount of vegetation needed to improve mood showed that “a view of vegetation through a window, through slides, or even in a scenic poster all produce positive psychological effects” (Cackowski).

Food Security & the Elderly

Food security is a problem in dense urban environments within the United States. In 2009 the U. S. reported 14.7% of its population (17.4 million people) were not food secure for the entire year (Nord). According to the USDA’s Economic Research Service, “the prevalence of food insecurity was higher for households located in principal cities of metropolitan areas” (Nord). There are multiple explanations for this, one of which is the lack of available areas to support food growth within the urban fabric. Food insecurity itself has many facets and can mean lack of access to food through both price and location. According to the United Nations Food and Agriculture Organization:

> ‘Food security’ means that food is available at all times; that all persons have means of access to it; that it is nutritionally adequate in terms of quantity, quality and variety; and that it is acceptable within the given culture. Only when all these conditions are in place can a population be considered ‘food secure’. (Koc 1)

When any of these conditions are not met, food insecurity arises. Food security is “vulnerable to…financial challenges” and a lack of money can cause an inability to buy enough nutritionally sufficient produce (Andrews). An economic recession caused a 44% rise (from 3.9 to 5.6 million) in numbers of households obtaining emergency food from food pantries from 2007 to 2009 (Andrews). Of adults surveyed as being food insecure in 2009, “95 percent…reported that they had eaten less than they felt they should because there was not enough money for food” (ERS *Definitions*). Food security is affected by price but the price can change depending on the grocery store location.

Grocery stores in urban areas tend to be smaller and more expensive[9] than in suburban or rural areas (*Access* 84), which can cause shoppers without much money to go in search of grocery stores farther away[10]. In 2008, participants in the food stamp program redeemed 87% of their benefits in large grocery stores and supermarkets which were, on average, 4.9 miles away from their homes. The USDA considers a distance of over one mile to the grocery store to be inadequate food access (*Access* 7-17).

These distances force shoppers to find transportation to access the affordable produce located outside their neighborhood. According to a 2008 USDA survey, vehicle access was a key determining factor in the accessibility of affordable and nutritious food (*Access* 17*)*. This also meant that the elderly had greater access problems because of a lack of mobility and an inability to drive to the grocery store (*The National Nutrition Safety Net*). A study on elderly food insecurity found that “food insecure seniors sometimes had enough money to purchase food but did not have the resources to access or prepare food due to lack of transportation, functional limitations, or health problems” (Senior). Even with grocery store access, seniors may not be able to afford the produce because 8.9% (3.4 million) of the American elderly live below the poverty line.

Feeding America, a nationwide network of food banks, found food insecurity among “this vulnerable population” to be “especially troublesome because they have unique nutritional needs and may require special diets for medical conditions” (Senior). Of those using the services of Feeding America, 30% of the households with seniors “indicated that they have had to choose between food and medical care”, while another

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[9] “In dense urban areas, land prices may be higher and zoning requirements of local governments may be more cumbersome and costly to meet relative to less dense suburban and rural areas. Consequently, it is likely that the fixed costs in urban areas are greater” (*Access 84-85*).

[10] “The middle of the 20th century saw a rise in automobile use, interstate highways, and movement of residences and businesses to the suburbs where large tracts of land were available for relatively lower costs. Supermarkets grew in size and carried an increasing variety of products…Reliance on their own distribution and inventory systems along with larger store sized allowed supercenters to charge lower prices” (*Access* 84).

35% had to choose “between food and paying for heat and utilities” (Senior). A study which examined the health and nutritional status of seniors found that “food insecure seniors had significantly lower intakes of vital nutrients in their diets when compared to their food secure counterparts” and that “for seniors, protecting oneself from food insecurity and hunger is more difficult than for the general population” (Senior). There are multiple assistance programs to help people in need, but “elderly households are much less likely to receive help through the Supplemental Nutrition Assistance Program[11] (SNAP) than non-elderly households”, shrinking the availability of a variety of affordable produce (Senior).

With both monetary and distance constraints on food choice, people are forced to buy cheap products from close-by stores. Within food deserts[12], these options are often high calorie, energy dense foods with little nutritional value (Parker-Pope). The lack of affordable produce makes affordable unhealthy food the prevalent source of energy. A survey by Adam Drewnowski, director of the center for public health at the University of Washington found that,

> “higher-calorie, energy-dense foods are the better bargain for cash-strapped shoppers. Energy-dense munchies cost on average $1.76 per 1,000 calories, compared with $18.16 per 1,000 calories for low-energy but nutritious foods.” (Drenowski)

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[11] Supplemental Nutrition Assistance Program (SNAP) is the new name for the federal *Food Stamp Program (*ERS *Supplemental)*

[12] Food deserts are defined in the 2008 Farm Bill as an “area in the United States with limited access to affordable and nutritious food, particularly such an area composed of predominantly lower income neighborhoods and communities” (*Access* 12).

This definition requires further defining of the terms affordable, nutritious and access.

Affordability, according to the USDA study on food deserts, refers to “the price of a particular food and the relative price of alternative or substitute foods” (ERS *Food*).

Nutrition, based on guidelines developed by the Department of Health and Human Services, “emphasize(s) variety, balance, and moderation in the total diet”, but does not make “recommendations regarding specific foods to include or exclude”. The *Dietary Guidelines for Americans* provides recommendations “based on gender, age, and level of physical activity” (ERS *Food*).

Access is commonly measured by the “distance from consumers’ residences to the nearest food retailer that offers healthy and affordable foods” (*Access* 11).

Using this same information, a daily 2,000 calorie diet would cost $3.52 for junk food and $36.32 for healthy food. Americans usually eat a combination of the two, resulting in a $7 daily spending average. Based on the same survey, the low-income average was $4 a day (Drenowski). Without the option of growing food, shoppers are forced to choose between expensive nourishing food and cheap empty calories. The price and location of produce limit the options of would be healthy shoppers and lead to unhealthy choices (Parker-Pope).

Community gardens try to provide healthy alternatives in available urban spaces while dealing with the "need of communities to obtain a safe, culturally acceptable, nutritionally adequate diet" (*Access* 91-92). When space is available, these gardens can alleviate some food insecurity by breaking the price and location barriers to affordable produce. The space is usually rare in dense urban environments. This project is about creating that space.

Building Benefits

Thermal Comfort

The building envelope is affected by the addition of plants and can therefore have a significant impact for the inhabitants by changing the interior thermal comfort of a building. Plants can be used as a form of insulation, buffering the building surface from solar radiation, to extend the building lifespan[13] and mediate temperature fluctuations. Plants evapotranspirate water, increasing humidity[14] and reducing air temperature, while also creating an air cushion along the building facade, factors which produce a change in the thermal conditions surrounding a building (Façade).

Plant foliage can reflect and absorb anywhere between 40% and 80% of the received radiation (Façade) which in turn shades the wall, creating a reduction in daily temperature fluctuation[15] by as much as 50% (Dunnett). The window is especially affected because the solar energy is not only kept off the building, it is kept from directly

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[13] UV light deteriorates building materials (Perini).

[14] Air humidity is between 2% and 8% lower in winter and between 4% and 20% higher in summer (Facade).

[15] This can be a difference of as much as 30 degrees Celsius (Façade).

entering it (See Figure 2.1) (Dunnett). This will dramatically reduce the amount of energy needed to maintain a comfortable interior environment for the building inhabitants.

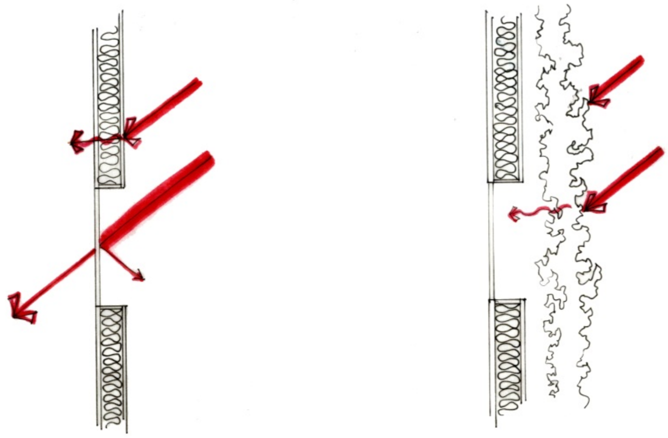

Figure 2.1. Plants buffering a building from incoming solar radiation.

Plants stabilize the conditions around the building envelope. Heat gain in summer is reduced, on average, 2 degrees with the addition of plant mass to the building envelope. The opposite is true in winter, with plants augmenting surface temperature by about 2 degrees. Heat loss from the wall in colder months can also be reduced by roughly 6% with the addition of a vegetated wall (Façade).

A variety of plants can be used for this purpose because the benefits associated are primarily due to the "total area shaded rather than the thickness" of the vegetation. Not surprisingly, vegetated building surfaces are therefore most effective when the plants are "used on the wall that faces the sun" (Dunnett).

This process lowers the amount of UV light hitting a building, extending a buildings life span. UV light deteriorates the "material and mechanical properties of coatings, paints, plastics, etc." and the addition of plants can therefore have an influence on the durability, and maintenance costs, of buildings (Perini).

Summary

Urban gardening has many associated benefits and should be seriously considered as a method of improving the health of both the city and the inhabitants. It is important to understand how plants can influence their immediate and distant environments in order to design beneficially for plants, people, and buildings.

CHAPTER III
RELEVANT RESEARCH AND BACKGROUND

Introduction

In order to find the best solution for answering the problems described previously, it is important to know what is currently available. Because of the nature of the questions being asked in this thesis, it is important to study the ways plants are currently being brought into the urban environment. These do not need to be food producing plants to inform this question because it merely looks at how plants in general can be grown in dense urban environments. It is also important to study the ways in which food producing plants are grown efficiently in small spaces and with minimal maintenance. These systems do not need to be used in urban spaces to be relevant. This research shows currently available options for this project and helps the design process to take shape.

Plant Growth in Urban Environments

There is currently a range of methods used to incorporate plant growth into the urban fabric. Green roofs, living walls and façade greening are all methods which have been used to combine plant growth with built urban forms (See Figure 3.1). Each of these options has a range of benefits but these options are not always practical or feasible for the production of food within housing.

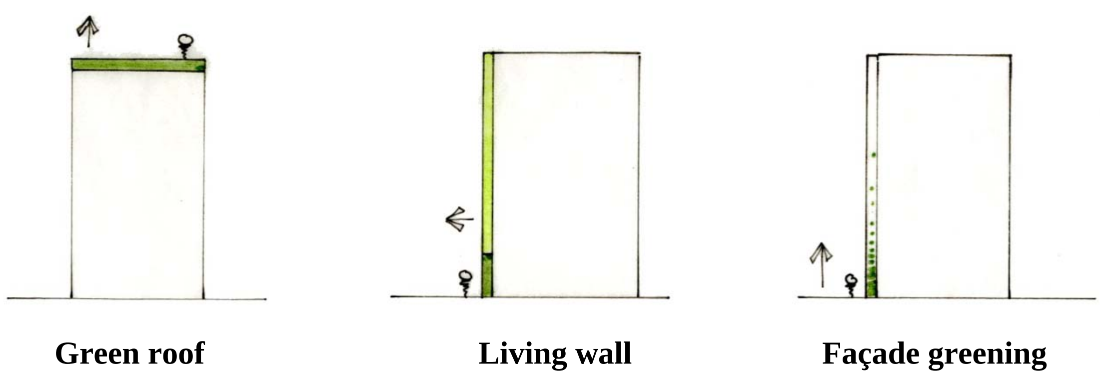

Figure 3.1. Methods of growing plants on buildings.

Green roofs, while not always affordable options, have been successfully used to grow food. One example of a thriving application is on the Earthpledge building in New

York where tenants are allowed access to the roof to grow food for sustainable cooking classes held within the building. Not all buildings allow roof access, and of those that do, not all of the structures are able to support food production. Once the roof structure is able to support the additional weight of a garden it may still not provide enough available space for each building occupant to have a practical personal garden. As far as useable space is concerned, the walls of a building typically have more available square footage than roofs (Dunnett).

Living walls are external wall mounted vertical gardens with plants growing perpendicular to the wall to create more surface area for plant growth. The living wall at the Longwood Gardens is the largest yet built in North America with 4,000 sq. ft. of growing wall, mostly ferns, which take out an estimated 15,500 pounds of dust and toxins yearly (Michler). Living walls are typically used for pollution control rather than food growth because anything higher than the first floor is inaccessible to the building users. There are small wall-mounted interior options which are made for plants which need little sunlight but still add value to the indoor air quality. Plant growth can help bring oxygen indoors to creating better air quality and remove toxins (Dunnett).

When grown on the exterior of a building, plants can also be placed in the ground and grown up a vertical trellis. This form is called façade greening and is typically used as an insulation buffer to extend the building life cycle and reduce the energy used in mediating temperature fluctuations. The shading on the surface of the wall can greatly reduce a yearly temperature fluctuation of 14°F-140°F to a range of 41°F-86°F. This provides an average 10°F temperature reduction on the inside of the building, creating a reduction in energy needed to supply the air conditioner by 50-70% (Dunnett 195). These performance benefits add to the long term affordability of a building, profiting the inhabitants while also creating habitat and adding to biodiversity within the city. These options for growing plants are topically applicable precedent studies meant to expand foundational knowledge for designing an interior accessed window mounted food growth system.

Methods of Food Growth

Plants need a combination of physical support, water, nutrients, light, and oxygen in order to survive. The support is typically given with soil, as are the nutrients. Over time the nutrients become depleted and plants do not grow as well as they could. Plants grow by absorbing mineral nutrients as inorganic ions in water. In typical growth systems, the soil holds the nutrients until they are dissolved in water and then absorbed by the plant roots, but the soil itself is not essential for the plant to grow. Hydroponics is a method of growing plants without the soil and placing the roots in a nutrient solution instead. The structure typically provided by the soil can be replaced either with an inert material or by a clip that simply holds the plant in place. The nutrient solution provided to the plant roots is then specifically tailored to provide exactly what the plant needs (Jantz).

Hydroponic growth systems have been approximated to use 70% less water than conventional farming methods. The water is applied more exactly and used more precisely than in traditional farming methods, eliminating excess water use, and is recycled. This keeps all the water and nutrients in the system and has no agricultural run-off. A study on greenhouses in New Mexico showed the difference in resource use between current conventional methods and possible hydroponic greenhouse systems. In this case study, water volume would shrink from 987,000 cubic meters to 13,500 cubic meters to produce the same amount (dry weight) of crop for the state. Hydroponically grown plants tend to have higher yields and can be grown in closer quarters, reducing the amount of space needed from 105,000 hectares to a mere 404 hectares of land for the same product (Jantz). Traditional farming methods lose significant amounts of water to evaporation and soil absorption. This can cause a salt build up in the soil which reduces the productivity of the soil. Hydroponic greenhouses have neither of these problems and do not require high-quality land in order to produce. The lack of soil eliminates the need for tillage and soil preparation, allowing for a shorter turn-around time for crops. Soil-borne pests and diseases are not a problem, nor weeding, reducing the amount of chemicals associated with crop production (Jantz). The lack of soil makes these systems lighter than other soil based methods, making it possible to have a smaller associated structure and impose less weight on an existing building if it were introduced into the built environment.

The main deterrent to using hydroponic systems is the cost. There is the cost to build it and then the cost to maintain it, mostly spent on the nutrients. The water needs to be regularly managed for the right amount of nutrients and pH levels. There can also be electricity costs if pumps are involved, which have the possibility of breaking. There are various forms of hydroponic systems[16] which can be chosen specifically based on the plant, the cost, the maintenance, and the space available. These constraints guide the design of the growth system in this project.

Health Benefits of Strawberries

A large variety of food-producing plants are currently grown hydroponically. The list of possible plants to grow provides the opportunity to pick a case study plant which has specific benefits associated with the goals of this project. The strawberry plant was selected to be tested in this hypothesis because of the useful properties connected with the plant and the berry. Strawberries are a source of anti-carcinogenic compounds[17] and they contain fisetin, a naturally-occurring flavonoid[18] known for treating both diabetes and Alzheimer's, in larger quantities than other fruits and vegetables[19] (Berger). Not only are the berries an excellent source of vitamin C and fiber, but the vegetative parts of the plants have been used in remedies for things ranging from clearing complexion to curing cancer (Alexander 99). They are also a specialty crop which will not stigmatize the user into being labeled as food insecure because of the use of this product.

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[16] Refer to the Appendix F on Hydroponic systems.

[17] Strawberries contain ellagic acid, a "naturally occurring polyphenol that is a potential inhibitor of certain chemically induced cancers. Because an estimated 80% of human cancers are caused by chemical carcinogens, this ellagic acid may have great medicinal value" (Alexander 99)

[18] Flavonoid is "any of a group of organic compounds that occur as pigments in fruit and flowers" (dictionary.com).

[19] Fisetin is also found in tomatoes, onions, apples, oranges, grapes, peaches, persimmons and kiwi (Fraser).

Summary

The methods of plant growth in urban areas and the information provided about the methods of growing food begin to inform the approaches taken in designing this project. The health benefits associated with strawberries narrow the research field and begin to inform the specifics of the project. These fields of study are then able to be applied to a case study site in order to find their validity.

CHAPTER IV
CASE STUDY

Introduction

The Ya-Po-Ah Terrace was chosen as the case study site for this project. Having a case study site is intended as a means of bringing the design goals and the reasons behind them together in one place where they can inform each other.

Ya-Po-Ah Terrace

The questions asked in this thesis involve problems of growing food in apartments nationally. In order to create a tangible product to these large scale issues, it is essential that this case study focuses on dealing with a representative sample of a general typology of buildings typically known to have food security issues. Because of the food security problems prevalent in senior housing, the focus study will be on a senior apartment complex which operates with government funds to allow affordable living options to its tenants. This narrower focus will allow the design to find a tangible solution and, although the case study is focused in the Pacific Northwest, the project will be designed to be adaptable for other regions of the United States.

The Ya-Po-Ah Terrace in Eugene, Oregon is an example of a high rise senior apartment complex located in an urban area without sufficient food access. Within it are three variations of apartment types, ranging from a smaller studio space to a larger bedroom apartment set-up, allowing for a range of living styles depending on the inhabitants wants and needs. Each living unit, regardless of size, uses the same window system throughout the entire building, making a space efficient window a high priority. There are affordable living options within that range of apartment types due to funding from the United States Department of Housing and Urban Development, keeping apartments affordable for tenants with low incomes.

The eighteen stories of the Ya-Po-Ah Terrace provide two hundred and twenty-two apartments, half of which are facing south and have a curtain wall system which can be adapted to grow food (See Figure 4.1). Each apartment has a set of three windows, each measuring 6’ tall by 42” wide (See Figure 4.2). Two of these have inset in them an operable window measuring 2’ tall by 42” wide. These operable windows are commonly used to house in-place air conditioning units to deal with the thermal gain from the southern exposure. The apartments are not protected from the southern exposure with any exterior shading devices. They are only provided with interior curtains. The glazing is the original single pane installation from the building’s construction in 1968. The heat in the south facing apartments has caused talk of replacing the entire curtain wall system in order to provide comfortable living situations for the elderly residents.

The testing of ergonomic comfort of the project will be possible because of the specific case study being used. The senior inhabitants of the Ya-Po-Ah Terrace provide an incentive to make the project focus on the physical and psychological benefits of gardening.

Figure 4.1. Southern façade of the Ya-Po-Ah Terrace, air conditioner units included.

Figure 4.2. Interior view of the curtain wall system provided in each apartment of the Ya-Po-Ah Terrace.

Summary

The case study site of Ya-Po-Ah Terrace in Eugene, OR makes it possible to gauge the impact that the proposed design could have. The current window system is a poorly insulated glazing which is desperately in need of replacement. This project aims to provide a physically and psychologically beneficial option to the building façade.

CHAPTER V

DESIGN CONCEPTS

Introduction

This project is about growing plants in an apartment in a dense urban city with no available garden space for the tenants. The plants can grow, regardless of building height, from the inside of the building. Indoor plants access light by being placed near sun receiving windows or by artificial light when sunlight is not available (See Figure 5.1).

