BSc Civil Engineering
BSc Thesis

Performance Measurements on Green Roofs – Water and Energy Resources

Student Youssef El Sadek

Supervisor: DR. K. VRIELINK (SEAN)

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UNIVERSITY OF TWENTE.

Preface

As I stand at the significant milestone of concluding my BSc Civil Engineering degree at the University of Twente, I take a moment to reflect upon the journey that brought me to the completion of this research project. The journey was filled with challenges and lessons that gave me knowledge but also a perspective grounded in the importance of sustainable development and environmental awareness. The initiative undertaken by Green Panels not only addresses the pressing climate issues but also envisions a sustainable future through the development of green roof systems. Being a future civil engineer, I feel privileged to have gotten the opportunity to learn more about this creative project and explore the effectiveness and potential of green roof systems in the context of Dutch climatic conditions. This thesis, therefore, presents an analytical perspective through research and experimentation on the performance of green roof systems and their potential to reduce the adverse effects of climate change.

I would like to thank my supervisor, Sean Vink, for the incredible support, guidance, and valuable feedback that significantly helped me complete my thesis project. I got to learn new skills such as using sensors and data loggers, which can be helpful in my field and others.

I would like to thank Aurélio Wijnands, CEO & Co-Founder of Green Panels, the start-up that entrusted me with this project, for their guidance and incredible support throughout this journey.

Finally, I think the knowledge gained from this research can serve as a foundation for future developments in this field and help Green Panels enhance their sustainable solutions. This project shows that it's possible to think about business success and taking care of the environment simultaneously. It opens up new paths for work that brings together progress and nature.

Youssef El Sadek

September, 2023

Summary

Climate change projections for the Netherlands show an increase in mean temperature, extreme precipitation, and sea level rise, which could significantly impact the Dutch economy and society, particularly regarding extreme weather events. Green Panels, the start-up company that commissioned the project, aims to develop an innovative concept for green roof systems. There are two categories of green roofs, which are intensive and extensive. Green roofs have various benefits, including efficient stormwater management, energy conservation, urban heat island mitigation, biodiversity enhancement, air quality improvement, noise reduction, and aesthetic improvement. Performance measurements are done to ensure that the developed systems are theoretically sound, practically applicable, and effective. The primary objective of this research is to evaluate the performance in terms of reduced energy consumption, mitigated extreme temperatures, and delayed flood runoff peaks. In order to achieve the research goal, the following list of research questions are investigated:

1. How do Green Panels' sloped green roof systems perform in terms of reducing energy consumption and mitigating extreme temperatures?
2. How do the Green Panels' green roof systems contribute to delaying flood runoff peaks and capturing and transpiring precipitation?
3. How do different materials, substrates, and configurations of green roof layers influence the performance of Green Panels systems?
4. How do laboratory test results compare with real-life performance measurements for Green Panels green roof systems?

An experiment is done comparing roof with Green panels green roof systems with a conventional roof. The experiment used two types of sensors: an environmental sensor (BME680) and a soil moisture and temperature sensor (truebner SMT50). After gathering data for five days, t-test statistical analysis compares variables to the weather temperature. The research fundamentally illustrates that except for the scenario involving Box 2, which exhibited a statistically significant temperature difference, most areas studied do not showcase significant temperature variations compared to general weather conditions.

Contents

Chapter 1

Introduction

Climate change has become a pressing global issue, with its wide-ranging consequences on the environment and human populations. The continuous rise in greenhouse gas emissions and the depletion of natural resources has significantly impacted the ecosystem, biodiversity, and public health. As the effects of climate change continue to rise, this growing challenge has required a renewed focus on sustainable development and the need for innovative strategies to combat its harmful effects. Consequently, engineers and urban planners are increasingly considering integrating climate-resilient infrastructure and nature-based solutions to create more sustainable and liveable cities. Climate-resilient infrastructure refers to the physical systems and buildings that can resist, adapt and recover from the impacts of climate change. On the other hand, nature-based solutions utilize natural processes and ecosystems to address climate change impacts. Green roofs are a pertinent example of a nature-based solution that can be implemented in cities to address climate change. Adding vegetation to the roofs of buildings can help absorb excess rainwater, reduce the urban heat island effect, and provide habitat for birds and other wildlife [1]. Additionally, green roofs can improve air quality, reduce energy consumption, and enhance the overall aesthetics of a cityscape [2]. Implementing climate-resilient infrastructure and nature-based solutions promotes a more sustainable, resilient, and healthy environment for communities where it considers their vulnerability to climate-related hazards, reducing the risk of potential damage.

