

ORIGINAL ARTICLE

Investigative Root Cause Analysis for Land Free Urban Microgrid Farm for Food, Water, and Energy

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ABSTRACT

Many urban farms are designed to be indoors or use traditional soil or energy generation techniques. Microgrids provide local electricity to a small network of users with power storage. Few urban farms and microgrids are designed and engineered to draw energy from extreme weather events producing electricity and water. The current study examines the feasibility of a self-sufficient, adaptive small-scale microgrid farm harnessing power from multiple renewable energy (solar and wind), and rainwater collection techniques while producing food. This study's objective is to conduct an investigative Root Cause Analysis of an outdoor hydroponic system named Pangea. The study findings suggest an outdoor hydroponic system shares many defects from exposure to shifts in climatic conditions to poor engineering and design. The concept and technological aspect of this work can be transferred to commercial, large-scale greenhouse.

KEYWORDS: *Pangea, Greenhouse, Energy Production, Sustainability, Food Harvest.*

INTRODUCTION

Weather patterns and behaviors share unknown risks from potential accidents to near misses. It can alter trade routes, influence industry, alter animal and human behaviors, force community relocation, and endanger citizens to extreme weather events like wildfires or flooding. A lot of adaptive and mitigative techniques have been used to combat these incidents. Adaptability and mobility are the essential characteristics practiced by the hydroponic garden system to minimize the human footprint and unaltered landmasses and ecosystems as mentioned by Leopold

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(1949), "preserving the biotic community will ultimately increase land use for humans by respecting both nature and humanity" [1]. While growing food, we need to enhance biodiversity and maintain economic gains supporting a carbon-neutral future.

Pangea is an outdoor hydroponic garden system that harvests food, water, and energy. The concept is a precursor on how to incorporate the technology from an outdoor hydroponic garden to a commercial-grade greenhouse adaptive to its environment. Through investigative Root Cause Analysis, the hydroponic garden share many flaws from the exposure to shifts in climatic conditions to poor engineering and design.

This study utilizes four Root Cause Analysis techniques. A 5-why's method identifies each problem in a question-answer format followed by a fishbone diagram and event correlation that provides a supplemental visual layout. The Failure Mode and Effects Analysis (FMEA) present an overview of the previous problems analyzed, plus potential future difficulties. The result of this paper is to analyze current and future hazards, inefficiencies, and vulnerabilities identifying or detailing how to address each.

This work plans to address all potential incidents through adaptive conservational design harnessing what we define as bad weather and produce positive results.

Literature Review:

Farming is the business of using land, labor, and capital for the production of goods (crops and livestock) to be sold. Urban farming is an indoor and outdoor plant cultivation that serves populations by processing and distributing food in cities. Urban agriculture currently produces 20% of the world's food globally [2]. Moreover, health and nutrition, food security, transparency, education, urban sustainability, and growing demand for local food are key factors contributing to the popularity and growth of urban farming. In 2017, the global urban farming market by revenue was projected to be \$210 billion, with a CAGR growth forecast from 2018 to 2023 of 1.99% (\$236.4 billion) [2]. By 2026, the urban farming market is projected to reach \$288.71 billion, with a CAGR of 3.6% [3]. The Food and Agriculture Organization of the United Nations (UNFAO) estimated that urban garden plots can be 15 times more

productive than rural farming, plus considered a solution for the effects of climate change and an important role in global food security [2].

Hydroponics is the growing method where plants are cultivated in a nutrient solution rather than soil. The US reports 3,214 businesses in the industry with total revenues of \$891 million; and an annual growth rate of 1.2% between 2013 and 2018 [4]. The global market in 2018 is estimated to be valued at \$27.94 billion, with a compound annual growth rate (CAGR) of 6.8% (\$35.51 billion), in the next five years [5-6]. Europe accounts for 47.3% of the overall market, Africa, considered the fastest-growing market [7].

There are many methods for hydroponic farming. Typically, hydroponic systems start their seed in a plug, a compact solid growing medium for seeds to germinate and bare-root. Techniques used in this paper, deep-water culture or float systems, are constantly exposed to nutrient-rich aerated water [8].

Microgrids are small power sources to supply local inhabitants with electricity. They can be centralized or decentralized from a city-states grid [9]. Typically, microgrids are known to store not generate power. This paper attempts to redefine the conventional meaning of a microgrid by discussing how to capture food, water, and electricity in the form of renewable energy to narrow the distribution gap.

Pangea – Outdoor Hydroponic Garden System Components:

Pangea consists of Garden Bed and Utility Box, Vertical Axis Wind Turbine (VAWT), and Water Reservoir as shown in Figure 1.