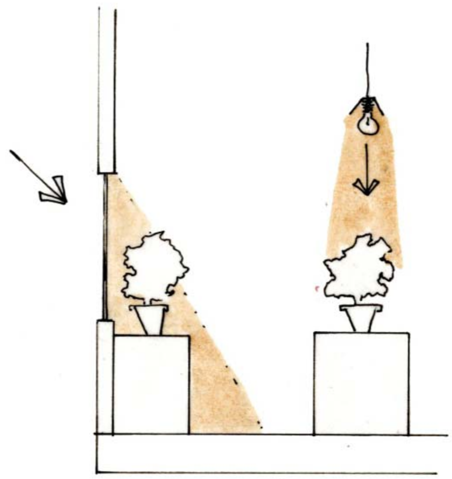

Figure 5.1. Natural and artificial lighting for plant growth, based on distance from a window.

The standard method of growth is in a pot or other soil containment system. Potted plants take up valuable space on countertops and floors, unless a pop-out window is installed, placing plants into the sun while taking up less interior space. This system still needs to support the growth medium and needs to be hand watered.

Artificial methods can provide light and a lightweight growing medium while hydroponic systems can deliver the needed nutrients. The plants themselves can be used for their thermal properties to enhance the building façade and the indoor comfort. This project is combining current research to create a lightweight building component which grows food inside of an apartment without taking up valuable space, while taking advantage of the thermal benefits of plants to enhance the building façade's thermal properties.

A setting for this design product is needed to be an example of how the core ideas from this project can be used on a larger scale in other buildings. Based on the previously described precedent studies and food security information, the Ya-Po-Ah Terrace building in Eugene, OR will be the area of study.

This product is designed to be adaptable to a range of food producing plants which grow well hydroponically. A specific plant, strawberries, is used as the case study plant to allow for a base of knowledge to be researched and designed around. The design specificity around one plant allows the projects viability as a food producing building component to be found. This will allow future research to be done on improving these core ideas.

Design Performance Criteria

In order to grow strawberries successfully in a window assembly, it is important to know what the strawberries need. Strawberries typically require a minimum of six hours of sunlight a day during the growing season for the plants to produce enough sugar to have flavorful berries. The plants should be spaced so that they get the amount of sun they need and since strawberries typically grow to be 10” wide and 6” tall, they can be spaced appropriately in the design so as not to over crowd each other and block essential light (See Figure 5.2) (Loucks, BHG). The amount of light can also affect the temperature of the growing space.

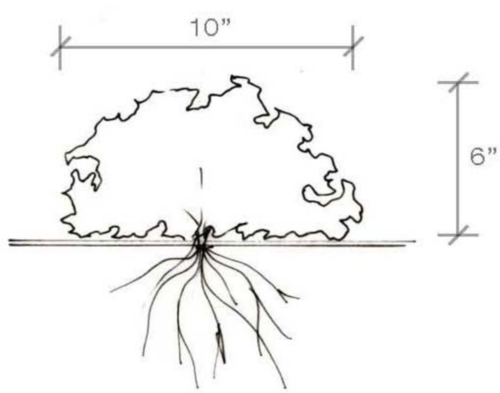

Figure 5.2. Strawberry plant dimensions.

The temperature the plants are grown in has a major impact on strawberry plant physiology and can control when the plants flower (Growing). If temperatures are too high or low, the plants can be kept from flowering, producing no fruit. The berries are also affected by temperature and if greenhouse conditions reach 86F, berries can turn soft and watery. The ideal strawberry growing temperature is 64-77 F (Sarooshi).

The window assembly is therefore designed to be kept within that temperature range. In Eugene, OR, the location of this design, the average winter temperature is 33 degrees F. This means that for the window to act as a greenhouse in winter, producing strawberries out of season, it needs to be roughly 30 degrees hotter than the outside air. In summer the average Eugene temperature is 82 degrees. The air in the growing space needs to not be hotter than the outside air and could benefit from being a couple of degrees lower.

When planting the strawberries, it is important to be aware of their susceptibility to fungal problems. The crown[20] of the plant is where new leaves and flower buds sprout from and should be kept away from damp environments because it will infect and affect the entire plant (Sarooshi). The roots, on the other hand, need to be kept in a moist, nutrient-rich, environment (See Figure 5.3). This environment needs to allow for oxygen absorption by the roots as well as space for waste gases to leave (Simply NFT). This allows air for the roots while keeping the roots from drying out and allows the plant to absorb essential nutrients needed for growth. The nutrient solution needs to flow past the roots, continuously moving to keep the water from pooling and creating areas of stagnation and possible root rot. The solution flow rate can vary but should be kept between 1 and 3 pints per minute (Fernandez).

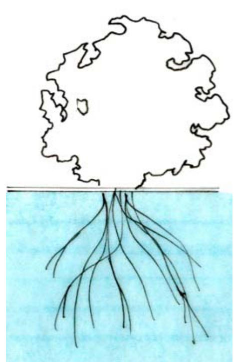

Figure 5.3. The roots of strawberry plants can handle moisture while the crown cannot.

[20] The crown is the main stem of a strawberry plant and it is from there that the leaves and flowers grow.

Strawberries need high levels of potassium for ideal berry growth and the nutrients provided in the solution should reflect these needs. Strawberries grow best when the pH of the water is kept between 5.8 and 6.2 because this allows for the maximum nutrient uptake by the plants (BHG). The nutrient solution needs to be accessible to the user in order for the solution to be tested and altered according to the requirements of the plants. The plants themselves need to be accessible to the user so that the plants can be tended and the fruit can be harvested.

Because of the amount of light needed by the plants and the need to vary the temperature within the plant growth area without negatively affecting the indoor temperature of the living space, it is important that there is a connection with the outside. This allows for sunlight to reach the plants and also for air to be circulated to the outside in summer so as not to increase the indoor temperature un-necessarily. This connection requires attachment to the building façade and needs to keep out unwanted air and water. Air and water can leak into the building as long as there is an opening and a force moving them through the opening. Water penetration can be dealt with by getting rid of the openings, keeping water away from the openings, and getting rid of any forces which would move water. Heat flow is an issue in building assemblies as well because it can cause energy to be wasted by negatively affecting the indoor temperature and can cause water damage by creating condensation in the windows. The window frame connection needs to prevent unwanted exchange of air, water, and heat between the inside of the building and the outside.

This project is designed to be installed within pre-existing construction and should therefore be kept to a minimum weight so as not to stress the existing building structure. It also needs to connect to the existing structure so as not to detach from the building once installed.

Methods of Meeting Performance Criteria

Plant Water and Nutrients

A nutrient solution is required to get the essential nutrients to the plant roots. Of the available methods of nutrient solution delivery, one fits the bill more than most. Nutrient Film Technique (Simply) is a hydroponic system where a shallow stream of water is re-circulated past the roots of the plant. The dissolved nutrients are kept in a water-tight gully so no nutrients are lost. The depth of the gully is variable and can be tailored for use by specific plants based on the size of their roots. The depth of the nutrient solution is a very shallow film, ensuring the roots are not overly saturated. The upper portion of the roots stays moist because of the confined environment with the nutrient solution and is supplied with abundant oxygen due to the thinness of the solution. NFT provides a means of getting abundant nutrients, water, and oxygen to the plant in ideal proportions. Water and air requirements for plants compete with each other in other hydroponic systems. NFT provides a way for all healthy plant requirements to be met at the same time.

Plant Support

The NFT system is able to provide the needed benefits for the plants by using a gully system. The gully is the structure which holds the water and plants, providing a space for them to interact. There are rigid and flexible systems available, depending on the needs for specific plants. Flexible systems are typically a polyethylene film which can collapse against the plants, causing gas exchange problems. The depth of the channel needs to allow for space between plant roots and nutrients to allow for oxygen to enter and to allow for waste gases to leave. Any waste gases which are heavier than air will flow out with the nutrient mixture and return to the storage tank. This tank needs to be properly vented to allow the release of these gases. It is also essential to create a way for the water to run down the center of the gully, typically having a flat channel with a concave base[21], giving the roots space to grow without damming the water. Round pipes are sometimes used for affordability but there is less surface area for the nutrient solution

[21] The concave base is usually ~ 1-2mm.

so when roots grow they raise the water level, shortening the amount of space for oxygen exchange (Simply).

NFT gullies are typically made out of PVC[22], which must be UV stabilized. The PVC used needs to have adequate strength to avoid sagging from happening, which will cause damming. Stronger gullies, depending on the weight of the specific plants and the angle[23] of the system, only need to be supported every 3-4 ft. Weaker gullies will need additional support, which can add to the cost. The angle of the system makes sure nutrients flow down the channel and do not pool or stagnate (Simply).

There exist a range of gully size options based on the root ball size of the plant being grown. Smaller plants, like strawberries, grow well in slightly narrower troughs. The typical size used commercially for strawberries is 4 inches wide by 2.5 inches deep and can be a one or two piece channel[24]. A detachable lid on the gully makes it easily maintained and cleaned (Developments), so that dead plant matter can be removed before it causes blockages or breaks down and enters the nutrient stream. This also allows the grower the option of a variety of growing methods[25] and plant sizes because,

> by using a variety of combinations, of base and lids, as the channel is available in sizes from 4" wide x 1 3/4" deep to 9" wide x 3 1/4" deep, you can grow almost any crop you like using NFT channels (Simply).

Plants are often placed within the gully lid in a "net pot[26]" or just by placing rockwool cubes directly into the nutrient solution[27]. Air pumps and misters are sometimes used in hydroponic systems but misters can have blockage problems because

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[22] Polyvinyl chloride

[23] The standard angle of the gully system is ~ 40:1.

[24] Two piece channels separate the lid and the base.

[25] The lid can be removed to adjust for different plant sizes as well as methods of growth. Plants can be held in the lid of placed directly in the channel in a growing medium.

[26] A net pot is a perforated basket that holds a growing medium that plant roots then grab onto.

[27] Rockwool cubes get dropped through gully lid holes and do not need net pots.

of organic matter and nutrient build-up. The NFT system provides enough space for oxygen to be accessed without misters or air pumps being necessary (Simply).

The net pot system is free-draining media[28] held in a basket and is the best method of keeping strawberry crowns above water in hydroponic systems. The crown can sit above the surface while the roots are allowed to grow downward, accessing the NFT solution through holes in the bottom of the basket. In an NFT system the water travels along underneath the media, allowing the capillary action of the media to draw it up for use[29]. NFT keeps the top surface of the media relatively dry, protecting the crown from moisture while allowing the roots to have access to nutrients. This system is currently used to grow strawberries commercially, with each plant producing an average of one quart of strawberries per fruiting cycle.

Hydroponic systems begin with either seeds or, as with strawberries, runners from the main plant. These need a structure for the roots to dig into to hold the plant upright, which can be any of a variety of growth mediums. Coconut fiber[30] is currently used as a renewable and cost affective growth medium and is used in this project (Knutson).

Thermal Performance

Thermal Mass[31]

Thermal mass can be used as a method to passively heat and cool a building. The mass acts as heat storage, absorbing heat during the day when the air is a higher temperature than the mass, and releasing the heat at night when the air is a lower temperature than the mass (See Figure 5.4).

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[28] Some common free-draining media options are gravel, scoria, expanded clay, rockwool, and coconut husk.

[29]Make sure to presoak the media in pH balanced water for at least half an hour before using because dry media will suck all the moisture from plants roots. (Simply)

[30] See Appendix B on Coconut Fiber for further research.

[31] See Appendix G on Passive Heating and Cooling for further research.

Figure 5.4. Heat flow through thermal mass.

This tames the temperature fluctuations which typically happen throughout the day and provides a more stable and comfortable interior temperature. The thermal mass can be designed to heat specific rooms or to act as heat storage for a larger area. This project focuses on using thermal mass to provide stable temperatures within the greenhouse space, giving heat to the plants at night and keeping them from over-heating during the day. The mass itself can be a variety of things, chiefly masonry or water (See Table 5.1). Water is more efficient than masonry and is used accordingly in this project.

Material	Thermal Conductivity (Btu/hr-ft-°F)	Recommended Thickness (in.)	Approximate Indoor Temperature Fluctuation as a Function of Thickness[1]					
			4 in.	8 in.	12 in.	16 in.	20 in.	24 in.
Adobe	0.3	8-12	…	18°	7°	7°	8°	…
Brick (common)	0.42	10-14	…	24°	11°	7°	…	…
Concrete (dense)	1	12-18	…	28°	16°	10°	6°	5°
Brick (magnesium additive)[2]	2.2	16-24	…	35°	24°	17°	12°	9°
Water[3]	…	6 or more	31°	18°	13°	11°	10°	9°

[1] Assumes a double-glased thermal wall. If additional mass is located in the space, such as masonry walls and/or floors, then temperature fluctuations will be less than those listed. Values given are for winter-clear days.
[2]Magnesium is commonly used as an additive to brick to darken its color. It also greatly increases the thermal conductivity of the material.
[3]When using water in tubes, cylinders or other types of circular containers, use at least a 9 1/2-inch-diameter container of 1/2 cubic foot (31.2 lb or 3.74 gal) of water for each one square foot of glazing.

Table 5.1. Temperature fluctuations with thermal mass (Foster).

The thermal mass of this project is in the form of a water tank at the base of the system, holding the nutrient solution needed for the plant growth (See Table 5.2). This acts as thermal storage for the greenhouse specifically, re-radiating heat only to the plant growing area. The heat from the base rises up and heats the whole greenhouse space at night, aiding in circulation by creating convection currents. When the exterior windows of the system are opened, the mass helps to create better circulation.

The thermal mass may be only re-radiating heat into the greenhouse space but that re-radiation creates a buffer between the interior and the exterior of the living unit in which this project is installed. By having a hotter night temperature within the building envelope, less heat is lost from the interior through the window in winter. Similarly, less heat is allowed to enter the interior space in summer because the plants and thermal mass are absorbing heat and blocking direct sun from entering the inhabited space. The plants and thermal mass combine to create an insulated building component which aids in the thermal function of the building façade.

Material	Recommended Thickness (in.)
Adobe	8-12
Brick (common)	10-14
Concrete (dense)	12-18
Water	6 or more

Table 5.2. Suggested thermal mass thickness (Foster).

Window Frame Assembly

The connection between the new window unit and the building is extremely important because it is where there is the most possibility of unwanted water and air penetration. The water can leak into the building as long as there is an opening and there is a force moving the water through that opening. There are multiple ways of combating water penetration, chiefly getting rid of the openings, keeping water away from the openings, and getting rid of any forces which would move water into the openings.

Openings in buildings are typically dealt with by using sealants and gaskets[32] which, when used "as a sole strategy…is unreliable" due to a number of factors[33] which can keep them from sealing properly or deteriorating over time. A "building skin that relies on sealants and gaskets alone for water-tightness will leak sooner or later" (Allen 5)

[32] "Sealants and gaskets are elastic materials that can be placed in a joint to block the passage of air and/or water while allowing for relative movement between the two sides of a joint. A gasket is a strip of synthetic rubber that is compressed into the joint. Most sealants are mastic materials that are injected into the joint and then cure to a rubberlike state. A gasket seals by adhering tightly to the surface" (Allen 35).

[33] Gaskets do not always seal correctly. This can be because it was not sized correctly, it was not with the correct amount of pressure, or that it was installed on the wrong kind of surface. Aging buildings and weathering can cause cracks and deterioration (Allen 5).

but when used correctly in conjunction with other components they can be successfully applied to eliminate water leakage.

A key component of controlling water penetration is keeping water away from the assembly. There are a variety of details pertaining to water control: wash[34], overlap[35], overhang and drip[36], drain and weep[37]. This array of details allows specific window assemblies to be made which can deal with the amount and type of possible water penetration for the specific window location and use, depending on the types of forces moving water into the assembly. The kinds of forces are: gravity[38], surface tension[39], capillary action[40], momentum[41], and air pressure difference[42]. A combination of details neutralizing these forces "can make a building entirely waterproof" (Allen 6). These building components can be incorporated along with other components meant to provide an air barrier or heat flow barrier.

Heat flow in building assemblies can create discomfort for building inhabitants, causing energy to be wasted by heating or cooling more air than should otherwise be necessary. It can also cause water damage because of condensation in windows. There

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[34] A wash "is a slope given to a horizontal surface to drain water away from vulnerable areas of a building". The slope can depend on the material used and more permeable materials should have a steeper slope to shed water faster" (Allen 7). A slope of about 1 inch per foot is a minimum slope for a window wash assembly.

[35] "In an overlap, a higher surface is extended over a lower surface so water moved by the force of gravity cannot run behind or beneath them. For an overlap to work, the surfaces must be sloping or vertical. Porous materials need a greater overlap and steeper slope to be affective" (Allen 12).

[36] "Adhering drops or streams of water running down the wall of a building can be kept away from an opening in the wall by a two-fold strategy: creating a projecting profile just above the opening and creating a continuous groove or ridge in the underside of the projection so that gravity will pull the adhering water free of the overhang" (Allen 14).

[37] This is a system which provides a back-up in case the previously mentioned methods fail at some point and water finds its way into the window assembly. "An internal drainage system is comprised of spaces and channels that conduct water by gravity to weep holes or other openings that direct the water back outdoors" (Allen 18).

[38] Gravity is neutralized with the wash and overlap details.

[39] Surface tension is dealt with in an overhang and drip system.

[40] Capillary action is dealt with in a capillary break detail.

[41] Momentum is dealt with in a labyrinth detail.

[42] Rainscreen and upstand details work against air pressure difference

are “three basic ways of minimizing heat transmission and maximizing thermal comfort” (Allen 49). The conduction and radiation of heat through the building envelope can be controlled and thermal mass can be used to regulate the heat flow.

The conduction of heat is typically dealt with in the wall system using insulation but is also dealt with in window assemblies by using thermal breaks[43] and multiple glazing details. Thermal breaks should be included in any assembly that connects the inside to the outside. In the case of this project, that is the window frame. An aluminum window frame conducts heat easily, causing problems[44] when the aluminum goes continuously from inside to outside. This has been dealt with by using thermal breaks within the aluminum members to bridge the inside and outside parts of the assembly with a low-conductivity material[45].

Glass is a bad thermal insulator, with a single sheet of glass “conducting heat about 20 times as rapidly as a well-insulated wall” (Allen 55). The glass can be layered to create spaces between the sheets of glass to provide more of a thermal buffer, with double glazing[46] only allowing in half of the heat flow as single glazing. “The thickness of the airspace, provided it is at least 3/8 inch, makes relatively little difference in its insulating ability” (Allen 55). The type of coating applied to the surface of the glass, on the other hand, can have a significant impact on the insulating quality and the amount of direct sunlight that gets reflected off of the window. There are multiple options available to reflect different amounts of solar energy, among those are clear glass[47], tinted glass[48], reflective glass[49], and invisible low-emissivity (low-E) glass[50].

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[43] “A thermal break is a strip of insulating material that is inserted into a building assembly to prevent rapid heat conduction through dense, highly conductive materials such as metal and masonry” (Allen 51).

[44]Water can be a problem in cold winter environments because water and frost can condense on the inside surface.

[45] One example of this is a hard plastic which is cast “into a groove in the aluminum member during manufacture. Then the groove is debridged (the thermal bridge is removed) by milling away the aluminum at the bottom of the groove. This leaves only the low-conductivity plastic thermal break to connect the indoor side of the member to the outdoor side” (Allen 52).

[46] A “second sheet of glass is added with an airspace between the two sheets” (Allen 55).

[47] Clear glass allows most of the sunlight hitting it to be transmitted to the interior space.

These options can be specifically tailored in a multiple glazing system to provide the correct amount and type of light for plant growth while keeping radiant heat from entering the inhabited space. The layer between the plants and the living space can reflect radiant energy back onto the plants and the thermal mass wall, having the double benefit of providing more light and heat where it is wanted in the middle of the greenhouse space while keeping unwanted light and heat from entering the inhabited space. These options can be used to create the ideal growing environment for the plants, allowing the proper amount of heat and light into the greenhouse space and creating a buffer to the interior.