1.1 Context of the research

Based on studies by the Royal Dutch Meteorological Institute concerning the observed and projected changes in climate for the Netherlands, the mean temperature has increased by 1.2°C since 1900, with an increase in extremely warm days and a decrease in extremely cold days. Yearly precipitation has increased by 18%, mainly in winter, spring, and autumn, with extreme precipitation during winter. Climate change projections for the Netherlands in 2050 [3] show an increase in mean temperature, extreme precipitation, and sea level rise, which could significantly impact the Dutch economy and society, particularly regarding extreme weather events.

Green Panels, the start-up company that commissioned the project, aims to develop an innovative concept for green roof systems. As the prototypes are being tested in both lab and real-world environments, it is crucial to perform performance measurements. Evaluating the prototypes form the project's backbone, ensuring that the developed systems are theoretically sound, practically applicable, and effective. According to Green Panels [4], gas and power prices are rising at rates that were never seen before, around 290€ on gas and electricity for a typical household in the Netherlands. Also, during the heatwave of 2019's week 30, 2964 lives were lost. Relying on air conditioners and fans can be effective, however far from a cost-efficient solution. Only 0.5% of roofs are covered with vegetation, while the remaining 95.5% are covered with concrete and roof tiles. This setup intensifies heat during the summer, worsening the environmental challenges. Green Panels offer a solution to this challenge with its green roof system. Furthermore, Green Panels utilize an installation process similar to solar panels and can be fitted on any sloped roof. They can be strategically placed on the less sunny side of the roof, where solar panels would not be efficient, or can even be installed alongside existing solar panels.

The University of Twente supports this project by granting access to the university's incubator NovelT/Incubase, providing an environment with considerable flexibility to conduct research. Moreover, providing a location for field testing. The project outcomes hold significance for multiple stakeholders who may benefit from implementing these green roof systems, including building owners, architects, urban planners, and local governments interested in promoting sustainable urban development. Also, the developed green roof systems can be applied to other regions worldwide, addressing similar urbanization and climate change challenges. Green Panels can provide its stakeholders with improved green roof systems, precise knowledge, and higher quality information and solutions. Leading to a more extended group of stakeholders attracting environmental organizations, the construction industry, and communities that value sustainable living.

1.1.1 Scope and limitations

The primary objective of the research was to be to examine the effectiveness of Green Panels green roof systems for sloped roofs. It involved testing prototypes with different materials, substrates, and configurations of green roof layers. Additionally, the research evaluated the Green Panels systems performance in controlled laboratory environments. The study aimed to assess these systems influence on energy usage, extreme temperatures and mitigating flood runoff peaks.

However, it is essential to note that this research faced some limitations. Firstly, the study was limited to a period of three months (10 weeks), thus analyzing long-term performance might be challenging. Additionally, the study was conducted within the constraints of an early-stage start-up environment, with potential limitations in resources and funding. The Green Panels green roof systems were specifically designed for sloped roofs, therefore findings might not directly apply to flat roofs or other types of green infrastructure. These findings are focused on the Green Panels green roof systems and cannot be generalizable to other green roof systems. Lastly, the research was influenced by availability of data and the accuracy of measurements obtained during the testing and evaluation process.

1.2 Problem statement

The expansion of cities in the Netherlands has led to an increase in paved surfaces, contributing to challenges such as urban flooding and intensifying the urban heat island (UHI) effect. The Netherlands is highly vulnerable to the impacts of climate change [5] as it will experience heavy rainfall events due to extreme temperatures and flooding. Additionally,

rising average temperatures will lead to severe heatwaves. The UHI effect worsens in areas with high population density due to the fact that concrete and asphalt surfaces absorb heat and release it into the environment. These challenges can have effects on health, agriculture and infrastructure[6].
The Dutch government and urban planners are increasingly integrating green spaces and nature-based solutions to mitigate these effects [7]. Green infrastructure and nature-based solutions, such as green roofs, can help to absorb excess rainwater, reduce flooding, and alleviate the UHI effect by providing shade and cooling through evapotranspiration [1]. Living roofs or vegetated roofs are referred to as green roofs. Among these nature-based solutions, Green Panels, a new concept of green roofs for sloped roofs, have emerged as a promising approach to addressing the environmental and socio-economic challenges of rapid urbanization and climate change.

1.3 Research dimensions

In this section, the research aim is defined. In order to achieve the research aim, a list of research questions needs to be answered using methods that will be discussed in the methodology section.

1.3.1 Research objective

The primary objective of this research is to evaluate the performance of Green Panels system for sloped green roofs in terms of reduced energy consumption, mitigated extreme temperatures, and delayed flood runoff peaks.

1.3.2 Hypothesis

Green Panels sloped green roof system will reduce energy consumption, mitigate extreme temperatures, and delay flood runoff peaks by effectively capturing and transpiring precipitation, leading to improved stormwater management and overall environmental benefits.