Fig 1. Pangea components

Garden Bed and Utility Box:

The garden bed and utility box are both most vital elements of this system. As shown in Figure 1 and Figure 2, a garden bed provides a means for plants to be grown and harvested while resting on the stainless-steel drum. The utility box stores electricity from solar

and wind power to a battery along with electrical components like a charge-controller directing the energy from the two renewable power sources, an inverter converting direct current to alternate current, and an air pump introducing oxygen into the water supply for the plants in the garden bed to survive.



Fig 2. Garden bed and utility box

Garden bed and utility box breaking sequence has been shown in Figure 3 by a Fishbone diagram.

Bones represents all the causes and head represents the effect.

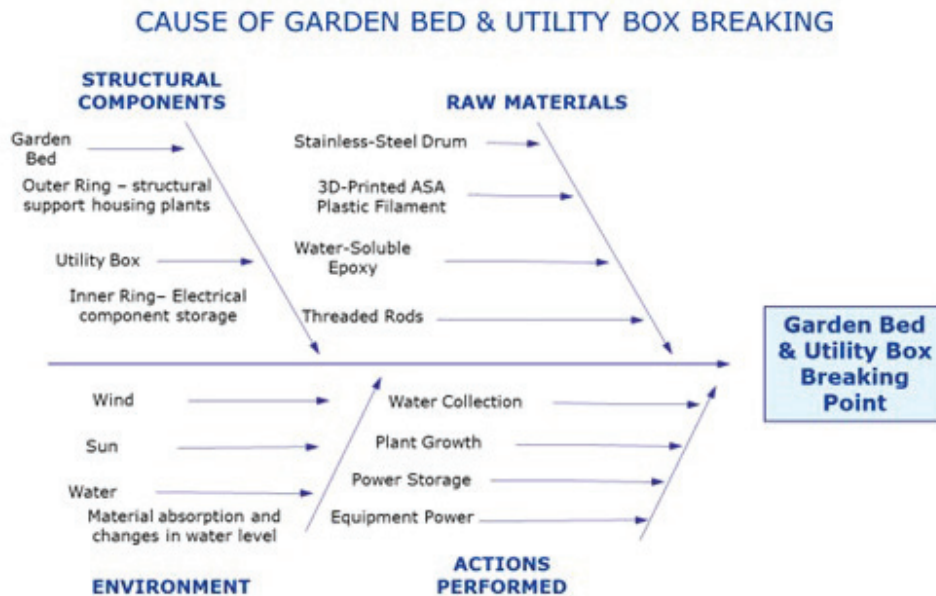


Fig 3. Garden bed and utility box breaking point Fishbone diagram

Garden Bed and Utility Box (5-Whys):

As shown in Figure 2, the garden bed is made of two separate 3D-printed components using ASA plastic filament, an inner (utility box), and an outer ring (garden bed) joined by a water-soluble epoxy solution.

- Problem
 - As indicated in Figure 4 by a red box, the breaking point of the outer and inner ring of the garden bed and utility box is splitting and collapsing upon itself.
- A. Why do the two separate 3D printed pieces break apart?
 - The inner ring has an added weight of electrical components forcing the inner ring downward, and the outer ring has three evenly spaced supports resting atop the stainless-steel drum causing the outer ring to shift upward.
- B. Why did threaded rods inserted and joined into the two pieces with epoxy solution still collapse?
 - The threaded rods helped secure the two pieces together but did not address the problem between the weight and force relationship between the two pieces. The 3D printed pieces are now known to absorb water, adding extra weight to the garden bed and utility box. When the water level in the stainless-steel drum decreases, the garden bed and utility box are no longer floating in the drum. The outer ring becomes reliant on the stainless-steel drum to support the two-pieces in its fixed position until the water reaches back to a higher position where the garden bed and utility box are floating again. The constant fluctuation in the water level gradually produces friction between the two pieces until a breaking point occurs.
- C. Why do the garden bed and utility box need to join together and be part of the same component?
 - There is no reason why this outer and inner ring design needs to be present. It was initially thought that the electrical components providing power to

- the garden needed to be in a grounded fixed position near the garden bed and away from water.
- D. Why do we need the garden bed and utility box to rest atop the stainless-steel drum?
- The garden bed and utility box do not need to rest atop the stainless-steel drum. The three structural supports of the outer ring were first introduced to stabilize and secure the garden bed and utility box in a fixed position. With the constant change in water-level and weight, we now know this causes structural damage, plus it does not provide a reliable source of water and nutrients for the plants to survive in the system. It is believed that the garden bed and utility box can be separate components.
- E. Why do we need to use the components 3D printed in ASA material?
- There is no benefit or reason for using the 3D printed ASA material. ASA was originally chosen because it can withstand and be exposed to an outdoor environment for long periods while maintaining its appearance and resistance. This design will cause us to reposition the utility box, which can rest on top of a clamping mechanism supporting a circular acrylic sheet to place the electrical components inside the utility box cover. The acrylic sheet can be tied down along six contact points fastening itself to the stainless-steel drum to maintain its balance.