Summary

The research into current building technology and available materials allows for the design process to happen. The design focuses on creating a specific habitat for plants and using that habitat to create a better building envelope. This chapter showed the variety of materials and methods available for research while the next chapter goes into detail about how these alternatives are used to create the food producing window unit.

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[48] Tinted glass reduces the amount of solar heat transmission but still passes most of the absorbed heat into the space.

[49]Reflective glass has a metallic coating on one surface which reflects solar heat before it enters the space and is "extremely effective in maintaining comfortable interior temperatures at a low cooling cost" (Allen 57).

[50]" Invisible low-emissivity (low-E) coatings also reflect radiant energy but allow more of it to enter than most types of reflective glass" (Allen 57).

CHAPTER VI

PRODUCT DESIGN

Introduction

The reasons for the project and subsequent research into methods of responding to those reasons led to a design prototype. This digital prototype is an example of how the resolve issues of food growth in an apartment and is placed within the existing context of the before mentioned case study, the Ya-Po-Ah Terrace (See Figure 6.1). There are a number of systems working together to make this project work and each system is described separately in this chapter in order to better understand how these systems work together within the project.

The project is broken up into three distinct zones (See Figure 6.2). Each zone has a different function and is designed accordingly. The top two feet of the prototype are used purely as a means of getting light into the inhabited room in winter and keeping it out in summer. This has a lightshelf and a shading device to accomplish these goals. The middle section of the prototype focuses on plant growth and their needed environment. The bottom section of the prototype is a water storage tank. Together these three zones comprise the entire project.

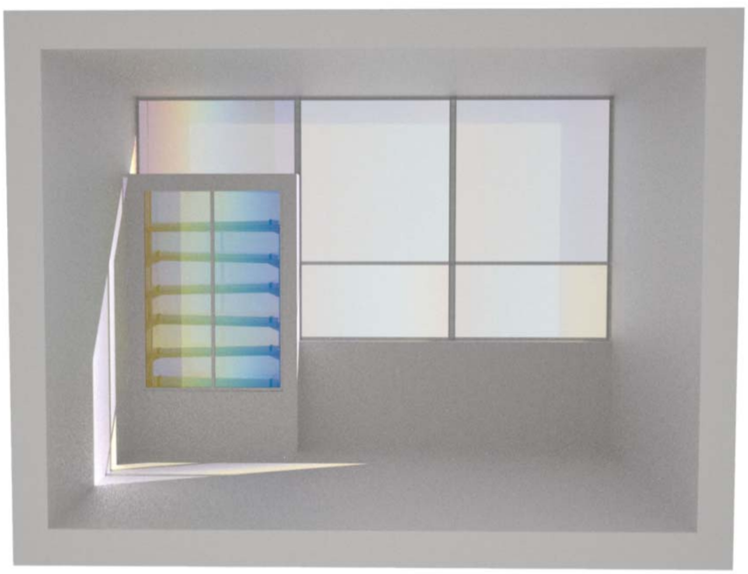


Figure 6.1. The prototype within the context of an apartment at the Ya-Po-Ah Terrace. The design is a retrofit which takes up one window bay out of three existing windows.

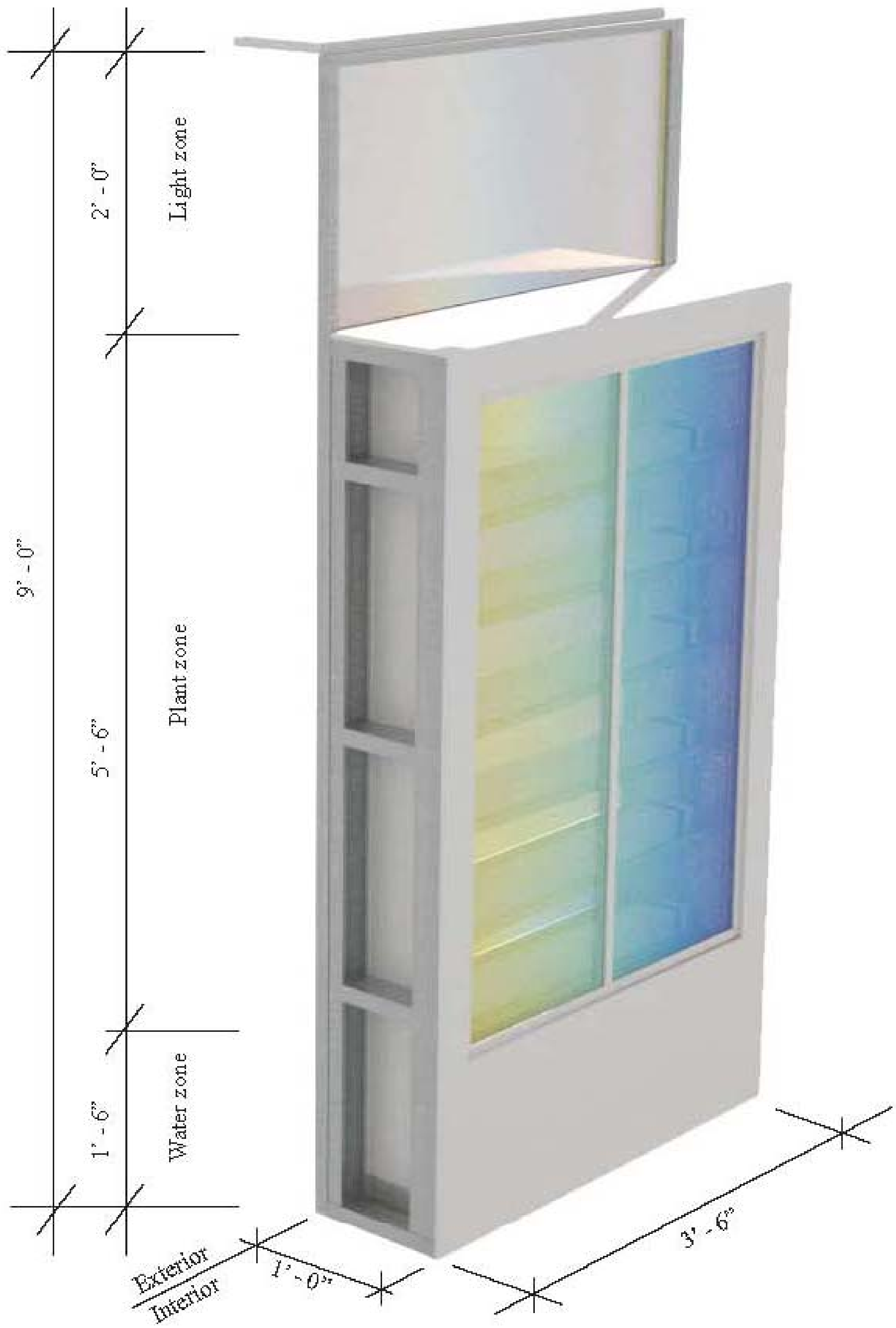


Figure 6.2. The prototype as a whole with all systems included: structure, glazing, gullies and associated support, water and nutrients, and lightshelf.

Gully System

Introduction

The gullies give support to the plants and provide a way for the plant roots to access the nutrient solution (See Figure 6.3).

Figure 6.3. Gullies within the system as a whole.

Gullies are the channels within which the water and plants are held and brought together (See Figure 6.4). These are a standard component of NFT hydroponic systems and are made out of UV stabilized PVC. Strong PVC only needs to be supported every 4 ft.. This prototype is 3.5 ft. in length, needing no additional structural support besides that provided along the outside edges of the design. This keeps the interior space open for access of the plants.

The gullies are installed at an angle of 1:40. This makes sure nutrients flow down the channel and do not pool or stagnate. Because of the length of the system is 40", this means a 1" drop from end to end of the gully. This vertical change is adjusted for in the support system.

The gully itself is 4" wide x 2 1/2" deep, running the length of the prototype. The size is a response to the small root ball of the strawberry plant, allowing it to grow in a narrow trough. For plants with significantly larger root balls, it will be necessary to change out the gully. The design can accommodate a variety of gully sizes up to 9" wide x 3 1/4" deep, which is the largest size currently available. The support system is designed to accommodate a variety of gully sizes.

The gully is a two part system, with a base holding water and a lid holding the plants. The lid is detachable, allowing it to be changed when a different variety of plants is grown. If the roots are the same size then there is no need to change out the entire gully system. The leaf canopy of the plant may require different spacing between plants, requiring the lid to be switched. The detachable lid also makes it possible to maintain the gully by cleaning the inside and removing any dead plant matter which may have gotten into the system before it causes blockages or breaks down and enters the nutrient stream.

When starting strawberry plants, the roots are not long enough initially to reach the nutrient film at the bottom of the gully. This requires a net pot system to be used until the plants are old enough to reach the water. The net pot is simply a perforated basket filled with coir, bringing water up to the roots. This provides both air and water to the plant while keeping the crown of the strawberry plant above the gully system and out of the wet air.

The net pots are removed once the roots are long enough to reach the nutrient film. This leaves the roots free to access water and air without being held in now unnecessary basket. The net pots require a 2” diameter hole in the lid of the gully and, once removed, need to be plugged. A foam disk 1/2” thick is designed to fill these holes and to hold the stem of the plant in place. This keeps the plants structurally stable while not allowing any of the nutrient solution to evaporate through holes in the gully.

Figure 6.4. Gully Drawings

Gully Details

The gully has a base for containing the liquid and a lid for holding the plants and keeping water from evaporating out. The lid is detachable for ease of maintenance and to change when plants change and need different spacing (See Figure 6.5). By removing the lid it is possible to swap out the plant varieties without changing the entire gully system.

Figure 6.5. Gully and lid separation

Holes are cut out of the lid of the gully, allowing plants to be placed with access to water and air. These holes are placed along the center of the gully and spaced 10” apart to give strawberries the space they need (See Figure 6.6). The gully itself is 4” wide and is flanked by a 3” air space on either side, giving the plants a 10” circle of space in which to grow.

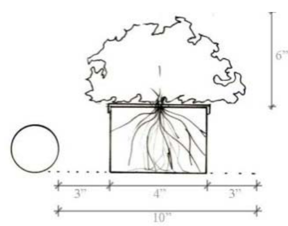


Figure 6.6. Plant dimensions

Starter strawberry plants are too small to reach the water film in the base of the gully. These are instead planted in a perforated basket system which is filled with coir. This brings water and air to the roots until they grow long enough to reach the water themselves (See Figure 6.7).

Figure 6.7. Starter plants in net pots transitioned to free-standing plants

Once no longer needed, the baskets are removed and replaced with a 2” foam disk which envelops the plant stem, giving it stability while allowing the roots to be unencumbered within the gully (See Figure 6.8). The disk separates the plant parts, keeping the crown above the gully lid and the roots below the lid in the water environment.

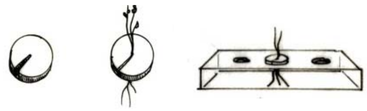


Figure 6.8. Disks for plant support

Gully Support and Attachment

Introduction

The gully attachment piece secures the gully to the wall while also being moveable in the event that the gully should need to change size or location (See Figure 6.9).

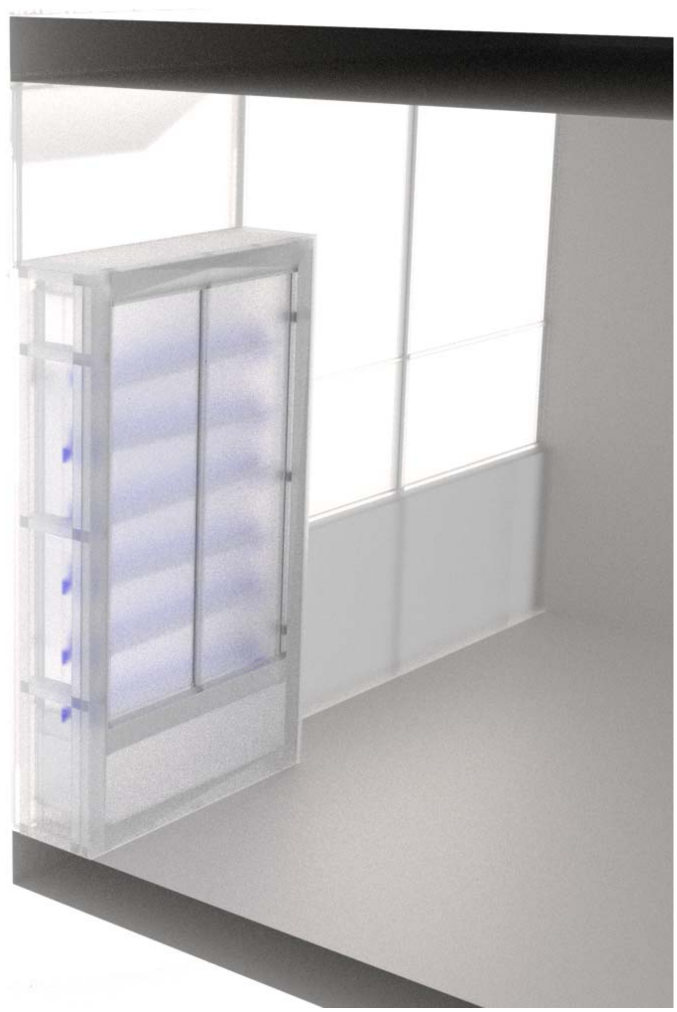


Figure 6.9. Gully attachment pieces along the walls of the system.

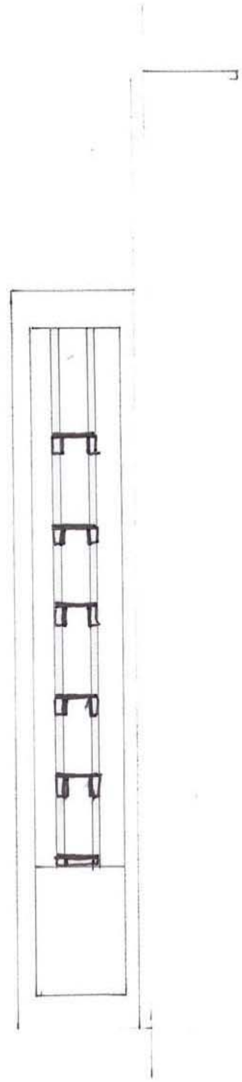
The gully system is inherently strong enough to not need additional structure and support besides the basic attachment of the gully to the sides of the prototype. This attachment system is designed purely to hold the gully in place and to attach it to the walls on either side of the prototype. The gully for growing strawberries is 4” wide x 2 1/2” deep but may change depending on what other plants are grown. The support and attachment methods are versatile in order to be used for any possible gully size.

The support itself is a horizontal 4” square 1/4” steel plate with triangular vertical steel plates welded underneath to keep the main plate from bending. The horizontal plate has a 2” wide x 1” long section cut out of it to provide space for the plumbing which is running vertically along the wall. this fits around the pipes without needing to remove them in order to change the position of the gullies.

These vertical plates provide the attachment surface needed to screw the horizontal support piece onto the wall. The support screws into a pre-drilled vertical steel strip which runs without stop from the top of the prototype at 7’ from grade to the top of the water tank at 18” from grade. This allows the gullies to be installed at any point vertically within those dimensions, keeping it within the range of average human movement (See Figure 6.10).

The gully rests on the horizontal plate and is kept in place with an adjustable strap which wraps around the gully. This belt is attached to both sides of the horizontal plate and can be adjusted to accommodate gullies of various sizes. The belt itself is made of flexible water proof fabric which will not be affected in the moist conditions within the greenhouse space. It will also keep the gully secure from unwanted movement in the case of someone accidentally knocking into a gully of the weight of plants shifting the gully position.

Plan _ 3/4"=1'



Side Elevation _ 3/4"=1'

Front Elevation _ 3/4"=1'

Figure 6.10. Gully Attachment Drawings

Gully Attachment Detail

The gully system is attached with a belt system to a steel plate. Vertical supports keep the steel plate from bending and give space for screws to attach the support to a vertical attachment bar (See Figure 6.11).

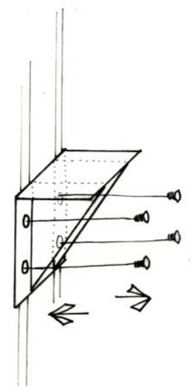


Figure 6.11. Attachment steel piece mounted to the wall

The vertical bar has pre-drilled screw holes every inch to allow the support system to move if the gully needs to be placed higher or lower along the wall (See Figure 6.12).

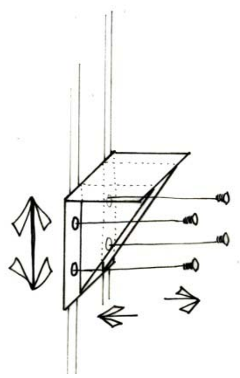


Figure 6.12. Attachment steel piece moving on the wall to adjust spacing

A space is notched out of the plate, allowing the water pipes to travel vertically from gully to gully.

Plant Water and Nutrients

Introduction

The nutrient solution is held in a tank at the base and pumped up into the gully system so that it can feed the plant roots (See Figure 6.13).

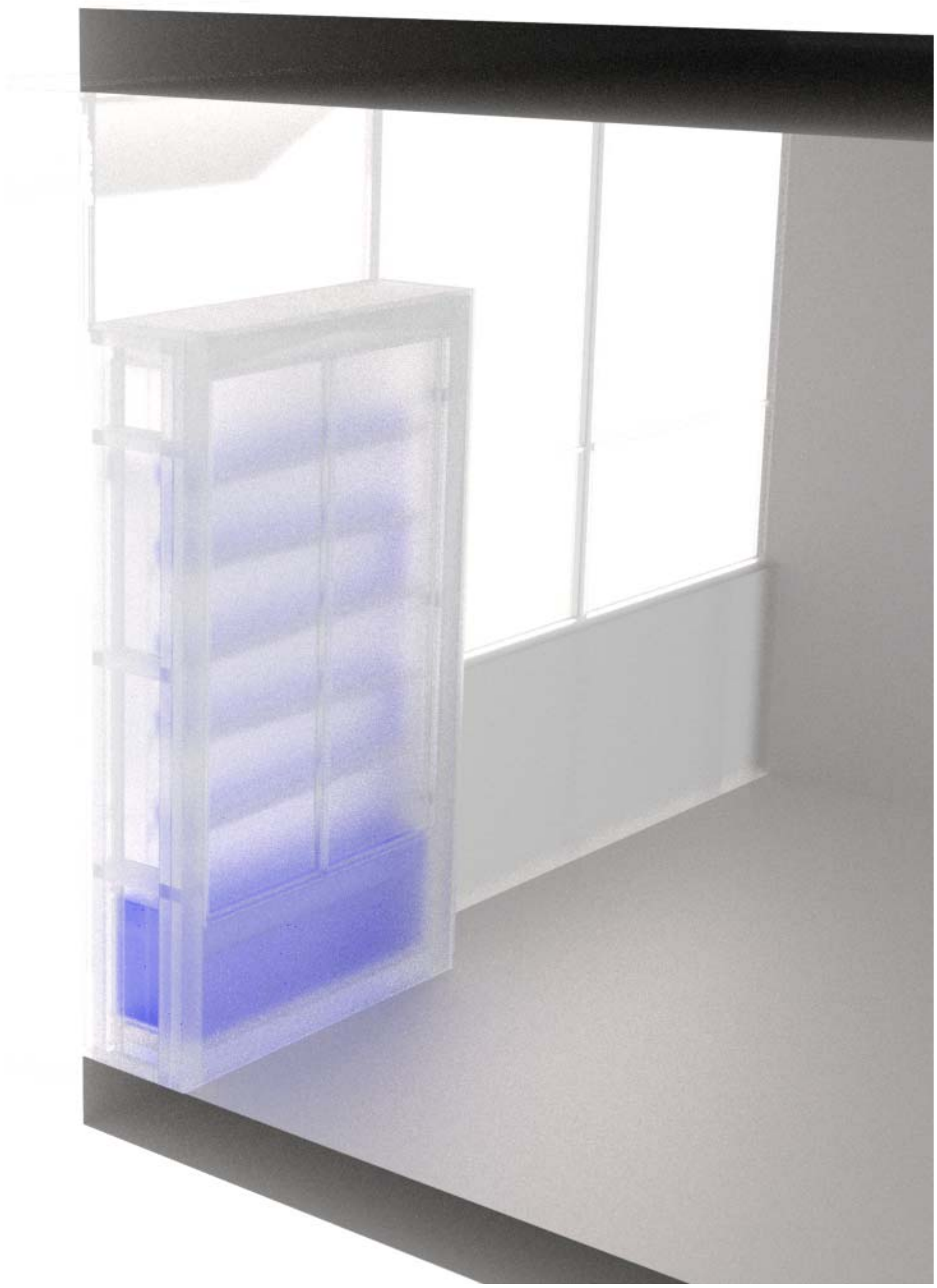


Figure 6.13. The water tank and the gullies holding the water.