1.3.3 Research questions

The list of research questions is the following:

1. How do Green Panels' sloped green roof systems perform in terms of reducing energy consumption and mitigating extreme temperatures?
2. How do the Green Panels' green roof systems contribute to delaying flood runoff peaks and capturing and transpiring precipitation?
3. How do different materials, substrates, and configurations of green roof layers influence the performance of Green Panels' systems?
4. How do laboratory test results compare with real-life performance measurements for Green Panels green roof systems?

1.4 Reading guide

This section serves as a reading guide for this report, providing an overview of the content and organization of the document. Following this guide, readers can navigate the report effectively and understand its structure and flow.

Following the introduction section, the literature review section offers an overview of roofs, exploring their definition, characteristics and importance. It also delves into existing research on green roofs, focusing on their benefits and various measures to quantify their performance.
Moreover, the methodology section outlines the research design employed in the study, including the experiment design, experiment setup, sensor selection, and placement. It also discusses data collection, analysis techniques, research limitations and delimitations. Additionally, a timeline is provided to represent the experiment duration.
The results section presents the findings of this research, specifically evaluating the performance of Green Panel's systems for sloped green roofs in terms of reduced energy consumption, mitigated extreme temperatures, and delayed flood runoff peaks.
For the discussion section, it critically analyzes and interprets the results obtained in the research, considering their implications and significance. Then, a conclusion is given which summarizes the key findings and their relevance to the research objective. It also offers insights into the broader implications of the research and potential future directions.
Finally, The recommendation section suggests practical recommendations based on the research findings to enhance the performance of Green Panel's systems potentially. These recommendations are intended to guide future initiatives and improvements in experimenting.

Chapter 2

Knowledge on Green Roofs Construction and Performance

2.1 Green roofs

The placement of plants and soil on unused conventional rooftop surfaces involves the concept of adapting green roofs. This concept has emerged as a popular approach to enhancing building sustainability. A typical green roof system comprises several components with distinct purposes. These include vegetation, substrate, filter fabric, drainage materials, a root barrier, and insulation. Green roofs different layers are shown in the figure below.

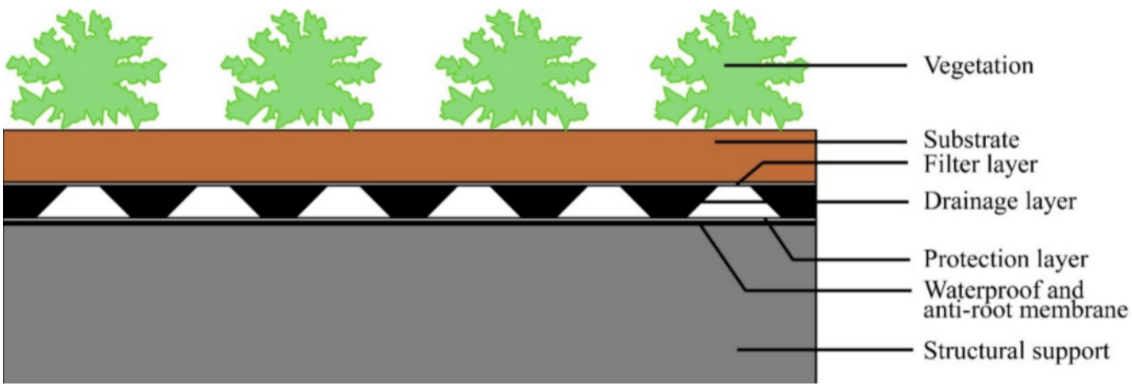

FIGURE 2.1: Green roofs different layers [8].

There are two categories of Green roofs: intensive and extensive [9]. Intensive green roofs are similar to rooftop gardens with a deeper soil layer, while extensive green roofs have a shallow soil depth, require low maintenance, and demand less water. The difference between the two types considers plant variety, construction materials, management, and intended purposes.

Intensive green roofs feature a thick substrate layer (20–200 cm) and can accommodate a wide variety of plants. However, carry a higher cost and weight. Due to their ability to support diverse plant selections, including shrubs and small trees, they require regular maintenance [8].
Contrastingly, extensive green roofs, with their thinner substrate layer (less than 20 cm), are lower in cost and weight and require minimal maintenance [9]. They can only support

a limited variety of vegetation, such as grasses, moss, and some succulents.

Moreover, a new type of green roof has emerged, semi-intensive green roofs, which lie between the two existing categories. Due to its moderately thick substrate layer, it can house small herbaceous plants, ground covers, grasses, and small shrubs. They require regular maintenance and come with higher costs, but they offer a middle ground between the two extremes.
Extensive green roofs are the most common globally because they take into account factors such as the weight limit of buildings, costs and maintenance needs, which makes them more preferable [2]. Table 2.1 displays the difference between the two primary types.