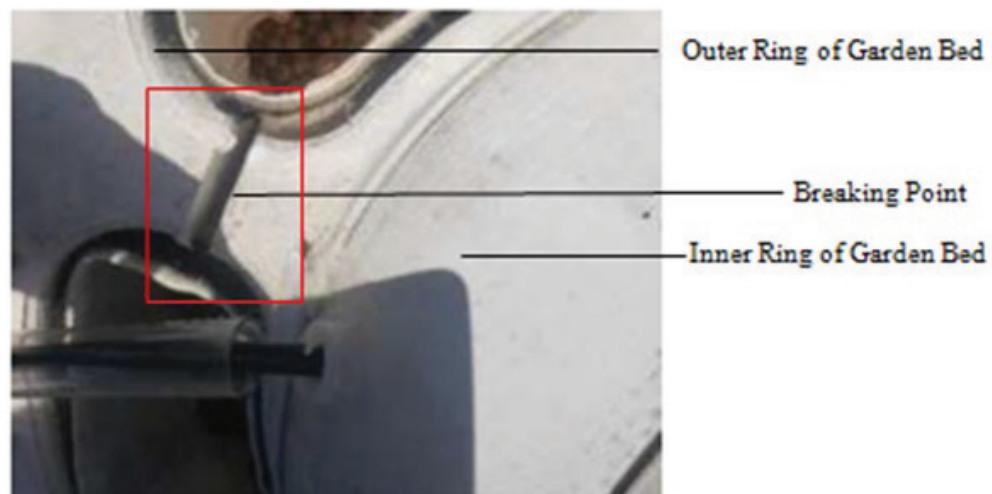


Fig 4. Inner and outer ring of garden bed component broken

Due to tensile force, water filling inside the gaps of the 3D printed garden bed component, constant fluctuations of water level in the stainless-steel drum, and pressure from the weight of the utility

box and VAWT cause the garden bed component to fracture, which has been presented in Figure 4. Redesign has been conducted to avoid this situation and is shown in Figure 5.



Fig 5. Current garden bed and utility box after redesign

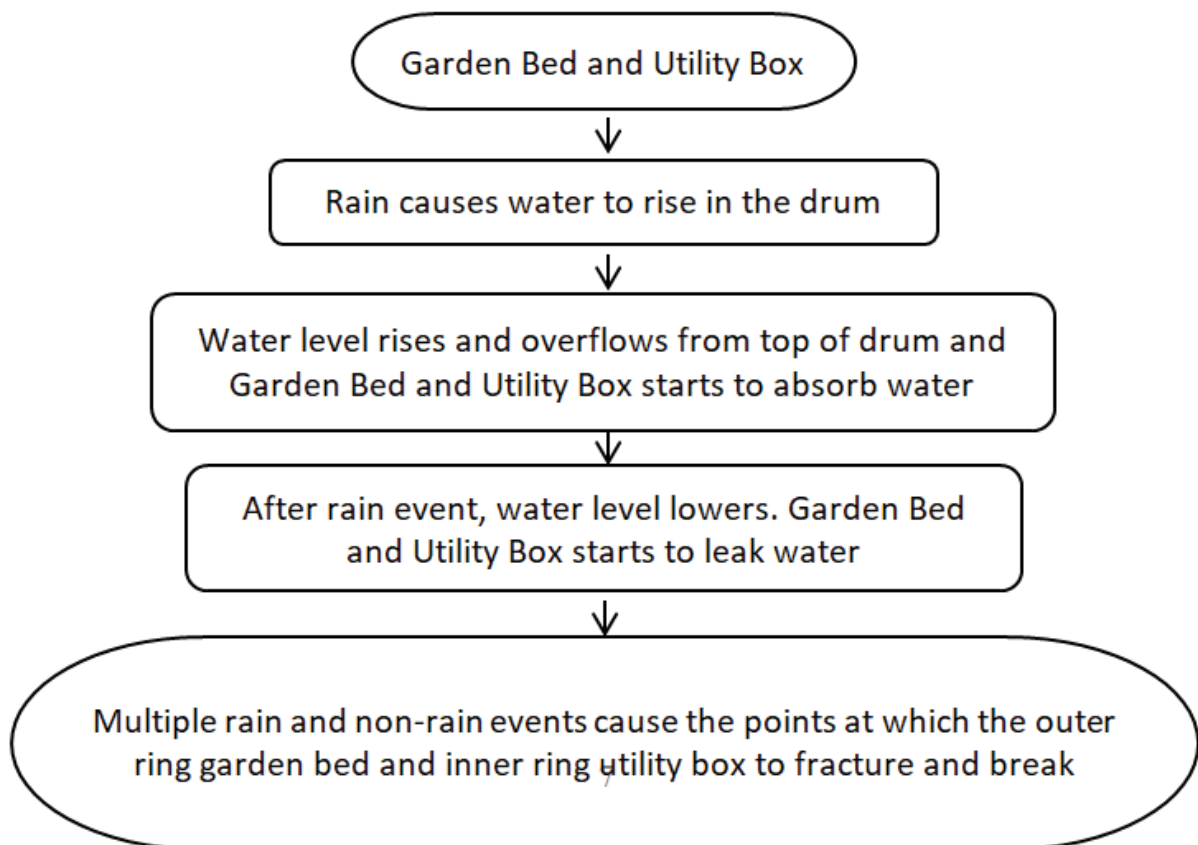


Fig 6. The flow chart of garden bed and utility box event correlation

Garden Bed and Utility Box Event Correlation:

The flow chart of garden bed and utility box event correlation has been illustrated shown in Figure 6.

Vertical Axis Wind Turbine (VAWT):

Two designs are tried. The previous design is shown in Figure 7. The new design forces the VAWT to be repositioned for the garden bed as shown in Figure 8. Originally the VAWT rested rigidly fixed on the inner ring of the garden but must be relocated due

to the new garden bed design. The utility box rests atop an acrylic circular plate and anchored by clamping mechanisms. Another acrylic circular plate and clamping mechanism allows the VAWT to be vertically raised or lowered based on the current location, obstructions, and wind speeds. The human hazards involved with operating the garden and striking into the VAWT while it's in operation have been addressed but must be developed, executed, and tested. Power utilities and electronics are placed further away from the water, which reduces the risk of electrical shock.



Fig 7. Previous design of VAWT for Pangea

Vertical Axis Wind Turbine (VAWT)

(5 whys):

- Problem
 - The new design for the garden bed and utility box forces the VAWT to be repositioned.
- A. Why does the VAWT need to be repositioned?
 - The garden bed and utility box are no longer resting atop the stainless-steel drum. The garden bed is now a polyethylene sheet floating in the stainless-steel drum. The utility box is now supported by a clamping mechanism fastened by

Velcro nylon straps from an acrylic circular sheet to the stainless-steel drum.

- B. Why does the utility box need a clamping mechanism?
 - The utility box needs to be out of contact with water. The clamping mechanism allows the utility box to roam and fix itself freely upon the z-axis of the center pole.
- C. Why do we need Velcro nylon straps?

- The Velcro nylon straps allow the utility box to fit fixed and securely along the center pole. Without the Velcro nylon straps, the utility box, VAWT, and center pole will move when wind and rain are present. It has also been observed that without fastening the utility box and VAWT, the VAWT will not spin and rotate when the wind is present.
- D. Why would the utility box need to roam freely upon the z-axis of the center pole?
 - The VAWT will not spin and generate power with any obstructions from the wind. These obstructions can be plant heights in the garden bed or other plants and structures surrounding the Pangea system. Ultimately, the higher the VAWT, the more power it can generate from higher wind speeds known to be present at higher altitudes.
- E. Why does the VAWT need to be positioned above the utility box?
 - The utility box shelters the VAWTs gear-motors and wiring cables from the elements. When the utility box is repositioned, so is the VAWT.



Fig 8. Current design of VAWT for Pangea

Water Reservoir:

The water reservoir and center rods are made from stainless steel and 6061-aluminum. These metals are known to hold up well in marine environments, but white rust and algae have been spotted on both the rod and drum. Algae and rust do not bode well when

growing food for human consumption. Marine paint or coating and regular maintenance can be applied as mitigation and adaptive techniques. In the future, replacing stainless steel with clay could be a more desirable alternative. The added benefit of clay being it acts as a coolant in contact with water.

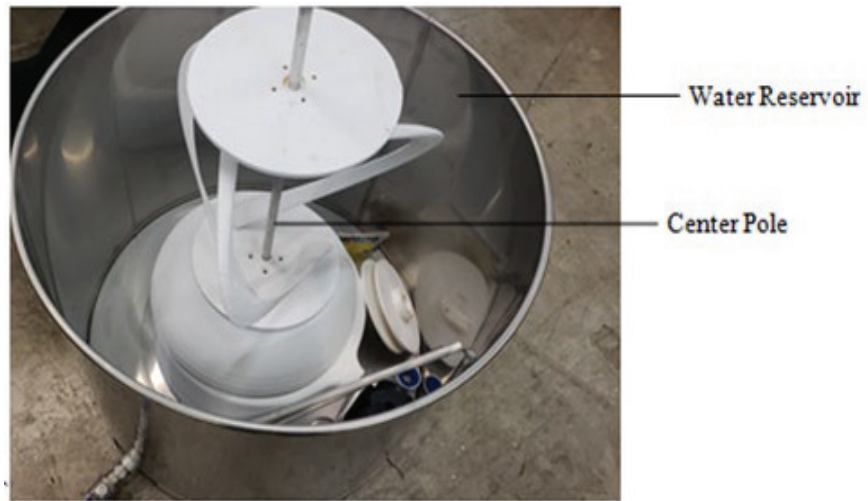


Fig 9. White Rust and Algae presence

The flow diagram of white rust and algae presence sequence has been presented in Figure 10.