Water is held in a black PVC tank at the base of the prototype (See Figure 6.14). The tank has a covered opening on the top which serves as a place to add nutrients to the water. The nutrient solution is then pumped up to the highest gully with a Bermuda 1000 pond pump which provides the right amount of pressure to meet the 1-1.5 liter/minute flow rate required for optimal plant growth.

The pump is hooked up to a 1” PVC pipe which goes through a sealed hole in the top of the tank and connects with a plastic seal in the top gully. Here the water runs along the base of the gully in a thin stream, hitting the plant roots. The gully angle of 1:40 keeps the water flowing from one end to the other and funnels the water into a 1” PVC pipe at the lowest point of the gully. This nutrient solution is then taken straight down to the next gully and the process starts again. The water is run through each of the six gullies. At the end of the last gully the water is dropped through a 1” PVC pipe into the water tank where it is recycled into the system. The NFT system requires a constant flow of water to be cycling along the plant roots.

Nutrient and salinity gauges are mounted within the water tank so that the user can keep tabs on the level of nutrients and salt within the water. This makes it obvious when new nutrients need to be added to the water solution and if salt build up has occurred. If this happens, steps can be taken to bring the salinity back within the acceptable range.

The tank is placed on top of a steel stud structure providing stability to the system as a whole. This puts the tank 3” off grade of the apartment. The top of the tank is determined by a standard seat height and the associated range of motion for providing an accessible plant.

The water is also acting as thermal mass within the greenhouse space, collecting heat during the day and releasing it at night to keep the plants from having extreme temperature swings. Water weighs 62.3 lbs./cubic foot, meaning that the water within the 15” tall x 8” thick x 3’ - 6” wide tank weighs roughly 200 lbs. This provides a mass of water to collect heat for the plants. A 1” air gap is provided between the water tank and the exterior glazing. This allows for heat to collect and move upward, becoming part of a convection cycle which vents out of the operable windows in summer and collects warmth in winter.

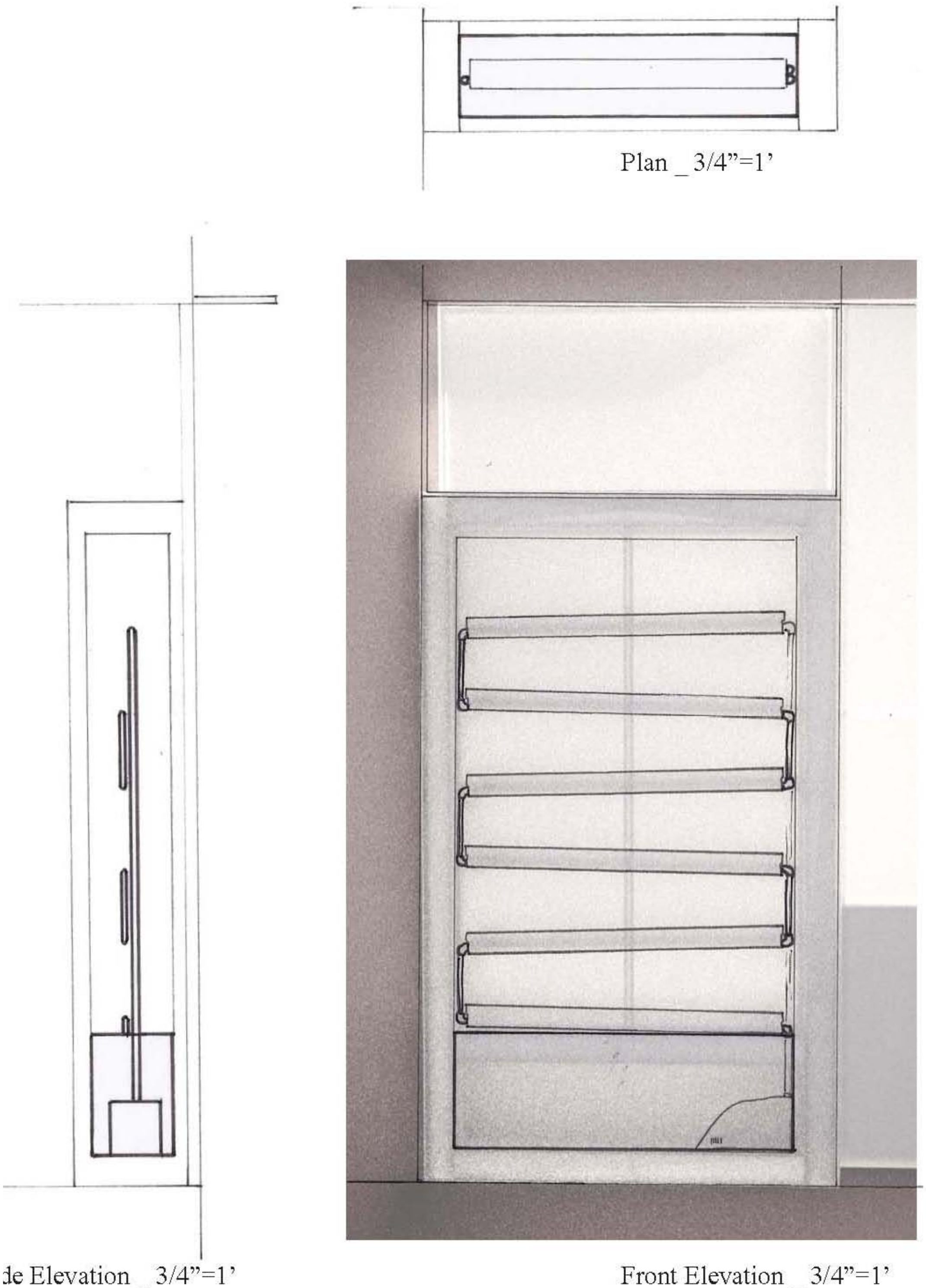


Figure 6.14. Drawings of the water tank and the gullies holding the water.

Water Details

Water is stored in a 10” wide x 3’ long x 16” tall tank made of black PVC (See Figure 6.15).

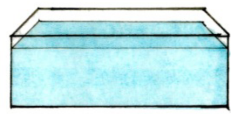


Figure 6.15. Water tank

A place is provided to add nutrients to the water (See Figure 6.16).

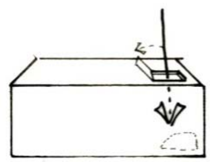


Figure 6.16. Nutrient addition to the water tank

A pump takes the water up to the high point of the top gully in a 1” diameter PVC pipe and releases it into the gully system. The pipes are attached with plastic seals onto the gully, keeping the system water-tight. The water flows from the low end of one gully to the high end of the next gully directly under it (See Figure 6.17). This is done with 1” PVC pipes which seal to the gullies with a plastic seal and keep them water tight.

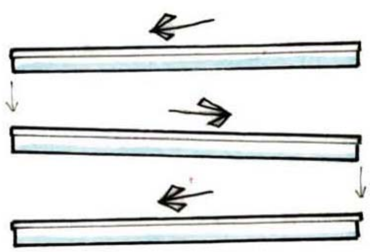


Figure 6.17. Water flowing down the gully system

Handrails

Introduction

Handrails provide a secure method of harvesting the berries without damaging the gully system and provide a sense of security when leaning into the window (See Figure 6.18).

Figure 6.18. Handrails inside the system as a whole.

Handrails are provided to ensure a sense of security when using the prototype (See Figure 6.19). They give less mobile people something to hold onto while maintaining and harvesting the plants. They also provide something to rest on so that a person leaning into the system will not inadvertently hit the gully system and jeopardize the structural integrity of the gullies. The handrails provide the knowledge that one using the system could lean in without worry of hitting something delicate.

Because the handrails are provided for mobility, they are designed according to ADA handrail standards. They are 1-1/4” diameter brushed steel pipe and have a 1-1/2” open air space between the handrail and the gully. This gives room for a hand to grab the bar without hitting the gully.

The handrails are placed as frequently as the gullies and are installed so that the bottom of the handrail is level with the bottom of the gully. This provides a consistent horizontal aesthetic without the addition of multiple lines cluttering the prototype. By lining up with the base of the gully instead of the top, it provides additional space for plant foliage.

The handrails are attached to the walls on either side of the prototype. A vertical pre-drilled 1/4” thick steel plate is attached to the wall into a steel stud, providing a secure base onto which the handrails are attached. The pre-drilled holes are spaced every inch so they can match the gully spacing and can move if the gullies change position.

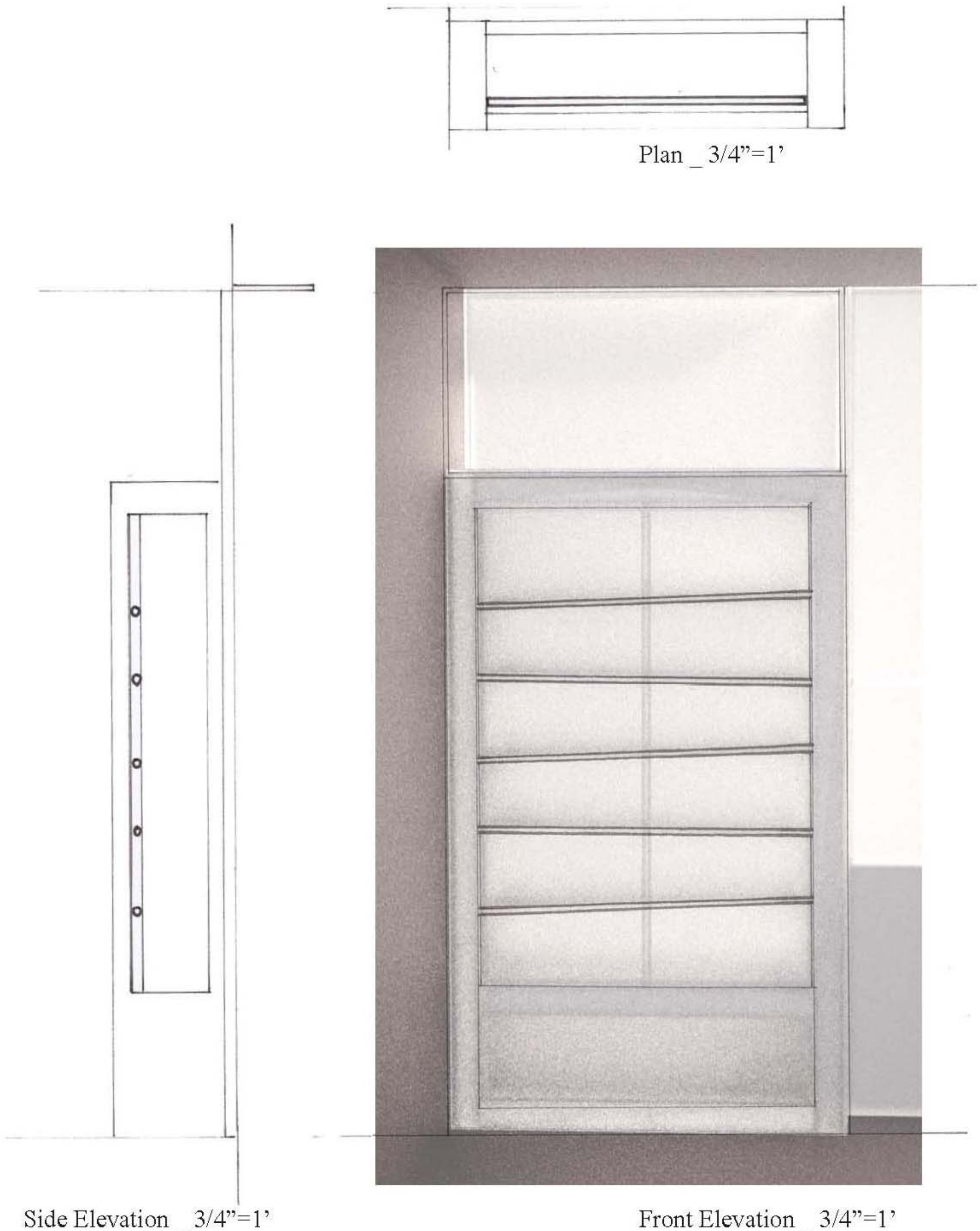


Figure 6.19. Handrail drawings

Handrail Details

Hand rails are provided in order to allow for more security in mobility when accessing the plants. These also give support as something to rest on so as to not push on the gully system and give a place to clip on a basket for harvesting the strawberries. The handrails are 1-1/4” in diameter and are placed 1-1/2” away from the gully system, all according to ADA handrail specifications.

The handrails are at the same angle as the gully so that they do not provide a confusing amalgamation of horizontal lines within the entire system (See Figure 6.20).

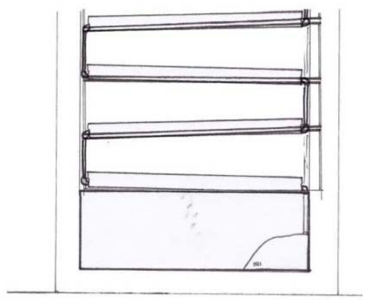


Figure 6.20. Handrail angle

The handrails are screwed to a pre-drilled vertical support which allows for their movement whenever a gully needs to be moved (See Figure 6.21). This also connects them to the structure of the wall, providing a stable base.

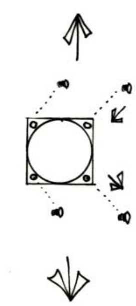


Figure 6.21. Handrail attachment

Lightshelf

Introduction

The lightshelf reflects light into the inhabited space while simultaneously acting as a roof for the greenhouse space below it (See Figure 6.22).

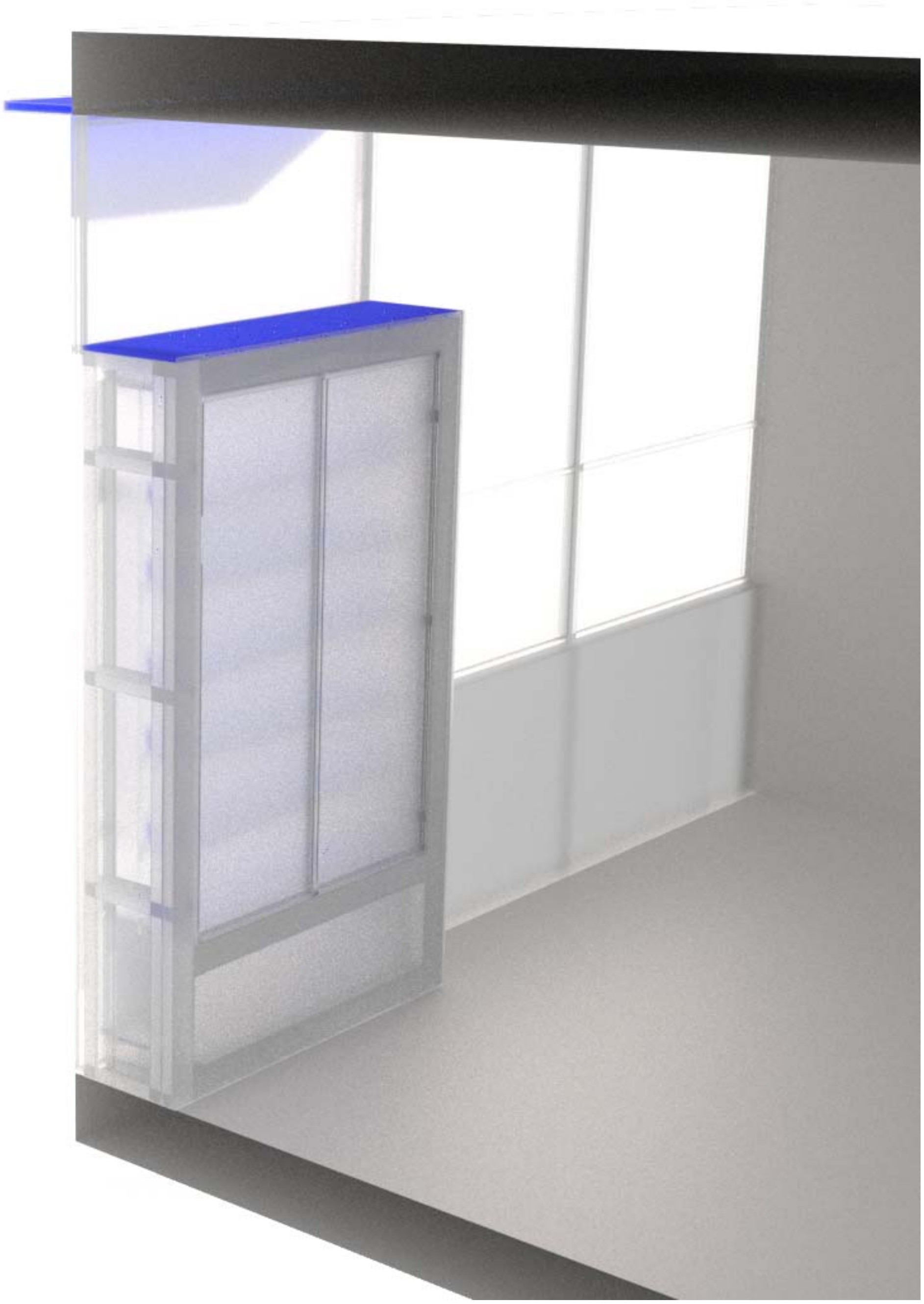


Figure 6.22. Lightshelf within the system.

A lightshelf is used on the top of the planting zone as a means of bringing light farther into the inhabited space. A shading device placed on the exterior of the building and at the top of the prototype keeps direct light in summer from getting to the lightshelf, and therefore from heating up the space. The lightshelf is the depth 12", covering the greenhouse space completely so that it becomes a distinct enclosed space (See Figure 6.23).

The surface of the lightshelf is a rough white paint so have light reflect as much as possible in a fragmented form. The diffused light is then reflected back onto the ceiling further into the space, providing more day lighting and less need for artificial light.

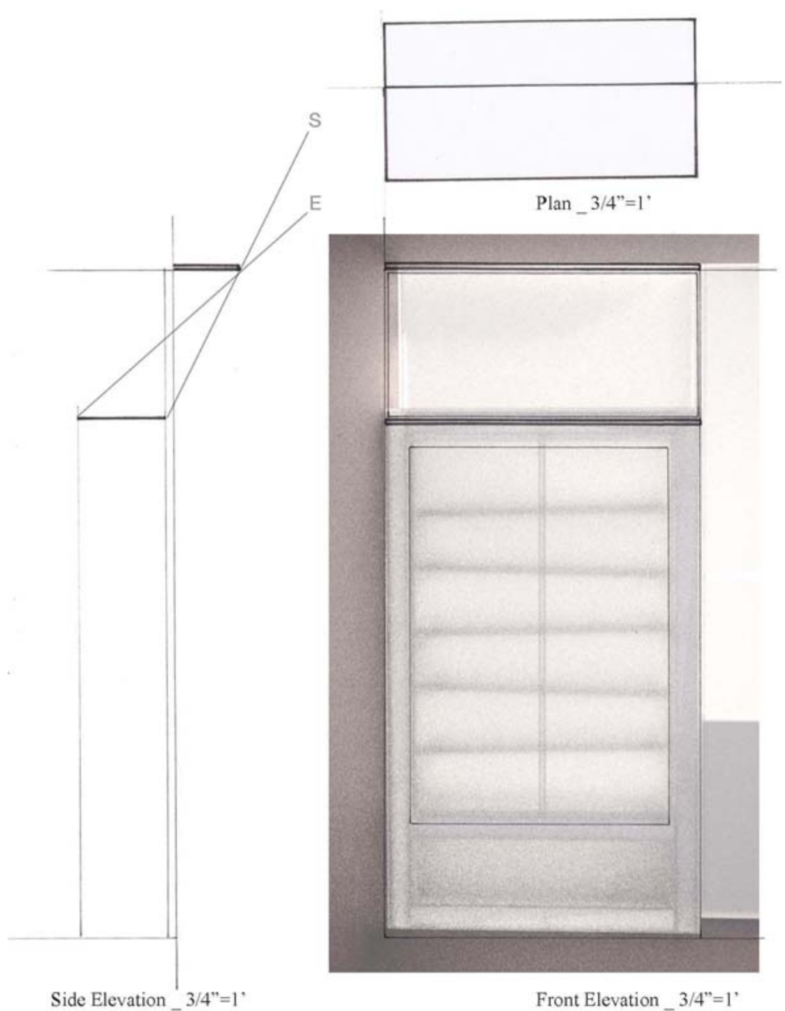


Figure 6.23. Lightshelf drawings

Lightshelf Details

A shading device is used to prevent sunlight from entering the interior space in summer, keeping out excess heat (See Figure 6.24).