Attributes	Extensive	Intensive
Thickness of growing media	Below 200 mm	Above 200 mm
Accessibility	Inaccessible (fragile roots)	Accessible (usable for recreation purpose)
Weight	60–150 kg/m^2	Above 300 kg/m^2 (may require a reinforced structure)
Diversity of plants	Low (moss, herb and grass)	High (lawn or perennials, shrub and tree)
Construction	Moderately easy	Technically complex
Irrigation	Often not necessary	Necessity of drainage and irrigation systems
Maintenance	Simple	Complicated
Cost	Low	High

TABLE 2.1: Classification and main attributes of green roofs [1].

The best layer configurations of green roofs are the following [8]:

1. **Waterproofing membrane**: The waterproof membrane is a crucial component of green roof technology, protecting against water infiltration and degradation from temperature fluctuations and solar radiation. Its primary requirement is water-tightness, and it offers stability, cold flexibility, resistance to static loads, and artificial aging protection, including protection against UV rays, thermal fluctuations, and hail shocks. The most common membranes are bituminous flexible membranes, including elastomeric, plastomeric, and elasto-plastomeric types. They can be laid in a single or double layer with 3 or 4 mm thicknesses.

2. **Root barrier**: In designing a green roof, it is crucial to account for the aggressive capacity of root systems. Root barriers protect the waterproof membrane and roof structure from damage caused by vegetative roots. The anti-root layer is essential in a green roof and is integrated with the waterproofing membrane. When adding a living roof to an existing building, an additional anti-root protection layer is covered on the waterproofing membrane. The anti-root membrane must be resistant to microorganisms and contain repellent ingredients. It is usually about 4 mm thick and installed with hot-air welding or a chemical solvent. Concrete, felts, and polyethylene films are unsuitable as anti-root barriers, but metal sheets can be an alternative.

3. **Drainage layer**: The drainage layer is essential for a green roof's proper functioning, providing ventilation and preventing waterlogging. It helps maintain a balance between air and water, reduces structural load, and enhances thermal performance. The two primary materials used for the drainage layer are granular materials and modular panels. Granular materials suit small-scale green roofs on flat or slightly sloped surfaces. Modular panels, with higher performance and versatility, are used for larger green roofs but have cost and disposal limitations. The choice of the drainage layer depends on factors such as rainfall, construction needs, structural requirements, costs, green roof size, roof slope, and plant species.

FIGURE 2.2: Green roof drainage materials: Modular panels presented on the left and granular materials presented on the right [8].

4. **Filter fabric**: The filter layer in a green roof serves to separate the substrate from the drainage layer, preventing small particles and debris from clogging the drainage system and reducing its performance. The filter layer must have high water permeability, at least ten times higher than the substrate. Common materials used for the filter layer include granular materials (e.g., pozzolana, pumice, lapillus) with water permeability greater than 0.3 m/s and non-woven geotextiles able to absorb 1.5 L/m^2. Geotextile materials are generally preferred. Key parameters for the filter layer include weight and punching resistance, tensile strength, deformation resistance, effective pore opening, oscillation resistance, and resistance to aggressive agents.

5. **Substrates**: The substrate is crucial for the long-term benefits of a green roof, including water quality improvement, peak flow reduction, and noise and thermal insulation. It plays a key role in plant growth by maintaining optimal physical, chemical, and biological conditions for vegetation development. Substrate thickness and weight depend on the following factor: vegetation type, roof geometry, climate, and irrigation strategy. The weight can range from 12-14 kg/m^2 for extensive green roofs to about 600 kg/m^2 for intensive ones. Substrate properties include physical parameters (density, particle size, water permeability, maximum water and air volume) and chemical parameters (pH index, electrical conductivity, organic matter). Choosing the wrong substrate can lead to issues such as compaction, imbalances in water and air, root asphyxia, increased weight, reduced drainage, and altered nutrient levels.

6. **Vegetation**: A green roof's success largely depends on the health of its plants, which contribute to water and air quality, thermal performance, visual appeal, substrate erosion prevention, and habitat for various animal species. When selecting vegetation, consider climate conditions, substrate mixture, and the roof installation site. Suitable plant species for extensive green roofs vary based on soil depth:

   - 0-5 cm: Sedum, mosses, lichens
   - 5-10 cm: Short wildflower meadows, perennials, grasses, alpines, small bulbs
   - 10-20 cm: Perennials, grasses, bulbs, annuals, wildflowers, hardy sub-shrubs

   The roof installation site influences the choice of plant species, as factors like air emissions, chemical components, shading, and solar radiation affect the green roof environment. However, limitations such as water availability and building load constraints restrict the types of vegetation that can be used on a green roof.