Bones represents all the causes and head represents the effect.

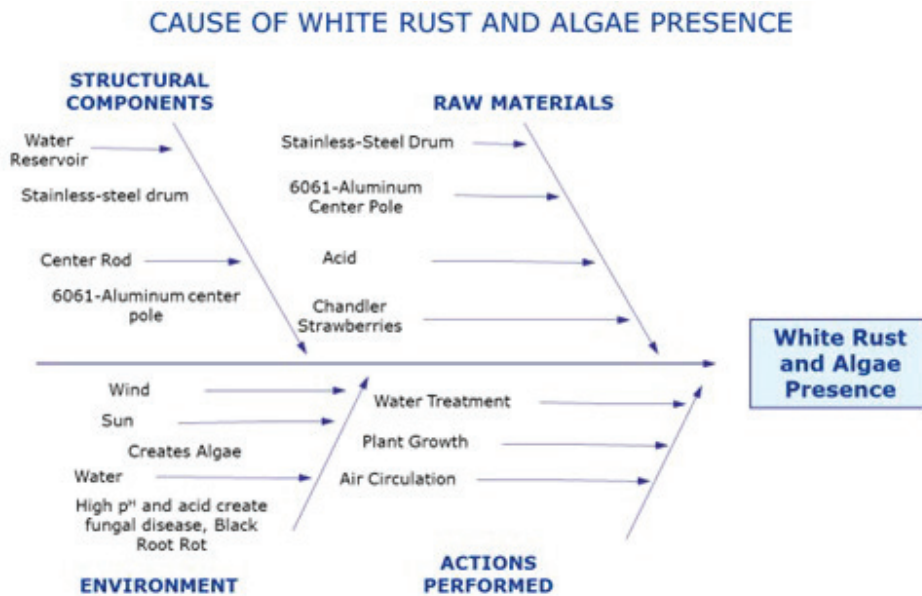


Fig 10. Fishbone diagram of white rust and algae presence

Water Reservoir (5-Whys):

- Problem
- White rust and algae are spotted on the 6061-aluminum center pole and stainless-steel drum, which is not preferred when growing food for consumption.
- A. Why is white rust present?
 - Acid was frequently introduced in the water daily around the outer lip of the stainless-steel drum to regulate the water P^H . As showed in Figure 9, white rust was present in the outer lip of the stainless-steel drum and the 6061-aluminum center pole.
- B. Why is acid needed to regulate the water P^H ?
 - All plants require a specific NPK (Nitrogen, Phosphorous, and Potassium) value and P^H , regardless if they are grown in soil or soilless environments. Acid is a common ingredient used to lower a water's P^H while also causing metals to rust in water.
- C. Why would algae be present in the stainless-steel drum?
 - Algae's presence was due to a combination of chemical imbalances in the water supply and

abundance of sunlight. Other factors could include poor air circulation and oxygen or total dissolved oxygen in the water supply.

- D. Why is there more white rust present on the 6061-aluminum center pole than the stainless-steel drum?
 - The manual treatment of acid was not the primary culprit for the white rust occurring. Algae's presence in the water supply indicates that the health of the plants in the garden bed and the plant roots proximity to the center pole causes white rust to occur.
- E. Why were the plants poor in health?
 - Human error and poor chemical imbalance management caused the plants to degrade in health. The chandler strawberries started to experience black root rot and are caused by a fungal disease known as, *Thielaviopsis basicola*. This fungus flourishes in wet, cold environments with high acidity over 5.8 P^H .

A combination of poor water and chemical management plus unfavorable environmental conditions and metal presence caused a fungal disease to occur known as black root rot, as shown in Figure-11.