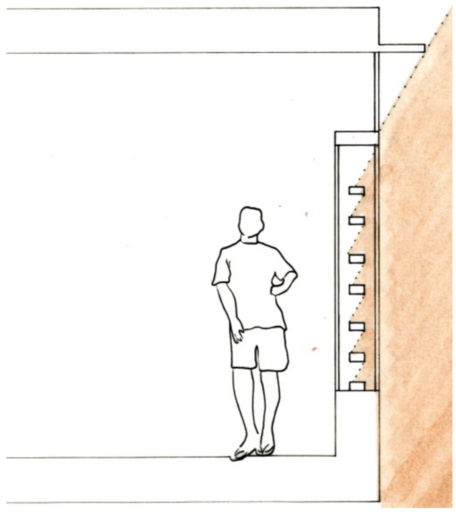


Figure 6.24. Shading device blocking harsh summer sun

The lightshelf is a foot long, keeping direct light from hitting the floor of the space from the spring equinox to the fall equinox. Direct light enters the floor area of the space in the colder months surrounding winter. During all of these seasons the light is being reflected onto the ceiling and spread farther in the interior space (See Figure 6.25).

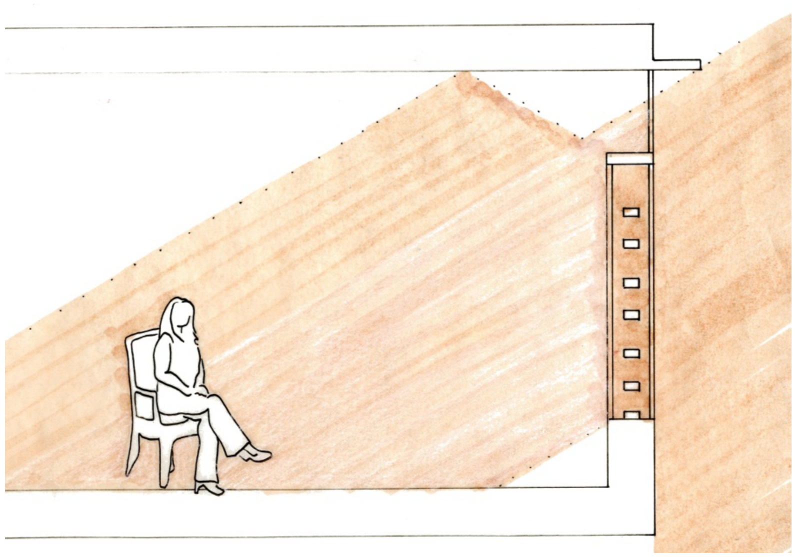


Figure 6.25. Lightshelf reflecting sunlight farther into the space in winter

Glazing

Introduction

Glazing is a key component in determining how much light and heat get into the building and the greenhouse space (See Figure 6.26).

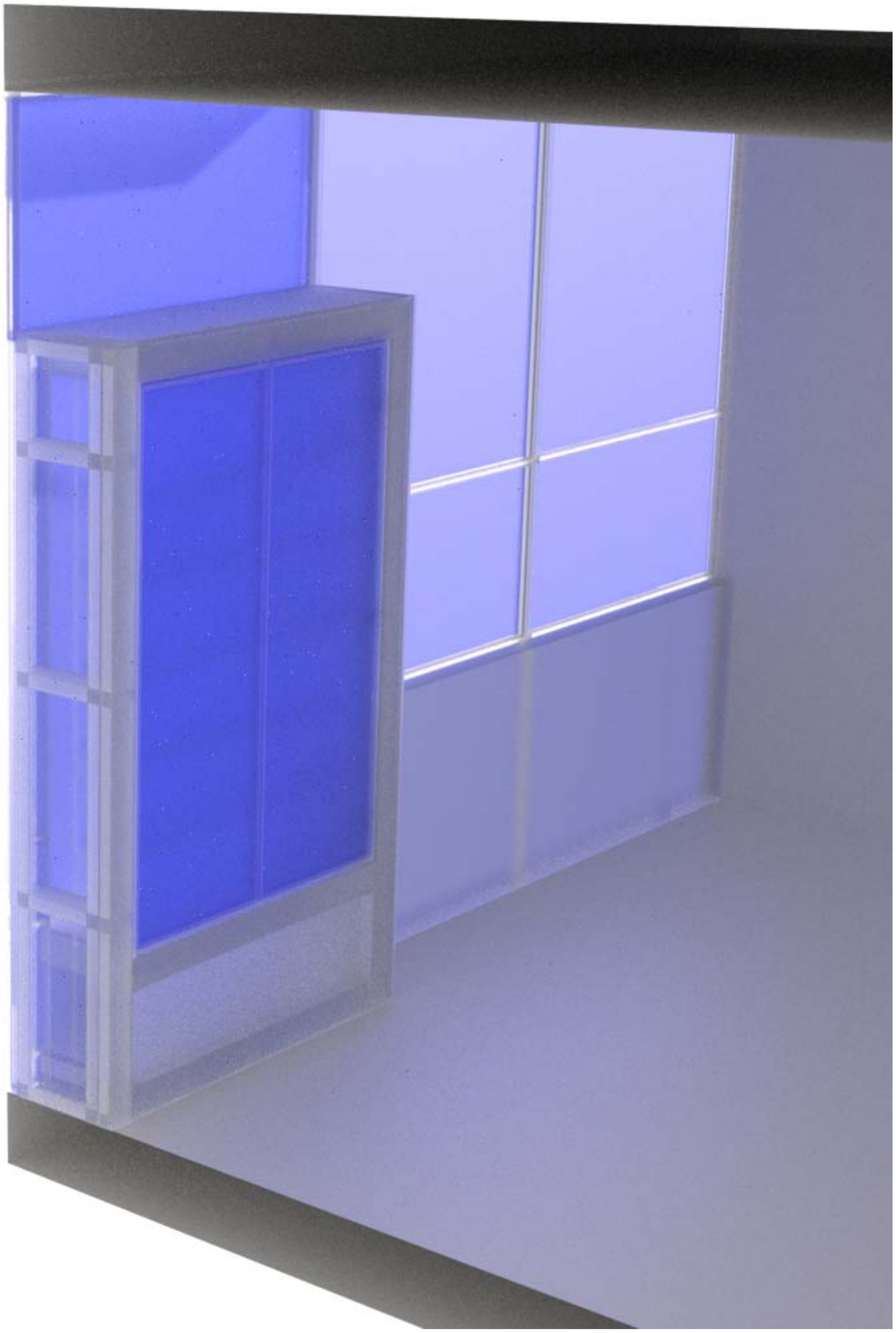


Figure 6.26. Glazing within the entire system.

The windows in this prototype are designed to act as thermal barriers between the interior and exterior of the building (See Figure 6.27). The top portion of glazing, used for the lightshelf, is an inoperable double paned glass window used purely for light. This extends from the wall of the apartment to where it meets up with the existing facade glazing being left in place. The existing glazing is single paned and it is recommended that these be changed as well to provide for the thermal comfort of the inhabitants.

The glazing within the greenhouse zone of the prototype is also a double paned system. There are two different glazing conditions within this one zone. One condition is between the exterior of the building and the interior of the greenhouse space. This allows in as much light as possible to the plants. There are two operable hopper windows placed within this condition to allow for summer ventilation. The bottom hopper window is placed at the top of the water tank, allowing the window to be accessible. This window is 10” tall. The second window is at the top of the greenhouse space and is 14” tall, allowing the handles at the base of the window to be accessible. These act as the ventilation and can be closed in winter to keep in as much heat as possible.

The second condition in the glazing system of the greenhouse space is between the interior of the greenhouse space and the interior of the building. This glazing is meant to reflect light and heat back into the greenhouse space without allowing heat to enter into the inhabited space. This makes the greenhouse a completely separate enclosed space which is not negatively affecting the interior comfort for the inhabitants. This condition is where the inhabitants access the plants and is a bi-fold window which can be tucked to the wall of the apartment, allowing the greenhouse space to be completely open to the interior of the building. The bi-fold design makes it easily opened by people with limited mobility.

The walls of the prototype butt up to the facade and have a different glazing condition from any of the open glazing conditions. These areas are not allowing light to penetrate and are instead a tinted glass, keeping the same window aesthetic without revealing the structure of the wall to the outside. This matches the existing facade of the Ya-Po-Ah Terrace which has portions of tinted glass to hide walls within the facade.

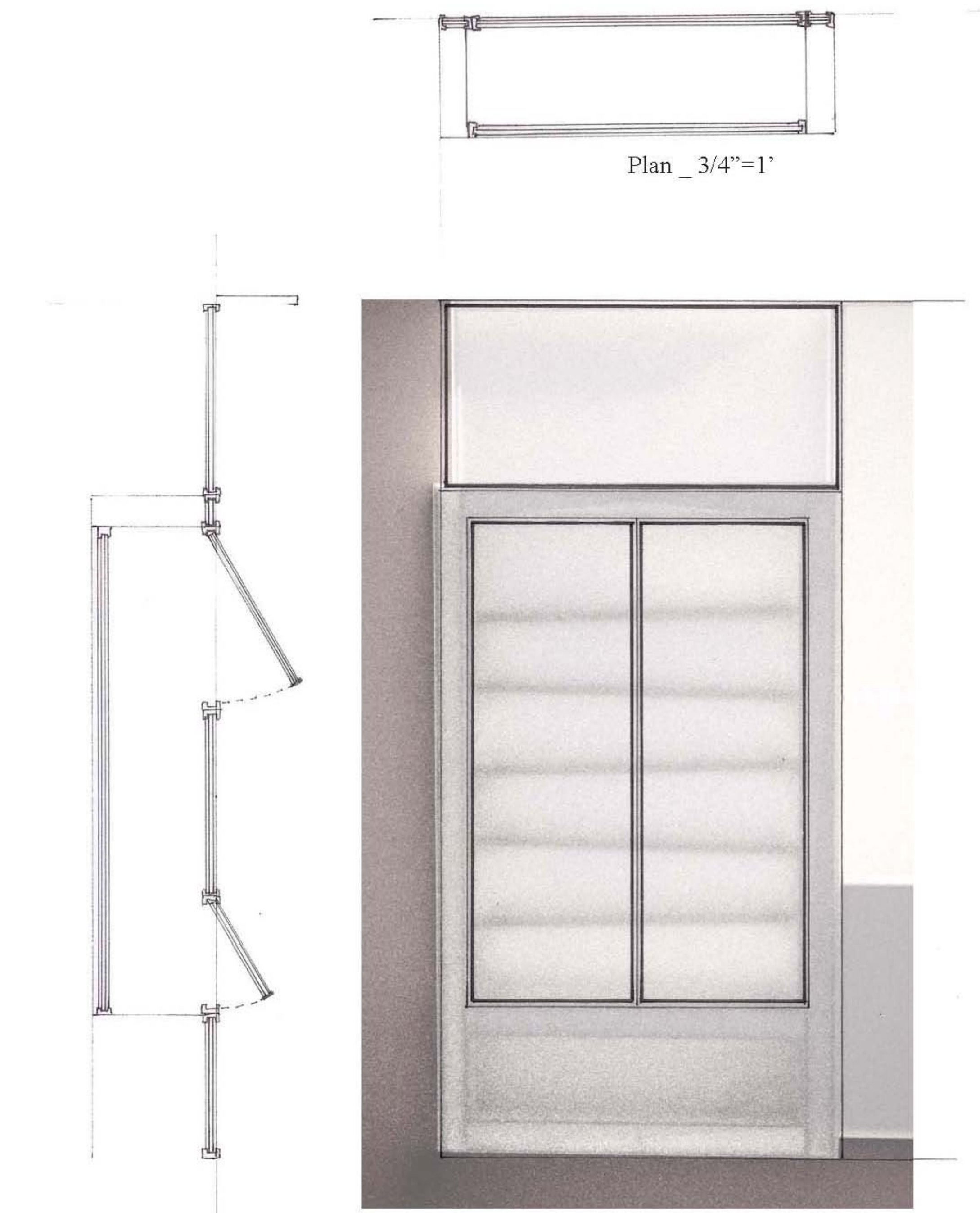


Figure 6.27. Glazing drawings

Glazing Details

The interior window is a double paned bi-fold door, allowing access to the plants in an easily maneuverable fashion without taking up much interior space (See Figure 6.28). The seal on this window is treated as a seal to the exterior of the building. This keeps the greenhouse conditions within the greenhouse space.

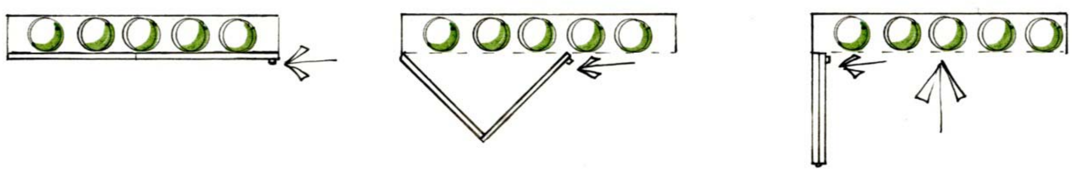


Figure 6.28. Bi-fold interior window for plant access

The exterior window is a double paned system alternating between operable hopper windows and inoperable panes of glass (See Figure 6.29). The hopper windows serve as ventilation for the greenhouse space in summer.

Figure 6.29. Exterior hopper windows serve as ventilation

Summary

The details of this project are founded in the research done on similar construction. This project is designed for the case study site of the Ya-Po-Ah Terrace but the ideas within it are meant to be transferable to other building types and users. The research that went into the design can be used to design a similar system for various existing building facades. This project is meant to be used by a range of people, including those with limited mobility. The details of the project are meant to make the system ideal for plant growth as well as functional for the user . (See Figure 6.30)

Figure 6.30. Using the system with impaired mobility.

Once the window unit is installed, it is meant to become a building component and to act as a part of the furniture within the living unit in which it is installed (See Figure 6.31). The glazing within the system allows the project to act as a window, allowing light and views to be seen past the strawberry plants. The operability of the project allows it to open when needed but to act as a closed window assembly when not in use.

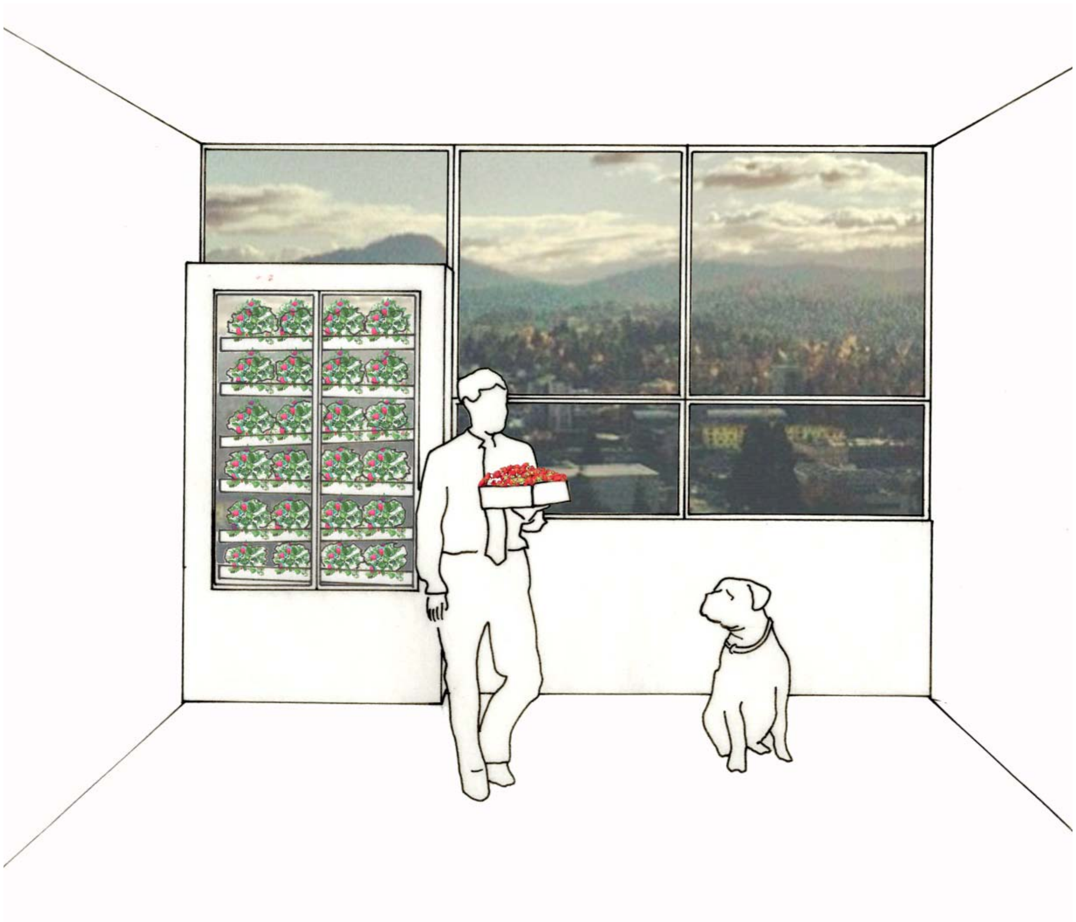


Figure 6.31. The system as part of a living unit.

CHAPTER VII
FINDINGS, LIMITATIONS, AND SIGNIFICANCE

Introduction

This chapter reviews the original research questions from Chapter I and discusses the findings of the research. Each question is addressed according to the depth in which it was researched. The final design is intended for the Ya-Po-Ah Terrace site but the research behind the design is meant to be used to inform designers about applying the principles to other sites.

Review of Questions

1. What are current methods of growing plants in urban environments and combining plant growth with the built environment?

Within the entire range of possible areas of plant growth in the urban environment, due to a limited amount of time, the research focused only on plant growth when combined with buildings. Greenroofs, living-walls, and façade-greening were the three main combinations found of plants grown in and on buildings. These options were then accessed for their ability to grow food producing plants, thus combining food growth and the built environment.

The current research found ways of growing plants on buildings but a gap was found when trying to grow food producing plants on the building façade which were accessible from the interior of the building.

2. What are compact and efficient methods of growing food?

The idea of looking for compact and efficient food production methods was to find methods which could fit into an apartment without taking up more space than necessary. Space, energy, and resource efficiency were looked at in evaluating possible precedents for food growth. A properly executed soil-less system uses water and space more efficiently than current conventional farming methods. An in-depth study was done on the five most common applications of soil-less methods to find which would best suit the needs of the project.

The use of space is critical when considering installation into an apartment. Some of the space efficient methods of growth worked well and efficiently in the context of a larger farm but were not found to be suitable for this project. Conventional farming methods on a larger scale can be impractical when looking at the smaller scale of a living unit. Simplicity was also a factor in choosing a system for use which would not need professional assistance or a background in gardening.

3. Can an ideal environment for food growth be created in conjunction with an inhabited space?

Plants are currently grown inside buildings with a variety of methods which range in size and complexity. These systems are often not the ideal environment for food production and are meant only to grow a few plants. Plant environment combines the temperature, moisture level, amount of sunshine, amount of water, components of the water, and available space for optimal plant growth. The need for light in the plant environment makes the building surface a sought after site. Artificial lights can be used for plant growth to create the needed plant environment but are more costly and complicated than direct sunlight as thus were not researched as a viable option.