2.2 Current research on green roofs

In the context of urban and environmental resilience, the topic of green roof research is quickly developing. Keyword searches were performed in academic databases such as Google Scholar to ensure a comprehensive literature review. Keywords included 'green roofs', 'sloped green roofs', 'urban heat island mitigation', 'stormwater management', 'biodiversity', 'air quality improvement', 'social benefits' and 'sustainable building materials for green roofs'. A total of ... papers were chosen and considered relevant to the research. The scope of current research on green roofs reflects both the benefits and limitations of its implementation. It highlights the ongoing efforts to understand better and optimize green roof performance, leading to more sustainable and resilient urban environments. Several essential research topics include:

- Thermal performance and energy savings: Studies are investigating how green roofs can affect a building's thermal performance and energy usage. They are particularly interested in how green roofs provide insulation, absorb heat and mitigate the heat island effect [1].

- Stormwater management: Researchers are exploring how green roofs can help manage runoff, decrease the intensity of peak flows and enhance water quality [2]; [10].

- Biodiversity and habitat creation: Research is being conducted to explore the potential of green roofs to promote biodiversity by creating habitats for a range of plant and animal species, especially in urban areas [11].

- Air quality improvement and carbon sequestration [1].

- Psychological and social benefits: Researchers are exploring the psychological and social benefits of green roofs, such as improved mental health, increased social interactions, and community engagement [7].

- Green roof materials and design: Studies are focused on optimizing green roof materials, substrates, and plant selection to improve performance, reduce maintenance, and lower costs [12].

- Lifecycle assessment and cost-benefit analysis: Researchers are conducting lifecycle assessments and cost-benefit analyses to evaluate green roofs environmental and economic performance over their entire lifespan [13].

2.2.1 Benefits of green roofs

Green roofs have emerged as a revolutionary approach to urban construction and landscaping, offering a range of environmental, economic, and social benefits, thus addressing the different challenges posed by urban living. The benefits of green roofs include efficient stormwater management, energy conservation, urban heat island mitigation, biodiversity enhancement, air quality improvement, noise reduction, and aesthetic improvement. The descriptions of the benefits are the following::

- Water management: Green roofs absorb and retain rainwater, reducing runoff and helping to prevent flooding [10]. With their deeper soil layers, intensive green roofs can retain more water than extensive green roofs. When rainwater enters a green roof, a portion of it is absorbed by the growing substrate or retained in the pore spaces. The vegetation can also take it up and store it in plant tissues or transpire back into the atmosphere. The remaining water passes through a filter fabric and enters the drainage element. The potential to store water between pores or compartments allows for water detention. This process helps to regulate the flow of stormwater, preventing overwhelming the drainage system and reducing the strain on urban infrastructure during heavy rainfall events [2].

- Energy conservation: In terms of energy conservation, green roofs have a number of advantages. In both warm and cold climates, they are quite effective at lowering interior temperature variation and building energy consumption levels [1]. Green roofs help to regulate inside temperatures by adding more insulation, which reduces the need for cooling and heating systems. This may result in significant reductions in energy consumption and reduced utility costs. Intensive green roofs generally offer better insulation due to their thicker soil layers and larger plants.

- Urban heat island (UHI) mitigation: The UHI effect refers to the phenomenon where urban areas experience higher temperatures compared to surrounding rural areas due to human activities and the built environment [6]. Green roofs help decreasing ambient air temperature in urban areas, absorb and dissipate solar radiation using the presence of vegetation, thus helps in reducing temperature, providing shading and absorbing heat. Both types of green roofs contribute to this benefit, but intensive green roofs may have a more significant impact due to the greater variety and density of vegetation.

- Biodiversity: Green roofs help create habitats for a range of plant and animal species, enhancing the biodiversity within urban areas. Intensive green roofs, with their greater soil depth and plant diversity, can support a wider range of species compared to extensive green roofs.

- Air quality improvement: Plants on green roofs improve air quality by absorbing air pollution and producing oxygen. Both intensive and extensive green roofs contribute to this benefit, but the larger and more diverse vegetation on intensive green roofs may provide a greater air quality improvement.

- Noise reduction: Green roofs can absorb and block noise, providing a quieter environment [14].

- Aesthetic improvement: Green roofs contributes to overall urban aesthetics by making buildings more visually appealing. Intensive green roofs often offer more aesthetic value due to the greater variety of plants and the ability to create more complex landscape designs. However, extensive green roofs still contribute to improved aesthetics compared to conventional roofs.

2.2.2 Performance measurements

A critical part of the research lies in measuring various performance factors to understand and optimize the benefits of green roof installations. Moreover, these performance measurements are crucial in enabling Green Panels to understand their design's efficiency better. With comprehensive data on these performance factors, it becomes more straightforward to articulate the benefits of green roofs. The main performance factors to be measured include:

- Temperature reduction: Comparing indoor and outdoor temperatures of buildings with and without green roofs to determine energy savings and comfort levels.