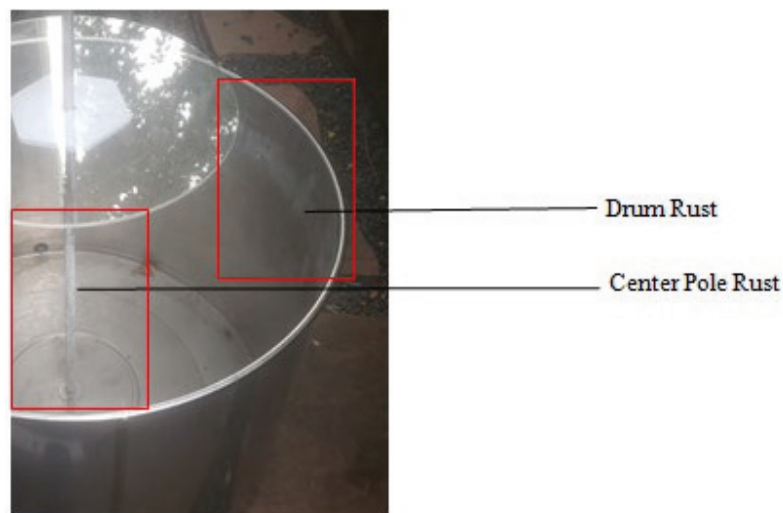


Fig 11. Pangea with white rust present on center pole and inside drum

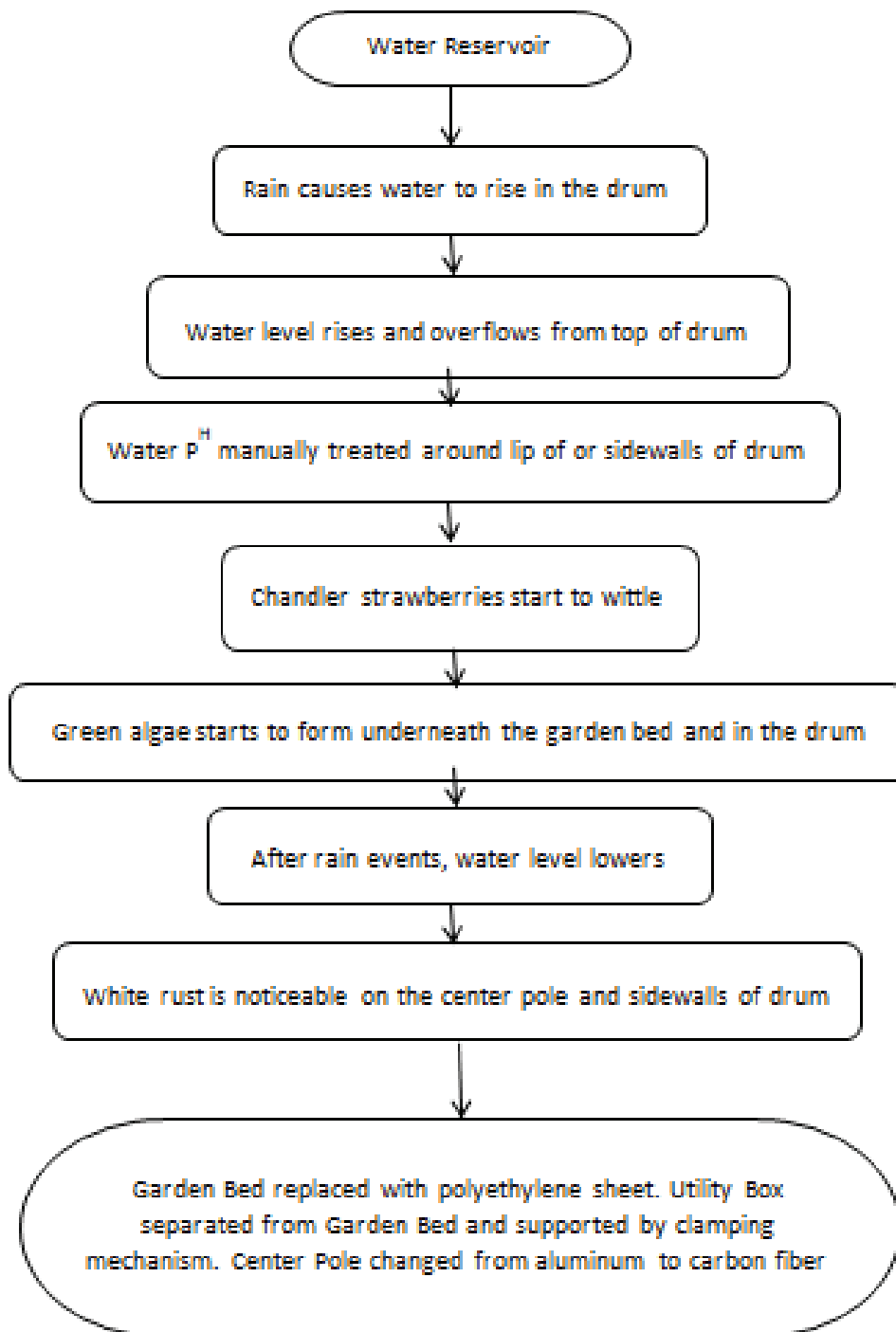


Fig 12. The flow chart of water reservoir event correlation

Water Reservoir Event Correlation:

The flow Chart of water reservoir event correlation is shown in Figure 12.

Design Failure Mode and Effects Analysis (DFMEA):

Design Failure Mode and Effects Analysis (DFMEA) for Water Reservoir have been presented in

Table 1. Design Failure Mode and Effects Analysis (DFEMA) for garden bed and utility box for grow plants, watering times, plant roots reach water and nutrients, structural integrity and strength, power storage are tabulated in Table-2 to Table-5. Design Failure Mode and Effects Analysis (DFEMA) for VAWT have been illustrated in Table 6.