The best growing environments for food were researched along with the preferred functionality of the building envelope. The building envelope was found to be a reasonable space for plant growth because of the access to natural lighting and ventilation. By combining the growing space with the building façade, it became possible to have plants access outside resources while the tender of the plants was able to access the plants from the inside of the building.

Greenhouses are used as the preferred method of growing plants on a commercial scale. They keep the plants the correct temperature while protecting the plants from the elements and pests. The materials used in greenhouses were found to also be used in building construction. This provides for an interesting combination of uses for a single building component. The habitat inside a greenhouse is ideal for plants but is not usually a comfortable living environment for people. The research became a method of finding ways to incorporate greenhouse properties for plants without forcing the building inhabitants to live in a greenhouse. The plants therefore need to be kept in a separate environment from the inhabitants so that each can have the ideal environment while maintaining access between the two. Windows are often layers of glazing with a series of air gaps in between and are used in apartment construction insulation. A greenhouse is essentially a window assembly with a large air gap in which plants are grown. This growing space can be used as a means of providing an insulated building envelope for the inhabitants of the building.

4. Can the thermal properties of plants be incorporated into the thermal function of a building façade to enhance interior comfort?

Plants grown in association with buildings have been found to promote building longevity as well as greater interior comfort. Plants act as thermal insulation, lessening the need for interior heating and cooling. The thermal properties of plants and of their growing environment can be used in conjunction with a building to create a more ideal inhabited space for people. The research found that not only can growing and living spaces be combined, but the two can supplement each other to create a better building envelope and more productive urban food environment.

5. What plants are well suited for merging an inhabited space with a building assembly?

Research into plant varieties stemmed from the types of growing systems used in this project. Plants were then chosen based on their compatibility with the growing method. Of the plants chosen for the Nutrient Film Technique, it was then based on the user group of the project. The Ya-Po-Ah Terrace is an elderly home and plants were chosen on their ability to provide essential nutrients for the elderly population as well as their ease of use. Strawberries were found to be one of the most beneficial hydroponically grown plants in terms of user health. Strawberries are also well suited to small scale production and tight spaces because of their small size.

Review of Hypotheses

This thesis predicts that an ideal environment for growing food producing plants can be created in a building assembly.

The design of this project shows that plants can be incorporated into the building façade. The growing space for the plants uses the associated thermal properties and available natural daylight of the southern building facade to create an ideal growing environment for the plants. Because a greenhouse is similar in properties to a window, it is possible to create a food producing environment within the windows of a building.

Secondly, the thermal properties of the plants and their growing environment can be used to enhance the thermal comfort of an inhabited space.

The research revealed that plants positively impact the thermal properties of a building. The nature of the greenhouse environment created in the window assembly also adds insulation to the building façade and aides in providing smaller temperature fluctuations within the associated living unit. Some research suggests that passive heating and cooling designs will drastically reduce energy consumption and give a possible percentage of the amount of energy which will no longer be used. Other sources give a range within which a properly designed passive strategy can reach. It is difficult to conclusively say to what extent this project will impact the interior comfort of the living unit. Each of the project components has been studied as a means of beneficially affecting the temperature fluctuations of the interior environment. As a whole they are all beneficial building components but have not been tested together as a cohesive building component. The thermal properties of plants and their growing environment can be used to enhance the thermal comfort of the inhabited space but quantifying the extent is a subject for further research.

This thesis also hypothesizes that these food producing plants can be easily maintained and harvested by the occupants from the interior of the inhabited space.

The design provided for an ease of maintenance within this project. The plants are able to gain solar radiation from the exterior of the building while being easily accessed from the interior of the building. The project was further designed to work for users with limited mobility. The interior window is treated as if it were on the exterior and seals to separate the growing environment and the living environment. This window can then be opened to allow for access to the plants whenever needed. The plants are grown within a vertical range that is accessible to most people but can be altered to grow only in the areas accessible by the specific user. A handrail is provided as an added sense of security when using this product and as a means of supporting oneself while harvesting strawberries.

Conclusion

This project aimed at finding if plants could be grown in conjunction with a building to provide food and a better building envelope. Research into current plant growing methods and building systems combined to find a way of producing food in urban areas using the building façade. Food production can work to promote health by providing nutrition and a higher quality of life. The plant the food is grown on can also enhance the thermal comfort of a building while producing nutrients for the inhabitants of the building on which it is grown.

Plants grown in a window can bring nature back into the city, promote urban gardening, and feed people. Food security is a problem in dense urban environments within the United States and this project has the potential to alleviate a small portion of this problem by allowing more food to be grown by individuals who do not have access to traditional garden space.

There exist a host of methods to grow food efficiently. Some of these methods are used commercially but there exist small scale versions of efficient growing systems which can be incorporated on a residential scale.

This thesis hypothesized that it would be possible to grow food in a window unit and for the building to create an ideal growing environment for the plants while the plants enhanced the building envelope. The research found that it is possible to incorporate food production into a building envelope while also enhancing the thermal properties of the façade.

Suggestions for Future Research

If time permitted, a physical prototype would have allowed for a more comprehensive testing of the design. Thermal properties could be quantified through different seasons. The prototype could then be tested over the course of a strawberry growing cycle to find the thermal properties as they change with the plant size. The plant variety itself could be expanded to include common garden plants as well as the commercially grown hydroponic crops. A future study could place the project into a multitude of building envelope types find how the project changes based on its surroundings. Testing of a physical prototype would be a great asset to this project.

The project itself can have more benefits than those researched in this thesis. Other topics for research could involve educating about food. People do not always associate the end product of food with where it comes from and how to grow it. The high visibility of this project in high-rise windows could become an educational tool in bringing food knowledge into dense urban areas.

Designing a project is never truly over. There are things which can be improved with more research or changed based on a different case study site or user group. A future research area would be continuing the design to find other ways of growing food-producing plants in a building façade. This might include finding a method of efficiently delivering the nutrient solution to the plants without the use of a pump. This would create a project with no needed electricity input.

The research broached in this project is constantly evolving and could be studied to make sure the most current options are being engaged. Hydroponics is a growing field and new methods of growing food may come to light.

APPENDIX A

USER'S MANUAL

Introduction

The operability of this system is described in this section. Opening windows, accessing plants, adding nutrients and installing gullies are all addressed in this section. Transferring plants into the system as seedlings is also addressed.

Accessibility

The inside window is a folding system on a track. The window opens from side to side and tucks up against the wall when completely open. To access the plants, simply push the handle of the window towards the wall (See Figure A.1).

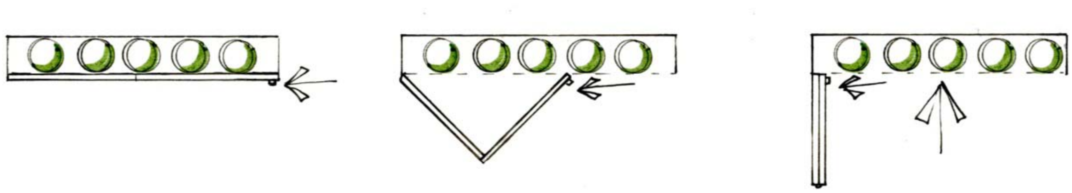


Figure A.1. Plan of the inside window operability and accessing plants.

There are two windows to the outside. One is at the base of the greenhouse space and the other is at the top of the greenhouse space. These are hopper windows and open out from the bottom. To open these, simply push the bottom of the window towards the outside (See Figure A.2).

Figure A.2. Section drawing of the outside window operability.

Adding Water and Nutrients

A water tank at the base of the system holds the water for the whole system. When first installing this product it will be necessary to fill the tank with water up to the fill line inscribed on the inside (See Figure A.3).

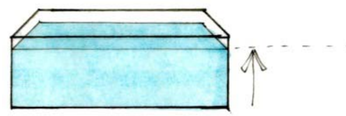


Figure A.3. Water tank fill line.

Nutrients will need to be added to the water for it to become the nutrient solution which feeds the plants. The nutrients should be added based on the suggested amounts on the back of the container provided by the manufacturer. For nutrient measuring purposes the tank holds 30 gallons of water when water is up to the fill line.

The lid of the water tank has a portion which opens to allow water and nutrients to be added (See Figure A.4). This hinged cover is placed over the water pump so that pump maintenance can be easily managed.

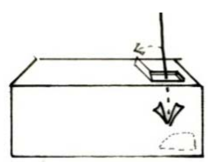


Figure A.4. Adding nutrients to the water tank and accessing the water pump.

Changing Gully Location

The space between gullies will need to change to accommodate a change in plant height when the plant varieties change. The smallest distance between the gullies should be the known average height of the plant[51](See Figure A.5).

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[51] Average heights of plants commonly grown hydroponically can be found in Appendix D on hydroponically grown plants.

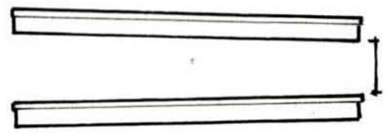

Figure A.5. Elevation of the shortest distance between gullies.

To change the gully to a different position in the greenhouse space, detach the gully from its current location (See Figure A.6). This involves unscrewing the 4 screws holding the gully attachment piece to the wall. Once the gully attachment piece is free, slide it up or down the wall to its desired location and re-insert the 4 screws.

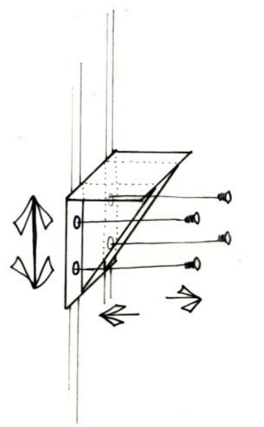

Figure A.6. Changing the height of a gully by moving the attachment piece.

The gully needs to be installed at an angle so that the water runs from one end to the other without stopping. The angle makes a one inch height difference over the width of the greenhouse space. This one inch difference means that the gully attachment piece will be installed one inch higher on one side of the space than on the other side (See Figure A.7).

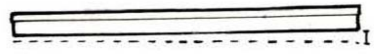

Figure A.7. One inch elevation change over the length of the gully.

To keep the water flowing back and forth down the system, the gullies need to alternate how they are angled (See Figure A.8). The high side of each gully will change from being on the left side of the wall to the right side of the wall as the gullies progress down the system. This lets gravity move the water to each plant.

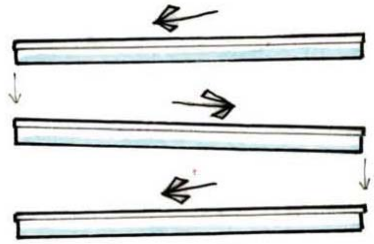

Figure A.8. Gullies alternating slopes.

When changing the gully location, it is important to change the location of the handrail as well. These should be installed at the same height so that the bottom of the handrail is at the same level as the bottom of the gully (See Figure A.9).

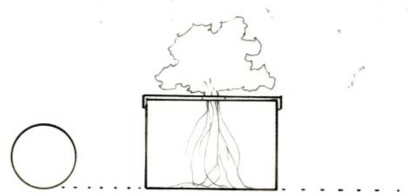

Figure A.9. The base of each handrail is installed level with the base of the adjacent gully.

The four screws mounting the handrail to the wall need to be unscrewed. The handrail can then be moved up or down as needed and re-installed at the correct height (See Figure A.10).

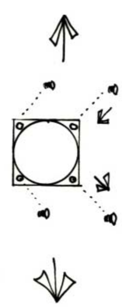

Figure A.10. Handrail installation and movement along the wall.

Changing Gully Size

Plants have different root ball sizes and need different gully sizes accordingly (See Figure A.11). The system works best when all of the water running through the system goes over the roots of the plants. Having the right size gully[52] based on plant variety will make sure this happens. If the plants in the system are changed to a different variety, it may be necessary to change the gully size.

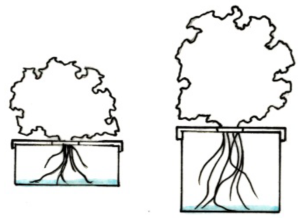

Figure A.11. Plants need different root space and gully size.

To change the gully size, first unscrew the plastic nut that is attaching the pipes on either end of the gully. Once these are completely detached, unbuckle the small belt strap holding the gully in place (See Figure A.12). This will free the gully and allow it to be removed and kept for future use.

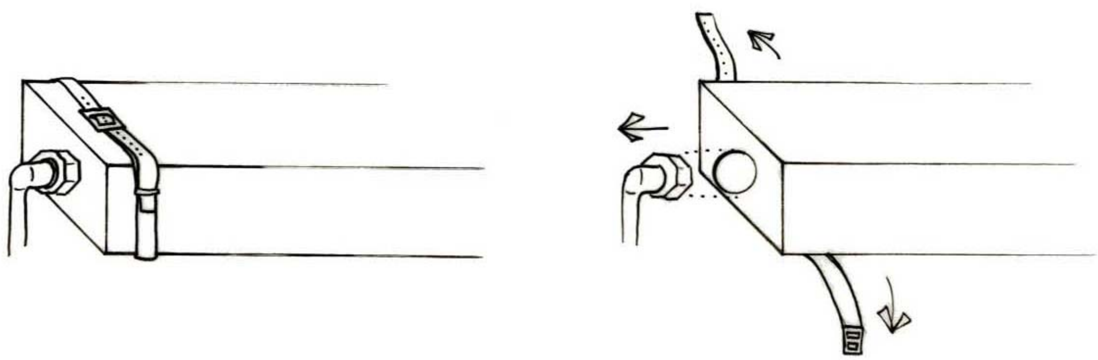

Figure A.12. Gully detachment.

The new gully can then be placed onto the gully attachment piece. Take the belt straps from under the front and back of the gully and buckle them at the top of the gully,

[52] Gully sizes for commonly grown hydroponic plants can be found in Appendix D on hydroponically grown plants.

making sure it is snug (See Figure A.13). There should be as little wiggle room as possible.

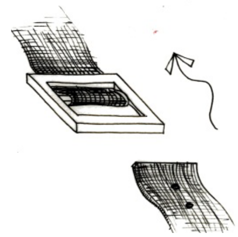

Figure A.13. Belting in the gully.

These straps are designed to accommodate a wide range of gully widths and may have an excess of belt if a small gully is installed. This excess can be tucked into the loops attached to the belt, keeping it out of the way. Once the gully is securely in place, re-attach the pipes on either end of the gully. The plastic nut on the pipe should be finger tightened into the hole on the end of the gully.

Changing Gully Lids

Gully lids have holes cut in the top to let plants get to the water. The holes are spaced the same distance as the plant is wide (See Figure A.14). If the plant variety changes then the distance between plants may need to change. If this is the case, the lid can be removed to install a different lid.

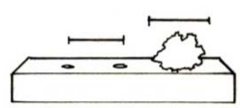

Figure A.14. Lid holes spaced the width of the plant.

To take the lid off, follow the instructions for changing the gully. The gully will need to be taken out of the system to change the lid. Once the gully is detached and out of the greenhouse space, the lid can be removed. The lid slides in a groove along the sides of the gully and can be pushed along the top of the gully until the lid is completely out of the gully grooves. The new lid can then be slid into the grooves until the lid completely covers the gully (See Figure A.15). The old lid can be kept for future use.

Figure A.15. Removing the gully lid.

Plants in the Gully

Plant starts and seeds are too small to reach the nutrient solution on their own. Instead, these are put in a net pot filled with coconut fiber[53] (See Figure A.16).

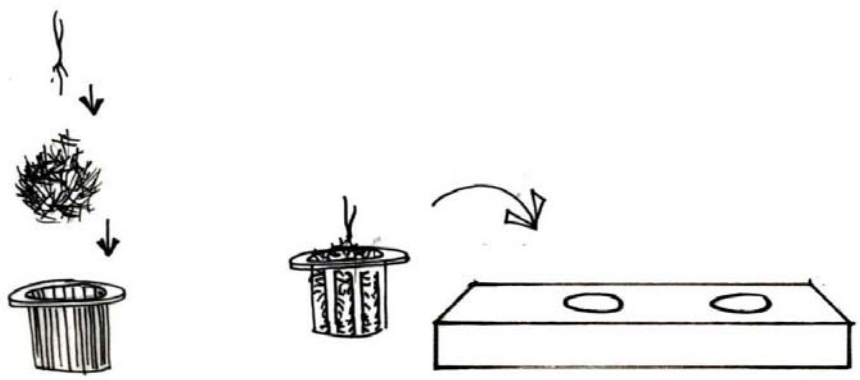

Figure A.16. Seeds and starts being planted in a net pot in the gully system.

The net pot fits into the holes in the top of the gully lid. The coconut fiber should be soaked in the nutrient solution overnight before being put in the net pot and should fill the net pot completely to the top. The seed or plant start should then be planted into the fiber just below the surface.

Once the plants have roots large enough to reach the nutrient solution on their own, they should be taken out of the net pots so they can get more oxygen. Take the net pot out of the gully lid and take the plant out of the coconut fiber. Once the plant is free of the fiber and net pot, it needs to be placed back into the gully system. This happens by inserting the base of the plant, above the roots and below the crown, into a circular foam disk. This disk fits into the gully lid hole and holds the plant in place (See Figure A.17).

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[53] See Appendix B on coconut fiber.

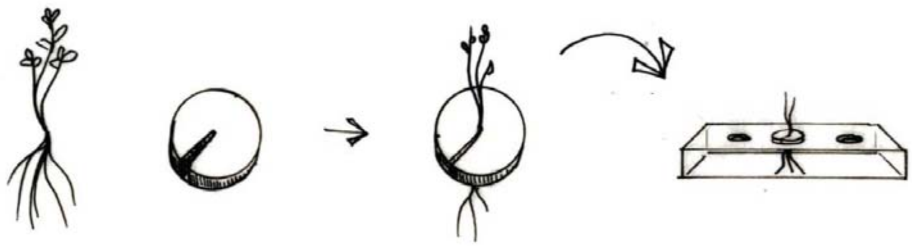

Figure A.17. Plants with long roots being replanted in the gully in foam disks.

Plants will eventually need to be removed from the system. When this happens, take the foam disk out of the lid hole and remove the plant from the disk. A foam disk should be put into every lid hole, regardless of whether or not a plant is in the hole. This seals the top and keeps water from evaporating out of the system (See Figure A.18).

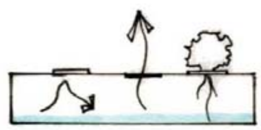

Figure A.18. Foam disks keeping evaporation from leaving the system.

APPENDIX B
COCONUT FIBER

Coconut fiber, also known as coir, is used in hydroponic systems as a plant growth medium. It is a decomposable renewable resource made from the outer husk of coconuts and is often an industrial byproduct, making it less expensive than other options of growth. It has a high lignin[54]content which holds its structure, making it extremely long lived and durable. Lignin decomposes slowly, keeping the structure, and therefore the air and water holding capacity, for long amounts of time. So long that it is used commercially for long term crops like grapes. Coir has the ability to absorb and retain large quantities of nutrient solution and the nature of its fibers does not allow waterlogging to happen at its base, which can happen with other mediums.

Coir is described as a better version of the common rooting material, high-yielding peat. It also happens to be moth and rot resistant. It has a high tensile strength which helps to insulate heat and retain water. Growth mediums are tested for porosity and water retention abilities in order to show the amount of air and water provided to the plant. Coir has been tested as having a high water holding capacity (81% container capacity[55]). It also tested as having 23% air-filled pores. This is within the recommended range for plant rooting materials. For plants that do not tolerate a wet crown, like strawberries, it can be mixed with perlite, pumice, or vermiculite to raise the air pore space which will in turn lower the water retention abilities.

Roots grow rapidly in coir because of the amount of water and air in the pores, making it ideal for starting seedlings. Coir keeps moisture evenly within it, preventing moisture loss from the surface while also preventing water logging at the base, which is a common problem among other growth mediums[56].

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[54]Lignin is "an organic substance that, along with cellulose, forms the woody part of plant tissue" (Knutson).