- Stormwater retention: Measuring the amount of rainwater captured, stored, and released by green roofs during precipitation events.
- Evapotranspiration rates: Monitoring the rate at which water is transferred from the green roof to the atmosphere through evaporation and plant transpiration [9].
- Biodiversity: Evaluating the number of plant and animal species found on green roofs compared to conventional roofs.
- Air quality improvement: Comparing pollutant levels and air quality in areas with and without green roofs.

By measuring these performance factors, convincing people to adopt these green roof systems and fully benefit from their potential in addressing urban and environmental challenges will become much more manageable.

Chapter 3

Methodology

3.1 Research design

In this section, the methodology is established for answering the research questions. Firstly, a flow chart will be presented with a clear overview of the steps in achieving the research goal. Then, the methods to answer each question will be discussed in detail, along with how to gather and analyse the data needed. Also, the limitations and delimitation during the application of these methods are mentioned. Finally, how to increase the reliability of the results is mentioned.

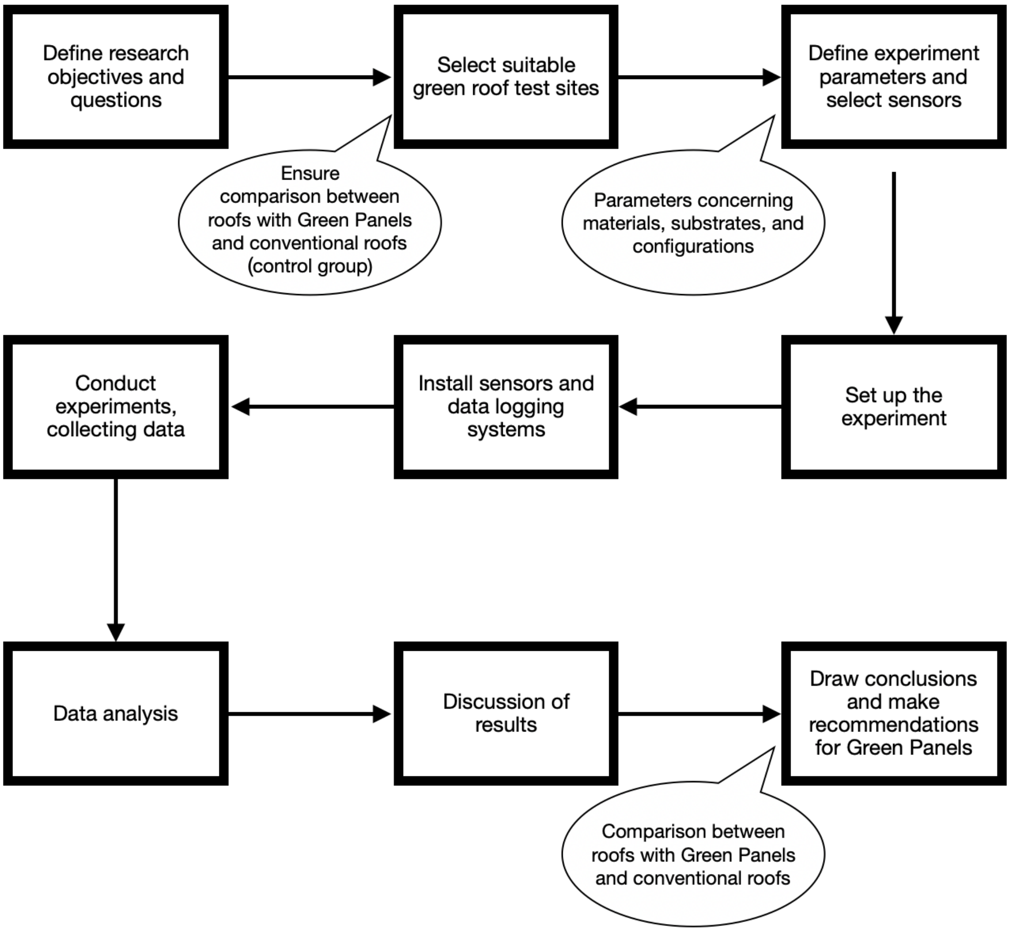

FIGURE 3.1: Flowchart presenting the proposed methodology

3.2 Experiment design

3.2.1 Experiment Setup

The green roof system being monitored is a Green Panel's green roof prototype. The experiment consists of four different setups with different heights and substrates, shown in Table 3.1. The green roof system, provided by Green Panels, covers an area of 2 m^2 and has a slope of 45°. The green roof is divided into two equal sections, one hosting the three different setups and one with no substrates, considered as control group (conventional roof).

Setup	Height	Substrate
1	1	1
2	2	2
3	3	3
4 (control)	1,2 and 3	None

TABLE 3.1: Different experiment setups

FIGURE 3.2: Experiment Setup.