Table 1. Design Failure Mode and Effects Analysis (DFEMA) for Water Reservoir

Item / Function	Requirements	Potential Failure Mode	Potential Effect(s) of Failure	Severity (0 - 10)	Potential Cause(s) of Failure	Current Design Controls Prevention	Occurrence (0 - 10)	Current Design Controls Detection	Detection	Risk Priority Number, RPN (SxOxD)	Recommended Action(s)
Water Reservoir	Capture and store rainwater into tank	Not enough water	Plants die or require extra source of water	7	Not enough rain	Manual watering	4	Routine observation, maintenance, and logging	7	196	Use supplemental water source like garden hose for manual water over the top of the tank or attaching to spiggot. Future consideration be atmospheric water
		Too much water	Water overflows the top or manually released by spiggot at bottom of tank	0	Too much rain or human error	Overflow from top or spiggot	6	Routine observation, maintenance, and logging	5	0	Release excess water into separate tank and utilize during times when not much water is present
	Water plants	Not enough water	Plants die or require extra source of water	7	Not enough rain	Manual watering	4	Routine observation, maintenance, and logging	7	196	Use supplemental water source like garden hose for manual water over the top of the tank or attaching to spiggot. Future consideration be atmospheric water generation
		Too much water	Plants die due to oversaturation or limit type of plants used in the system	2	Too much rain or human error	Overflow from top or spiggot	6	Routine observation, maintenance, and logging	5	60	Release excess water into separate tank and utilize during times when not much water is present
	Provide nutrients and acid	Not enough nutrients or acid	Plants die due to nutrient and water deficiencies or limit the growth cycle	9	Human error and poor water management	None	5	Routine observation, maintenance, logging, and periodic water tests	10	450	Develop routine tests measuring water contents with potential automation and dispensing capabilities eliminating human error
		Too much nutrients or acid	Plants die due to oversaturation or limit the growth cycle	9	Human error and poor water management	None	5	Routine observation, maintenance, logging, and periodic water tests	10	450	

Table 2. Garden Bed and Utility Box Design Failure Mode and Effects Analysis (DFEMA) for Grow Plants

Requirements	Potential Failure Mode	Potential Effect(s) of Failure	Severity (0 - 10)	Potential Cause(s) of Failure	Current Design Controls Prevention	Occurrence (0 - 10)	Current Design Controls Detection	Detection	RPN (SxOxD)	Recommended Action(s)
Grow plants	Not enough water	Plants die or require extra source of water	7	Not enough rain	Manual watering	4	Routine observation, maintenance, and logging	7	196	Use supplemental water source like garden hose for manual water over the top of the tank or attaching to spiggot. Future consideration be atmospheric water generation
	Too much water	Plants die due to oversaturation or limit type of plants used in the system	2	Too much rain or human error	Overflow from top or spiggot	6	Routine observation, maintenance, and logging	5	60	
	Not enough nutrients or acid	Plants die due to nutrient and water deficiencies or limit the growth cycle	9	Human error and poor water management	None	5	Routine observation, maintenance, logging, and periodic water tests	10	450	Develop routine tests measuring water contents with potential automation and dispensing capabilities eliminating human error
	Too much nutrients or acid	Plants die due to oversaturation or limit the growth cycle	9	Human error and poor water management	None	5	Routine observation, maintenance, logging, and periodic water tests	10	450	

Table 3. Garden Bed and Utility Box Design Failure Mode and Effects Analysis (DFEMA) for Watering times, plant roots reach water and nutrients

Requirements	Potential Failure Mode	Potential Effect(s) of Failure	Severity (0 - 10)	Potential Cause(s) of Failure	Current Design Controls Prevention	Occurrence (0 - 10)	Current Design Controls Detection	Detection	Risk Priority Number, RPN (SxOxD)	Recommended Action(s)
Watering times, plant roots reach water and nutrients	Not enough water	Plants die due to absence or consistence of water and nutrient deficiencies	10	Not enough rain or supplemental watering	Manual watering or redesign	5	Routine observation and maintenance	1	50	Redesign the garden bed so that it's in constant contact with water
	Too much water	Plants die due to absence or consistence of water and nutrient deficiencies	10	Too much rain	Overflow from top or spiggot	5	Routine observation, maintenance, logging, and periodic water tests	2	100	Release excess water into separate tank and utilize during times when not much water is present
		Plants die due to fungal infection like Black Root Rot	10	Too much rain or human error due to chemical Imbalances like NPK and acid values	None	5	Routine observation, maintenance, logging, and periodic water tests	7	350	Develop routine tests measuring water contents with potential automation and dispensing capabilities eliminating human error

Table 4. Garden Bed and Utility Box Design Failure Mode and Effects Analysis (DFEMA) for Structural Integrity and Strength