[55] Container capacity shows the "amount of water held in a container of a given depth after drainage is completed" (Knutson).

[56] Coir can replace most growth mediums: peat, bark, rockwool, vermiculite, perlite, expanded clay, and pumice.

NFT systems have successfully incorporated coir to raise seedlings. Net pots, small plastic pots with highly perforated sides and bases, are filled with coir. The coir has good capillary action which wicks water up, bringing the nutrients of the NFT system from the base of the gully up to the seed. Coir facilitates rapid root growth down and out of the net pot which is important when raising seedlings in NFT systems. The seedling is moved out of the net pot once it is big enough to reach the nutrients on its own (Knutson).

Anything placed in a nutrient solution has the ability to change the pH value, electrical conductivity (EC) and nutrient value of the solution. Growth mediums are tested to determine how plants and the nutrient solution will be affected (See Table B.1). Some nutrients are beneficial to the plants, like calcium and iron, while others are detrimental, like large amounts of ammonium and sodium. Coir is relatively inert, having inconsequential amounts of both positive and negative nutrients so it will not alter the composition of nutrient solution (See Table B.2). The pH is slightly acidic (5.5-6.8), which is ideal for the highly controlled pH levels of the solution used in hydroponic systems.

ANALYSIS OF COCONUT FIBER	
(From Luzon in The Philippines)	
pH	6.1-6.5
Electircal conductivity	260
Total organic matter	96-98%
Cellulose	20-30 w/w%
Sodium	78 mg/L
Potassium	210 mg/L
Calcium	0.50 mg/L
Ammonium	0.40 mg/L
Chloride	70 mg/L
Sulfate	11 mg/L
Carbon:nitrogen ratio	80:01:00
Air-filled porosity	9.5-12.5%
Total pore space	93-95%
Lignin	60-70 w/w, dry%
Phosphorus	4-8 mg/L
Magnesium	4-6 mg/L
Iron	5-8 mg/L
Nitrate	0.3-1.0 mg/L
Water-holding capacity	80-88%
Color	Light brown
Appearance	Earthen granular with some short fibers

Table B.1. Components of coir which might affect the nutrient solution (Knutson).

PHYSICAL PROPERTIES OF SOME COIR FIBER MIXES	Air-Filled Porosity (%)	Container Capacity (% Water)
Palm peat alone	23	81
Palm peat + perlite (50:50)	43	63
Palm peat + pumice (50:50)	29	77
Palm peat + vermiculite (50:50)	36	68

As indicated by these figures, any increase in air-filled porosity, or the amount of oxygen held within the mix, results in a loss of water-holding capacity. But with these types of mixes, it's possible to select the best combination for your crop and growing system.

Table B.2. Properties of coir fiber mixes (Knutson).

APPENDIX C

NUTRIENT SOLUTION

Introduction

Nutrient amounts and pH levels are described, as well as methods of changing them should they become unfit for plant growth. The nutrient solution is the key component in hydroponic systems and determines how well the plants produce food. It is important to make sure the nutrients are the appropriate nutrients for the specific plants being grown. The nutrient solution can be used in stages to accommodate the growth cycle of the plants.

Components of the Nutrient Solution

Nutrient solution is a combination of water and the nutrients needed for plant growth. The nutrient combination added to water can be bought at a gardening store. A Dutch base solution is commonly used commercially to ensure plants get the nutrients they need. The solution is based on a 2-part formula for the different plant needs in both the 'grow' and 'bloom' stages of development. 1-part formulas can have nutrients which bind and solidify together, making them un-absorbable to the plants and a waste of minerals (DNF).

The solution can also be adjusted for the weather conditions to aide plants in times of stress. Low light conditions in winter can be a tenuous time for plants and promotants are sometimes added to provide less taxing conditions. Some common promotants are Agronomix[57] and SGP[58] (Stocker).

Maintaining the Nutrient Solution

It is important to test and maintain the nutrient solution when it is recycled through the system. The nutrients are added to the water to create the perfect balance of what the plants need so it is critical to know what is already in the water. Water should

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[57] Agronomix is typically used at 20gms/20Kg of dry powder mix.

[58] SGP is commonly used at 500mls/20Kg dry powders.

be tested for mineral content and pH. The pH and mineral levels may need to change based on the type of plant being grown.

The pH can be altered to be at the desired levels. It can be lowered by adding Phosphoric Acid, Nitric Acid, or a Phosphoric/Nitric Acid mix. Nitric Acid is used by itself to lower pH when it is higher than 7.8. Potassium Hydroxide, also known as Caustic Potash, can be added to raise the pH to the needed level (Stocker).

Summary

The water quality and content are some of the most important aspects of hydroponic growth and should be constantly monitored to make sure the plants are getting the nutrients they need. The pH is important as well because it has the ability to affect how well the plant roots are able to absorb the nutrients being provided in the water.

APPENDIX D

HYDROPONICALLY GROWN PLANTS

Introduction

Following are plants commonly grown hydroponically. These have different requirements for nutrition, plant spacing, water pH and electrical conductivity. The different gully sizes associated with each plant based on root size and the spacing between gullies based on plant height are below. There are plants which use the same size gullies and can be planted accordingly.

Tomatoes, cucumbers, peppers and zucchini use a 155mm wide x 70mm deep gully. This is a narrower trough for large leafy plant varieties. Strawberries and heads of lettuce are smaller plants and use a narrower trough, 100mm wide x 68mm deep. Herbs and loose leaf lettuce are smaller-leafed plants and need a thinner, shallower trough 100mm wide x 50mm deep. Flowers and animal fodder use a 225mm wide x 80mm deep gully (Hydroponic Developments).

Pollination for plants can be broken down into three basic categories. Leaf and root crops do not need pollination because the fruit is not what is being harvested. Lettuce and herbs are hydroponically grown plants which do not need pollination. Of pollinating plants, there are two varieties, self-pollinating and cross-pollinating. Self-pollinating plants have flowers which contain both the male and the female parts of the flower. Hydroponically grown plants that are self-pollinating are tomatoes, peppers, and greenhouse varieties of cucumbers. These do not typically need assistance from the user to pollinate. Cross-pollinating plants have separate male and female flowers and need assistance in crossing the pollen. Of the common hydroponic plants, cucumbers that are not greenhouse varieties are the only kind which will need to be hand pollinated (Stella).

Plant Types[59]

Tomatoes

Pollination: Vibration[60]

Spacing: 16 inches apart

Height: 3 – 6 feet

Gully size: 155mm wide x 70mm deep

pH: 6.0 - 6.3

EC: 1.5 - 3.0 mS

Days to harvest: 100[61]

Nutrients:

Element	*ppm (mg/L)*
Nitrogen (N)	140
Phosphorus (P)	50
Potassium (K)	352
Calcium (Ca)	180
Magnesium (Mg)	50
Sulfur (S)	168

[59] Sources for this section are: Hydroponic Developments, Gardener, Resh, and Stella.

[60] An electric toothbrush can be put behind stem and turned on for 4 seconds to create the vibration needed for the plant to pollinate.

[61] Tomatoes will keep producing but will have smaller yields after 10 months.

Cucumbers

Pollination: N/A[62]

Spacing: 8-10" apart

Height: 3-6 feet

Gully size: 155mm wide x 70mm deep

pH: 5.5 - 6.0

EC: 2.2 - 2.7 mS

Days to harvest: 60 - 70[63]

Nutrients:

Element	*ppm (mg/L)*
Nitrogen (N)	210
Phosphorus (P)	50
Potassium (K)	380
Calcium (Ca)	190
Magnesium (Mg)	50

[62] Greenhouse varieties of cucumbers are self-pollinating and do not need to be pollinated. Other varieties may need to be hand pollinated (Stella).

[63] Cucumbers are grown in 3 or 4 month cycles and start being harvestable within 6 weeks of planting. This continues for 8 weeks after, allowing for 3 or 4 crop cycles per year (Resh).

Bell Peppers

Pollination: Vibration

Spacing: 16 inches apart

Height: 4 -5 feet

Gully size: 155mm wide x 70mm deep

pH: 5.8 - 6.1

EC: 3.5 – 4.0 mS

Days to harvest: 72 days

Nutrients:

Element	*ppm (mg/L)*
Nitrogen (N)	208
Phosphorus (P)	40
Potassium (K)	340
Calcium (Ca)	170
Magnesium (Mg)	50
Sulfur (S)	360

Strawberries[64]

Pollination: Wind

Spacing: 10 inches apart

Height: 6 inches

Gully size: 100mm wide x 68mm deep

pH: 5.8 - 6.2

EC: 2 - 3 mS

Days to harvest: 42 from bloom time

Nutrients:

Element	*ppm (mg/L)*
Nitrogen (N)	207
Phosphorus (P)	55
Potassium (K)	289
Calcium (Ca)	155
Magnesium (Mg)	38
Sulfur (S)	51

[64] A more in-depth view of strawberries can be found in Appendix E.

Head Lettuce

Pollination: N/A

Spacing: 6 inches apart

Height: 12 inches tall

Gully size: 100mm wide x 68mm deep

pH: 5.5 - 5.8

EC: 1.5 - 2.0 mS

Days to harvest: 30

Nutrients:

Element	*ppm (mg/L)*
Nitrogen (N)	180
Phosphorus (P)	50
Potassium (K)	210
Calcium (Ca)	180
Magnesium (Mg)	50
Sulfur (S)	51

Loose Leaf Lettuce

Pollination: N/A

Spacing: 7 inches apart

Height: 12 inches

Gully size: 100mm wide x 68mm deep

pH: 5.5 - 5.8

EC: 1.5 - 2.0 mS

Days to harvest: 40

Nutrients:

Element	*ppm (mg/L)*
Nitrogen (N)	180
Phosphorus (P)	50
Potassium (K)	210
Calcium (Ca)	180
Magnesium (Mg)	38
Sulfur (S)	51

Herbs

Pollination: N/A

Gully size: 100mm wide x 50mm

Height, spacing, pH, EC, nutrients, and harvest time will change depending on the variety but can be grown in the same gully size.

APPENDIX E

STRAWBERRIES

Introduction

Strawberries can be divided into three categories based on what effect day length has on their flower initiation. Runners set out in early autumn will produce more crowns and a heavier crop in the first season than when they are kept from being planted until winter or spring.

Varieties of Strawberries

Short-day types

In cold winter areas flowers start in the short days in autumn[65] and stop when the plants become dormant. In warm winter areas where plants do not become dormant, the flower initiation will go through winter. These types do best in areas with mild winters (55 F) and warm summers (82 F). If the plants receive too much chill, they will be mostly vegetative[66] with fewer fruit. Only one crop is produced yearly and runners are sent out once fruiting is finished.

Day-neutral types (Ever-bearing)

These were developed to initiate flower growth regardless of day length. They do best in areas with long cold winters[67] and mild summers (75 F). The flowers, fruit, and runners are all produced at the same time and should be planted as soon as they are chilled enough in order to grow vigorously.

Long-day types

Long days are the initiator of flowering. The cycle is typically to flower, fruit, and flower again, usually not producing many runners. The flowering can be altered,

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[65] Short days are considered to have less than 12 hours of daylight.

[66]Vegetative refers to the amount of foliage on the plant. The plant spends energy producing large leaves and lots of runners instead of producing fruit.

[67]Strawberries can be chilled in the refrigerator if there is no long cold winter.

advancing it by keeping the plants under glass, or delaying it by keeping plants in cold storage and planting later in the season.

Propagation

Plant runners[68] can be used to propagate new strawberry plants or they can be bought at a nursery as either fresh dug runners[69] or cold-stored runners[70]. They can be grown out of season if a greenhouse or heated space is used. After chilling[71] they should be planted in a space that is 68F. Leaves will happen quickly, with flowers following in about three weeks. After the flowering, fruit should be ready in six weeks if a warm temperature is maintained. The nutrient solution can be heated as a substitute for warming the air. If these conditions are met, there should be a large crop of highly flavored fruit produced (Sarooshi).

Seedling started in an NFT system need to be propagated first in an inert material in a net pot. This will wick water up from the thin film of water at the base of the gully and give it to the small plant roots. The plants should be removed from the net pot once the roots are long enough to reach the base of the gully (Fernandez).

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[68] Runners are creeping branches produced at each mode on the stolon and form roots whenever the node touches the ground. These can be taken to form new plants but make sure they are healthy because viruses and disease are passed from mother to daughter plant.

[69]To dig your own runners, "carefully remove the runners or new strawberry plant from its container. Remove as much of the earth as you can by gently shaking and massaging the roots. Submerge the entire root system in a bucket of cold water for about 10 minutes then rinse roots under cold running water to remove any remaining dirt. Be very careful to inflict as little damage as possible to the roots and tiny root hairs as too much breakage will seriously stress plants and impair growth. Dry or brittle leaves and roots should be removed at this time. It is important to keep the roots moist while planting. Exposure to the sun or wind will quickly dry out the tender rootlets. This drying will cause failures in the establishment of the planting. A convenient way to keep the roots moist is to wrap them in wet burlap and then carry them in a pail or basket" (Simply).

[70] Cold stored runners have already started making flower buds and will immediately produce flowers if planted in warm growing conditions.

[71] To chill your own strawberries: bring them in during spring-summer, trim them, dip them in fungicide, and wrap them in plastic. They need to be chilled in a refrigerator for a minimum of 3 months (or you can buy chilled runners).

Planting

The crown is the most important part of the plant because it is where new leaves and flower buds grow from. An infected crown will spread to the leaves and flowers and the whole plant will rapidly deteriorate. Crown rot happens mainly from inadequate drainage causing waterlogging. The plant can either survive with reduced yields and smaller leaf size or can die completely. To avoid this, the crown needs to be in the sun and air where fungal problems will not start. To keep the plant in the air, it is important that the crowns must not be completely buried in media and that ¼ of the crown is under the media, leaving ¾ of it above the media (Sarooshi).

Free-draining media[72] held in a basket is the best method of keeping the crown above water in hydroponic systems. The crown can sit above the surface while the roots are allowed to grow downward, accessing the NFT[73] solution through holes in the bottom of the basket. In an NFT system the water travels along underneath the media, allowing the capillary action of the media to draw it up for use. NFT keeps the top surface of the media relatively dry, protecting the crown from moisture while allowing the roots to have access to nutrients. This system is currently used to grow strawberries commercially, with each plant producing an average of one quart of strawberries per fruiting cycle. The average American consumes "more than 3 lbs. of strawberries per year" (Alexander 99), meaning that twenty-five plants will be enough for a typical family of four (Gao).

The United States is the world leader in the sheer volume of strawberries produced, a large portion of which are grown outside, with an increasing amount being grown hydroponically. Hydroponic systems allow year round strawberry production in heated greenhouses without the need to mulch around the plants to keep berries from soiling. Greenhouse-grown strawberries also do not need protection from birds, which can be a large problem outside (Sarooshi).

Pests and diseases

Strawberries get fungal diseases when in poorly drained conditions. Some common ones that thrive in wet humid conditions and cause strawberry death are the

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[72]Free=draining media can include gravel, scoria, expanded clay, rockwool, and coconut husk.

[73] Nutrient Film Technique

fungi red core[74] and gray mold[75]. The best solution is to provide a warm, dry environment where the berries are exposed to the sun (Sarooshi).

Nutrition for Plants

Strawberries need high levels of potassium for ideal berry size, flavor, and yield. Once the fruit has begun to form, a potassium-to-nitrogen ratio (K/N) of 1 to 4 or above is recommended. This can be bought or home-made. A two-part bloom formula is recommended (Simply). General conductivity levels are also an important component of strawberry production. Nutrient conductivity and flavor are related, with an increased nutrient solution conductivity level reducing the amount of water being taken up, concentrating the flavor in the berry. An extreme conductivity level for a succulent fruit such as strawberries will make small, woody berries. The ideal range of conductivity levels is between 20 and 30 (2-3 mS cm) (Sarooshi).

The pH of the water should be tested to make sure that it stays between 5.8 and 6.2, the ideal pH for strawberries to have the maximum nutrient uptake. This can be adjusted higher by adding sodium hydroxide or adjusted lower by adding sulfuric acid. The application rate should be found on the instructions on the package and is based on the volume of water in the system (Loucks, Simply).

Plant Size and Spacing

This case study focuses on growing strawberries and is designed to be tailored to the specific needs of this plant. The plants typically grow to be 10” wide and 6” tall (BHG). This data will allow the product to use space efficiently to fit these plants specifically. There is a range of space allowed between plantings which will affect the amount of sun provided per plant, and therefore the plant health and berry production[76]. The plants should be spaced 6 inches to 1 foot apart for them to receive an appropriate amount of light. The runners produced by plants should be taken off to keep the space

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[74] Red core is also known as Phytophthora fragariae.

[75] Gray mold is also called Botrytis cinerea. It attacks as the berries are ripening and quickly spreads to other berries. It is most often found when the fruit gets damp.

[76] Berry production can fluctuate based on the planting density. “An increase in planting density from 5.35 to 9.35 plants/m2 lowered marketable yield per plant and fruit acidity but gave 41% higher yield on an area basis” (Sarooshi).

from getting over crowded. Day-neutral[77] cultivars “do not produce long runners that require extra space” and are therefore ideal for hydroponic systems (Loucks).

[77] Refer to Appendix E for more information.

APPENDIX F

HYDROPONIC SYSTEMS

Introduction

There are a number of soilless options for growing plants. Among them are hydroponics, a nutrient water solution, and aeroponics, a nutrient mist system. These systems can be tailored for specific needs of different crops, available time in maintaining them, and amount of available capital input. Within hydroponic systems there are both aggregate and liquid (non-aggregate) systems.

The liquid system provides no growth medium for the plant roots and instead exposes the roots directly to the nutrient solution. The solution can be heated in winter or cooled in summer so that commercial growers can heat the nutrient solution instead of having to heat the greenhouses. The aggregate hydroponic systems use the same nutrient solution technology but have a growth medium for the plant roots. Both liquid and aggregate systems can be either open or closed.

Open systems do not recirculate the nutrient solution. Instead, once the solution has been given to the plants it is then discarded. A typical commercially used open system uses plastic bags filled with growing mix[78]. The bags are UV-resistant polyethylene with a dark interior and a light exterior to reflect radiation and keep the growing medium from excessive heat. These are placed in lines on the floor with the regular spacing for that crop and a drip irrigation system delivering a nutrient solution. A hole is made in the top of the bag for the plant and two slits are cut in the sides to allow drainage. The drainage is then discarded (Thiyagarajan).

Closed loop systems are more efficient than open systems because the water is recirculated and reused continuously. Nutrients are added to the water as needed but the associated cost is lower due to the minimal water use. Following are examples of closed loop nutrient solution systems.

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[78] This system typically uses a growing media made of peat, vermiculite, or a combination of the two with perlite.

Examples of Hydroponic Systems

Water culture is simplest form of hydroponics (See Figure F.1). Plants are in a floating tray above a water tank filled with nutrients. An air pump keeps oxygen circulating in the water but the plants are always in contact with the water, having no need for a water pump. There is then no danger of a pump failure drying out the plant roots. This system is good for lettuce, strawberries and herbs.

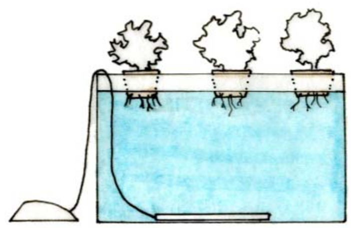

Figure F.1. Hydroponic water culture system.

Drip systems are based on having a water tank which feeds small drops of water to the plants (See Figure F.2). The nutrient solution in the water tank is pumped to another container where it is fed through small tubes to direct the water to each plant specifically. These plants are held in a growth medium which holds the solution and the roots while allowing the excess water to drain back into the main water tank. This system has both air and water pumps running constantly. The nutrients have been known to clog the emitters. This system is good for plants with large root balls.

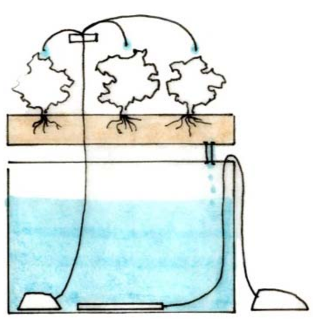

Figure F.2. Hydroponic drip system.