Experiment location

The experiment was located in Enschede, at the University of Twente campus, on the roof of the 2nd floor of the Horst building.

FIGURE 3.3: Experiment Setup.

Material used

The material used for all setups is High Density Polyethylene (HDPE). HDPE is a durable and lightweight thermoplastic material derived from petroleum, and it is known for its sufficient chemical resistance, low moisture absorption, and high tensile strength. HDPE is considered an ideal material for Green Panels due to the following reasons:

- Durability and longevity
- Chemical resistance
- Water resistance and low moisture absorption
- Lightweight
- Environmental friendliness
- Cost-effective

Substrates used

The substrates used for the setups are soil, recycled fabric and scheepwool. The choice of theses substrates for extensive green roofs can offer numerous benefits.

- **Rockwool (Rw)**: Rockwool is made from natural rock. It provides excellent water retention and aeration. It can hold a large amount of water, which can be beneficial during dry periods for the plants. Moreover, despite its ability to retain water, it also allows excess water to drain away, preventing waterlogging and providing good oxygen levels to the roots. Also, rockwool is not prone to pests or diseases, which makes it an excellent choice for a green roof.
- **Recycled Fabric (Rf)**: Recycled fabric is sustainable and eco-friendly, helps to reduce waste and conserves natural resources. It is also lightweight, since weight can be a limiting factor for green roofs. Fabric can absorb water, providing a reservoir for plants.
- **Soil**: To enable comparison of the effectiveness between different substrate.

These substrates all offer different benefits and to meet the specific requirements of the green roof design.

Vegetation used

The vegetation used for all setups is Sedum. It is considered the best choice for vegetation on extensive green roofs due to the following reasons [15]:

- **Drought Resistance**: Sedum can store water in their leaves and stems, thus making them highly resilient to drought conditions.
- **Low Maintenance**: Sedum requires minimal maintenance, makes them an ideal choice for locations like rooftops where constant maintenance is difficult
- **Wide Variety**: There are numerous varieties of sedum, allowing for customization based on aesthetic preferences and specific environmental conditions.
- **Temperature Tolerance**: Sedum can tolerate extreme heat and survive in colder conditions, making them suitable for various climate zones.
- **Ability to Reduce Runoff**: Sedum can absorb rainwater, reducing the volume of stormwater runoff like other vegetation, which benefits urban environments
- **Improvement of Air Quality**: Like other plants, sedum can improve air quality by absorbing carbon dioxide and releasing oxygen.
- **Energy Efficiency**: Green roofs with sedum can provide excellent insulation, helping improve a building's energy efficiency.

3.2.2 Sensor Selection

For the purpose of evaluating the performance of the green roof system, a combination of sensors was installed to measure variables of interest. These include thermal sensors, soil moisture and temperature sensors. Thermal sensors are used to measure temperature, thus providing data on the thermal performance of green roofs, which will help define green roofs' effectiveness in mitigating extreme temperatures. Soil temperature affects the rate of evapotranspiration, which is the process by which water is transferred from the land to the atmosphere by evaporation and plant transpiration, thus helping in evaluating evapotranspiration rates and ensuring that the green roof's environment is within the optimal range for plant health. Soil moisture sensors measure the moisture content of the green roof substrate, which provide data on water retention and transpiration rates of the green roof system. These sensors were chosen to provide a holistic view of how the green roof interacts with its environment and mitigates the impacts of urban heat islands and rainfall events.

Sensor types

Soil moisture and temperature sensor (truebner SMT50): The truebner SMT50 is a sensor that utilizes capacitance to measure both temperature and moisture levels in soil, making it an ideal tool for various home gardening applications. Capacitive soil moisture sensors function by creating an electrical field around the probes that they contain. This field extends into the surrounding soil. By assessing the resultant electrical capacitance of the probes, the sensor's measuring system can ascertain the soil's moisture content. The principle here is straightforward: a higher level of water content in the soil, the greater the measuring capacity of the sensor [16].

FIGURE 3.4: Truebner SMT50 sensor [16].

Environmental sensor (BME680): Numerous phenomena can be measured using the BME680 sensor including air temperature, relative humidity, air pressure, and air quality.

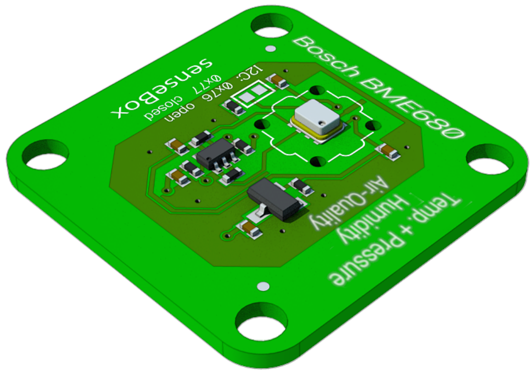

FIGURE 3.5: BME680 sensor [16].