Requirements	Potential Failure Mode	Potential Effect(s) of Failure	Severity (0 - 10)	Potential Cause(s) of Failure	Current Design Controls Prevention	Occurrence (0 - 10)	Current Design Controls Detection	Detection	Risk Priority Number, RPN (SxOxD)	Recommended Action(s)
Structural integrity and strength	Too much water	Material absorbs water	7	Too much rain or manual supplemental watering	Manual release water from spiggot	6	Routine observation and maintenance	7	294	Redesign the garden bed so that it does not rest rigidly fixed on the stainless-steel drum
	Not enough water	Water absorption weighs material and component down	7	Not enough rain	Manual watering with garden hose	4	Routine observation and maintenance	7	196	Redesign the garden bed so that it does not rest rigidly fixed on the stainless-steel drum
	Water level fluctuation	Friction and pressure from weight of objects resting on component fractures component	10	Inability to manage water level	Constant manual release and watering	3	Routine observation and maintenance	8	240	Redesign the garden bed so that it does not rest rigidly fixed on the stainless-steel drum
	Material and design choices	ASA plastic absorbs water due to 3D printing technique hollow component	10	Material choice and design, plus manufacturing assembly	Constant manual release and watering	3	Routine observation and maintenance	2	60	Redesign the garden bed so that it does not rest rigidly fixed on the stainless-steel drum

Table 5. Garden Bed and Utility Box Design Failure Mode and Effects Analysis (DFEMA) for Power Storage

Requirements	Potential Failure Mode	Potential Effect(s) of Failure	Severity (0 - 10)	Potential Cause(s) of Failure	Current Design Controls Prevention	Occurrence (0 - 10)	Current Design Controls Detection	Detection	Risk Priority Number, RPN (SxOxD)	Recommended Action(s)
Power storage	Not enough power	Air pump providing oxygen cause plants to die overtime	7	Not enough solar or wind	Two sources of renewable energy	3	Charge controller relays information on-site and remotely	6	126	Introduce failsafes to notify power readings and turn off devices for minimal loss
	Too much power	Severe damages or stop or limit system functions	2	Too much solar and wind	Charge controller regulating power	5	Charge controller relays information on-site and remotely	6	60	Introduce failsafes to notify power readings and turn off devices for minimal loss
	Electric components too hot	Severe damages or stop or limit system functions	10	Hot and humid temperatures	Fans, monitoring equipment, and design features	7	Charge controller relays information on-site and remotely	9	630	Introduce failsafes to notify temperature readings and turn off devices for minimal loss with potential insulation and design features to maximize air flow
	Electric components too cold	Damage or diminish performance	6	Cold temperatures	None	4	Charge controller relays information on-site and remotely	9	216	Introduce failsafes to notify temperature readings and turn off devices for minimal loss with potential insulation
	Electric components wet	Damages or diminish performance	9	Too much rain, overflow, or human error	Weathering strip and covering	3	Routine observation, maintenance, and logging	9	243	Ensure weathering strips and coverings are weather and waterproof, plus ensure other components are structurally sound

Table 6. Design Failure Mode and Effects Analysis (DFEMA) for VAWT

Item / Function	Requirements	Potential Failure Mode	Potential Effect(s) of Failure	Severity (0 - 10)	Potential Cause(s) of Failure	Current Design Controls Prevention	Occurrence (0 - 10)	Current Design Controls Detection	Detection	Risk Priority Number, RPN (SxOxD)	Recommended Action(s)
Vertical Axis Wind Turbine (VAWT)	Clamping Mechanism	Clamping force and weight limits	Clamp breaks and causes VAWT to collapse	10	Too much weight or friction caused by wind or gear motor	Added thickness near clamping mechanism	3	Routine observation, maintenance, and logging	9	270	Test clamping mechanism on periodic basis, potentially change material choice
	Balance	Too much wind or water causes center pole to become imbalanced	Center pole fractures or breaks and VAWT collapses	10	Too much weight or friction caused by wind or gear motor	Added tie downs securing pole in vertically centered position	7	Routine observation and maintenance	8	560	Introduce velcro nylon straps and tied downs to secure center pole in vertically centered position

CONCLUSION

This paper examines an outdoor hydroponic system using Root Cause Analysis (RCA) techniques. Four RCA techniques were applied: 5-Whys, Fishbone diagram, Event correlation, and Failure Mode and Effects Analysis (FMEA). The Pangea hydroponic garden is a precursor of how adaptive conservational design can harness the climate and environmental surroundings with a lower human footprint to unalter existing landmasses while fulfilling sustainable development’s goal is to narrow the gap between distribution and production, utilizing existing natural systems to produce energy, whether it be food, water, or utilities.

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CONFLICT OF INTEREST:

The authors declare that there is no conflict of interest in this paper.

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