Ebb and flow systems have two separate containers, the bottom one is the main water tank and the top container holds the plants (See Figure F.3). The nutrient solution is pumped up from the bottom tank in order to flood the top container. An overflow pipe drains the water back out of the top tank at timed intervals. The pumps switch on and off every 15 to 30 minutes, keeping the plants alternating between soaking up nutrients and absorbing oxygen. This system is good for plants with large root balls.

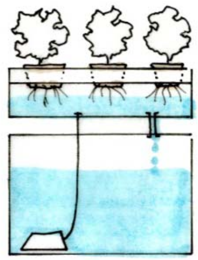

Figure F.3. Hydroponic ebb and flow system.

NFT, nutrient film technique, is made to run highly oxygenated nutrient solution over the roots of the plants in a thin continuous film (See Figure F.4). Water is pumped from a lower holding tank into the top of a plant holding gully. This gully is angled to allow gravity to bring the water along the roots of the plants and to then be recycled into the water tank. The gully is often PVC piping which serves to keep out light and prevent evaporation. These pipes are sloped, typically 3in. per 100ft., to avoid water pooling which can cause oxygen depletion and stunted growth. The water and salt content of the nutrient solution should be monitored and can easily be treated. The gully system provides oxygen so an air pump is not necessary. NFT is good for plants with small root balls like lettuce, strawberries, and herbs.

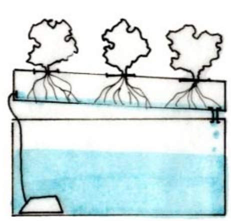

Figure F.4. Hydroponic NFT system.

Aeroponics is the most advanced of the hydroponic systems and can use 1/10 the amount of water typically used to grow the same crop in conventional open systems. Plant roots dangle from the top of the water container and are continuously sprayed with the nutrient solution (See Figure F.5). The excess nutrient mist falls back to the bottom of the tank to be sprayed onto the roots again. The spraying makes the solution highly oxygenated so an air pump is not necessary. This system is good for medium sized root balls like lettuce, herbs, tomatoes and peas.

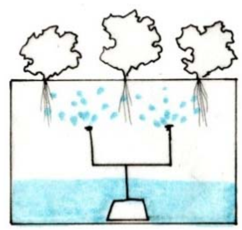

Figure F.5. Aeroponic mister tank system.

APPENDIX G

PASSIVE HEATING & COOLING

Introduction

Passive heating and cooling are methods of designing to provide comfortable interior temperatures without the need for air conditioners and heaters. The goal of passive cooling is to reduce heat gain in summer when it is unwanted. This can be done with various solar control methods, including shading, ventilation, and color choice. Night ventilation of a space can provide cooling, as can the use of evaporation. The shading methods can be one or a combination of things, including overhangs, awnings, and landscaping. Windows, vents, and fans are parts of the building which can be installed to provide for passive cooling. Passive heating involves building to gain solar radiation in winter to heat the interior of a building when the heat is wanted. This can involve thermal mass to store heat during the day which will radiate it into the space at night. Thermal mass can be on the floor or in the wall, but is more effective when within direct sunlight.

Thermal Mass

Windows are the "least effective heat flow inhibitors of a building's shell[79]" and can be adapted or combined with other building features to make for a better thermal building member (Arizona). Thermal mass has been used in conjunction with windows to temper the heat flow and to mediate the temperature changes that happen because of the window. Greenhouse additions have also been made on the exterior of windows as a way of using the direct light and keeping it from entering a house.

Thermal mass walls have been added to this combination as a way to deal with the temperature fluctuations. The greenhouse collects the solar radiation and is heated directly while the thermal wall collects heat and buffers the interior space from direct

[79] Single pane glass loses 20 times as much heat as an equivalent square foot of a standard 2x4 wood frame insulated wall when the outside temperature is 30°F and the inside temperature is 68°F. That's roughly 43BTU's per hour (Arizona).

light, heating it indirectly. The thermal mass can be made of masonry, stone, or water[80], each with a range of uses and benefits (See Table G.1).

Water walls are "much more efficient for thermal collection, storage, and re-radiation than masonry walls" because of the good convective properties of water. Water can shed heat in summer and gain heat in winter faster than other materials because of its dynamic nature and internal circulation (Bainbridge).

Specific Heats, Densities, and Heat Capacities of Common Materials

Material	*Specific Heat (Btus stored per pound per degree change of temperature)*	*Density (pounds per cubic foot)*	*Heat Capacity (Btus stored per cubic foot per degree change of temperature)*
Air (75°F)	0.24	0.075	0.018
Sand	0.191	94.6	18.1
White Pine	0.67	27	18.1
Gypsum	0.26	78	20.3
Adobe	0.24	106	25
White Oak	0.57	47	26.8
Concrete	0.2	140	28
Brick	0.2	140	28
Heavy Stone	0.21	180	38
Water	1	62.5	62.5

Table G.1. Specific heat of building materials (Foster).

The dynamic nature also means that while masonry can act as a wall by itself, water is fluid and needs to be contained[81]. The material holding the water should be a dark color[82] so as to absorb the most direct sunlight and also prevent algae growth. The mass is more efficient if it captures as much direct sunlight as possible (Bainbridge). The absorption of heat will regulate temperature swings in the house, and a water wall, specifically, will make it so that, "widely fluctuating interior temperatures are not often a

[80] 1 cubic foot of water for each square foot of south facing glass will reduce temperature fluctuations 25°F to 29°F.

[81] Steel tanks, fiberglass tubes and PVC containers are commonly used (Bainbridge).

[82] Bright reflective metallic and white surfaces reflect heat while dark surfaces absorb it (Allen 56).

problem" (Arizona). The right amount of water[83] to provide comfortable temperatures[84] can be calculated as a proportion to the amount of glazing[85] in the space.

Thermal mass in direct solar radiation will store four times more energy than shaded mass if proportioned correctly (Foster 7). The effectiveness of the mass depends on the time it takes heat to travel through the mass[86], which depends on its thickness. A deeper wall is insulated by the surface layers of the material, keeping heat from penetrating as quickly and therefore keeping it from storing as much heat as a thinner wall. Even though they both have the same mass, a 100 sq. ft. of 8" thick material is more effective than 50 sq. ft. of 16" thick material (Foster 8). The heavy materials should therefore be on the inside of the insulating envelope to be most effective in bringing heat to the space (Foster 6). Ventilation[87] can also be added to this system as a means of using the convection[88] process to heat[89] the inhabited space (See Table G.2 and Figure G.1).

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[83] It should be at least 8 inches thick (or 0.67 cubic feet for each square foot of south-facing glass).

[84] Comfortable temperatures are based on providing enough heat in winter to have an average temperature between 65 and 75°F over a 24-hour period.

[85] About one cubic foot of water for each square foot of glazing is needed. The ratio can be increased to 3 cubic feet to decrease daily temperature fluctuations by 6°F.

[86] Water has a specific heat of 1.0, which means that 1 Btu is required to raise 1 pound of water 1 degree. 1 pound of water in turn releases 1 Btu when it drops 1 degree (Foster 5).

[87] There should be two square feet of vent for each 100 square feet of thermal wall surface, equally distributed on the bottom and top of the wall.

[88] The heat moves up the outside of the wall and through the top vents of the mass wall into the space, pulling cold air into the bottom vents and creating a cyclical air movement through the wall.

[89] This gives heat instantly to the space and also heats the mass wall, providing heat storage for later (Arizona).

Determining Ventilation Air Flow

In stack-effect ventilation, air flow is maximized by the height of the stack and the temperature of air in the stack. Air flow is proportional to the inlet area and to the square root of the height times the average temperature difference, as follows:

$$Q = 540A\sqrt{h(T_1 - T_2)},$$

where

Q = the rate of air flow, in cubic feet per hour;
A = the area of the inlets, in square feet;
h = the height between inlets and outlets, in feet;
T_1 = the average temperature of the air in the "chimney," and
T_2 = the average temperature of the return air (normally just the outside temperature),

It is better to add heat (presumably using a passive air-heating collector) at the bottom of the chimney or stack than at the top. In this way the entire column of air in the chimney is hot, creating the desired bouyancy to cause the air to flow.

If outlet sizes are appreciably different from inlet sizes, the above expression must be adjusted according to the following ratios:

Area of Outlets / *Area of Inlets*	*Value to be substituted for 540 in above expression*
5	745
4	740
3	720
2	680
1	540
¾	455
½	340
¼	185

This information is from *Design with Climate* by Victor Olgyay, Princeton University Press.

Don't forget this one, either:
$Q = 540A\sqrt{h(T_1 - T_2)}$

Table G.2. Ventilation sizing data (Foster).

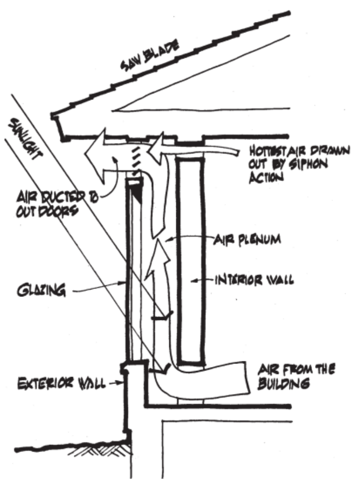

Figure G.1. Thermal mass ventilation diagram (Foster).

APPENDIX H

GREENHOUSE DESIGN

Introduction

Greenhouses are used as a means of growing plants when conventional open-field farming is not possible or has a host of issues associated with it. They are used as a means of protected cultivation and provide optimal conditions for plant growth while protecting plants from pests. There is often an increase in water use efficiency associated with greenhouse use. Some of the issues associated with open air cultivation are high solar radiation intensities, low night temperatures, flooding and surface run-off, plant disease (due to rain, humidity, and storm damage), weeds, erosion and decomposition of fertile soil, fertilizer leaching, higher pesticide use, high evaporation, climatic conditions.

Some of the benefits associated with greenhouse use are protection for the plants and less resource use. The protection is from heavy rainfall, wind, solar radiation, and insects. The lower resource use is due to water conservation with more focused irrigation and fertilization. There is also a lower amount of transpiration and evaporation associated with greenhouses because of the reduced direct solar radiation on the plants.

The amount of light that enters the greenhouse depends on the material cladding the structure. The thickness and amount of light transmittance varies by material and can be layered to have different effects. The orientation also plays a big role in the light transmittance of the greenhouse. The materials used in greenhouse design should have a high transmittance for visible light (photosynthetic active radiation PAR, with wavelengths 400-700 nm) and a low transmittance for long-wave radiation (FIR with wavelengths 3,000 to 20,000nm). It should have minimal aging associated with UV-radiation and a low accumulation of dirt and dust. The material should have no-drop properties so that condensation is a liquid film instead of drops on the inside of the material. The material also needs to have strength against wind (145).

Some prefer the material to be light scattering, reducing the danger of burn on plants while increasing the light spread into the greenhouse, but the PAR (photosynthetic active radiation) is reduced because of the scattering. Direct light is not often a problem in areas with overcast skies or in winter, so generally the PAR should be as high as possible to ensure the most sunlight for the plant growth (See Table H.1) (146).

Greenhouse Materials

There are a number of materials used in greenhouse construction mainly including glass, rigid plastic sheets, and plastic film. Some of the variations of these options are as follows:

- Glass
- Rigid plastic sheets
  - Acrylic double-wall sheets (PMMA)
  - Polycarbonate double wall sheets (PC)
- Plastic film
  - Polyethylene, PE, with UV stabilization
  - PE-IR with absorber for FIR radiation
  - PE-EVA (ethylenevinylacetate), coextruded film with low transmittance for FIR radiation
  - PVC (polyvinylchloride) with low transmittance for FIR radiation
  - ETFE (ethylenetetrafluorethylene) film with a high light transmittance of 93-95%, high transmittance for UV radiation, low transmittance for FIR radiation, and a duration of life of more than 10 years, but a limited width and a relatively high price for more than ten times compared to PE film

The use of plastic predominates in mild climate regions and has a minimal cost associated with it. It is used mostly in tropical, subtropical and arid climates. Turkey is the only country which still has a large amount of glass greenhouses. Rigid plastic is also used in arid regions. The cheapest material is PE plastic film and it can have different additives to create different properties. It may be cheap but it has to be changed frequently because it wears down with sunlight and the stability is reduced by heat and dust (147).

Material	Thickness (mm)	Direct light (%)	Diffuse light (%)
Glass	4	89–91	82
PE film UV	0.1–0.2	89–91	81
EVA film	0.18	90–91	82
PVC film	0.1–0.2	87–91	
ETFE film	0.1	93–95	85
PC double sheet	12	80	61
PMMA double sheet	16	89	76

Table H.1. Amount of light transmittance for glazing materials (Zabeltitz).

Greenhouse Ventilation

Ventilation can be added to greenhouses to keep the temperature from getting too hot. The purpose of ventilation is to exchange air form the inside and the outside. The carbon dioxide and oxygen are then switched while temperature and humidity are controlled. Ventilation is an important function of the greenhouse in order to have quality production. There are two forms of ventilation, natural and forced. Natural ventilation is opening windows and allowing circulation to move the air while forced ventilation is done with fans which rely on electricity to more the air and have higher associated costs because of electricity. Ventilation is required in humid areas where the mean highest temperature is greater than 80 degrees F. Similarly, vents will need to be closed to keep the heat in when the mean minimum temperature is less than 53 degrees F and the greenhouse may need to be heated (30).

Ventilation systems should look at the rate of flow, the temperature difference between inside and outside, the uniformity of the temperature distribution within the greenhouse and the air velocity. These factors affect the quality and quantity of plant growth within the greenhouse (193). Natural ventilation needs a physical pressure difference between the inside and outside of the greenhouse in order to function. These pressure differences are cause by temperature and humidity differences (stack effect) and wind on different surfaces (wind effect). Ventilation openings often have insect screens installed which reduce the efficiency of the ventilation system (194).

Insect Screens

Insects and pests can get into a greenhouse and damage the plants by eating them and by transmitting phytopathogenic organisms (See Table H.2). There are a variety of insect screens which can be installed to subdue the amount of damage. When picking a screen type it is important to know what kind of insects are being screened out. The screen picked will have an impact on the climate of the greenhouse based on the material and size of the pore size of the screen allowing air to move through it. The efficiency of the screen depends on the mesh size, the cross section, the color, and the tightness of the structure. The screen will only keep insects out if the mesh size is smaller than the widest part of the insect that it is intended to keep out (Zabeltitz 234). The components of the screen include the porosity, which is a ratio of open area to the total area of the screen, the mesh or hole size, and the thread dimension. Light transmittance affects the greenhouse and the color of the vent can influence pest behavior. The mesh represents the number of open spaces per inch in each direction and is not sufficient information to determine what screen to pick. Mesh does not tell about the diameter of the thread and therefore the hole size will not be completely accurate. When choosing a screen there should be data about thread diameter, hole size in both directions, and porosity. When installing ventilation, the ration of vent openings to floor area in unscreened greenhouses should be 18-29% (Zabeltitz 235).

Insect pest	Hole size (mm)	
	Bethke	Teitel
Leaf miners (*Lyriomyza trifoli*)	0.64	0.61
White fly (*Bemisia tabaci*)	0.462	0.46
Aphid (*Aphis gossipii*)	0.341	0.34
Greenhouse white fly (*Trialeurodes vaporariorum*)		0.29
Silverleaf white fly (*Bemisia argentifolii*)		0.24
Thrips (*Frankliniella occidentalis*)	0.192	0.19

Table H.2. Insect size to determine screen porosity (Zabeltitz).

APPENDIX I
LIGHTSHELF

Lightshelves are used to passively and naturally bring light deeper into a space. They create higher levels of daylight and an improved luminance gradient. This happens throughout the year and while the amount of benefit will change with the seasons, it will be an improvement in any season. The increase of light indicates “that lighting energy consumption and cooling energy due to lighting can be substantially reduced with improvements to visual comfort” (Beltran). Sunlight is reflected off of a shelf and onto the ceiling, bringing natural light farther into the space than possible with a conventional window, without increasing the daylight levels by the window. The redirection of sunlight improves visual comfort by making a more uniform light level on the walls and ceiling and diminishes direct source glare as well.

The surface of the reflective shelf can vary depending on whether the light is going to be reflected directly or refracted and diffused onto the ceiling. A study by the University of California, Berkeley showed that a south facing window area of 12 square feet can “achieve workplace illuminance levels of over 300 lux throughout the year…and can achieve over 50 lux at a distance of 27.5 feet from the window” (Beltran). This means that a light level high enough to be used for office tasks can be reached within 30 feet of the window using purely passive techniques. A white surface color allows for more reflectance onto the ceiling (Kawneer).

APPENDIX J
FEASIBILITY

The project focuses on the ability to combine a plant growing environment with a building façade. The feasibility of this venture is important to consider when contemplating how likely it would be that this project would be installed.

The cost of the system is primarily the initial cost of materials and installation. The capital needed to maintain the system is based purely on replenishing the growing nutrients and paying for the electricity to run the water pump.

There is an associated lower cost of electricity within the building itself when this product is installed. Daylight is admitted farther into the building than previously and heating and cooling costs are lowered due to the thermal properties of the system itself. There is less electricity used in heating and cooling the living unit because of the thermal properties of the project, providing a better building insulation than is currently installed in the Ya-Po-Ah Terrace.

Initial Material Cost[90]

Hydroponic System

Gully: $350.00

Net pots: $4.80 ($0.20 each for 24pots)

Coir: $3.00

Pump: $65.00

PPM/EC/pH meter: $100.00

Water reservoir: $65.00

Reservoir lid: $40.00

Tubing: $25.00

= $655 for the hydroponic system

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[90] Cost is based on store prices for similar materials in April 2012 and is found from these sources: Amazon, American Hydroponics, Home Depot, and Simply.

Wall

Drywall: $14.00

Steel Framing

Steel Studs: $2.50

Steel Track: $3.48

Denim Insulation: $36.00

= $65 for the wall materials

Windows

Exterior Upper Fixed Window: $150

Exterior Lower Window with Two Hoppers: $200 (Hoppers $25.00 each) ($150 fixed glazing)

Interior Bi-fold Window: $250.00

= $600 for the windows

= $1320 for the material cost of the entire system

Continuing Costs

Electricity Used

Pump use[91]: (3 Watt solar pump) (3 Watts x 24 hours/day x 365 days/year)/ 1000

= 26.28 kWh x 7.7cents/kWh[92]

= $2.02/year

[91] "You can use this formula to estimate an appliance's energy use:
(Wattage × Hours Used Per Day) ÷ 1000 = Daily Kilowatt-hour (kWh) consumption

1 kilowatt (kW) = 1,000 Watts
Multiply this by the number of days you use the appliance during the year for the annual consumption. You can then calculate the annual cost to run an appliance by multiplying the kWh per year by your local utility's rate per kWh consumed" (U.S. Department of Energy).

[92] Based on EWEB energy charge for residential customers (EWEB).

Nutrients

Cost of nutrients: $80.00 (5 liters)

Dutch formula suggests 100ml of Nutrient to every 10Litres of water (Hydroponics).

30 gallons = 114 liters

11.4 x 100mL = 1140 mL = 1.14 L initial amount added

Once established, top up nutrients as needed.

1.14 L/year x 80$/5L

= $18.25/year

= $20.26 /yearly to maintain the system

Comparison

Price of buying strawberries

25 plants will feed the average family of four annually.

The average person eats more than 3 lbs. of strawberries per year.

This product produces an average of 12 lbs. of strawberries/year.

Avg. $2.28/lb. for strawberries (Anderson) x 12lb

= $27.36 for 12lbs of strawberries

The research states that plants can greatly reduce the amount of energy used for heating and cooling the inside of a building. Plants and air spaces act as insulation and reduce the amount of thermal movement through the building façade. The beneficial effects of plants and of the associated building components within this project all work to create a better building envelope.

Energy use is reduced because of increased light reflection into the space and a more insulated building envelope. The research suggests that energy use would be reduced significantly with the use of this project. Previous studies done on the effects of the various components of this project often give a range of possible benefits. The combination of these components is therefore difficult to quantify.

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