Sensor placement

For the section of the roof where the panels are installed, there is four environmental sensors used: on top of vegetation, bottom of the panel (HDPE), top roof tile and bottom roof tile. Moroever, six soil moisture and temperature sensor are placed for each substrate. On the other section of the roof (conventional roof), there is two environmental sensors used: top roof tile and bottom roof tile. In total there are twelve sensors used, six environmental sensors and six soil moisture and temperature sensors. Sensors placements are shown in the following figures, along with the correct installation of the soil moisture and temperature sensor .

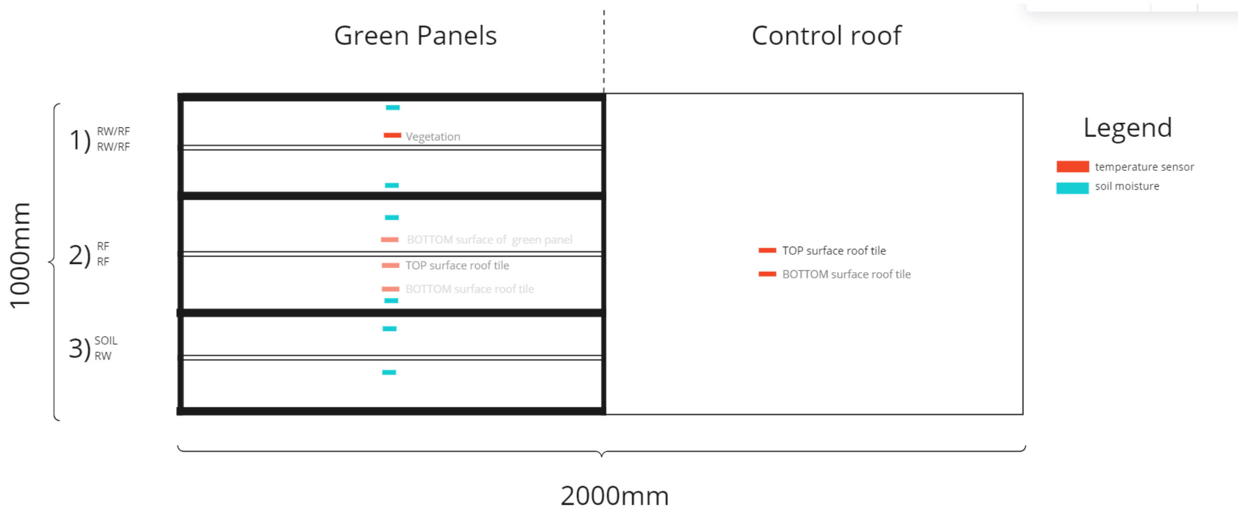

FIGURE 3.6: Sensors placement [4].

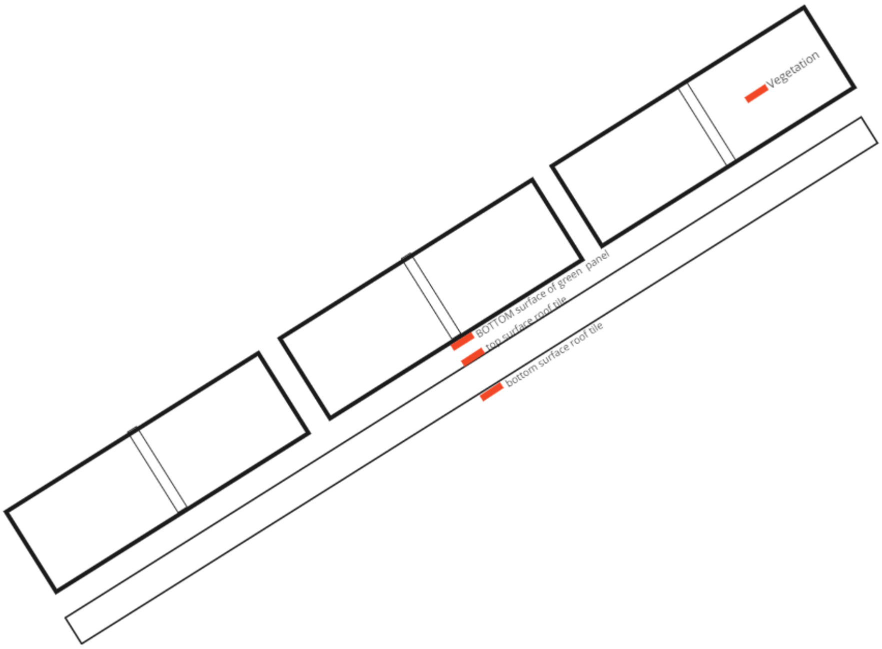

FIGURE 3.7: Sensors placement [4].

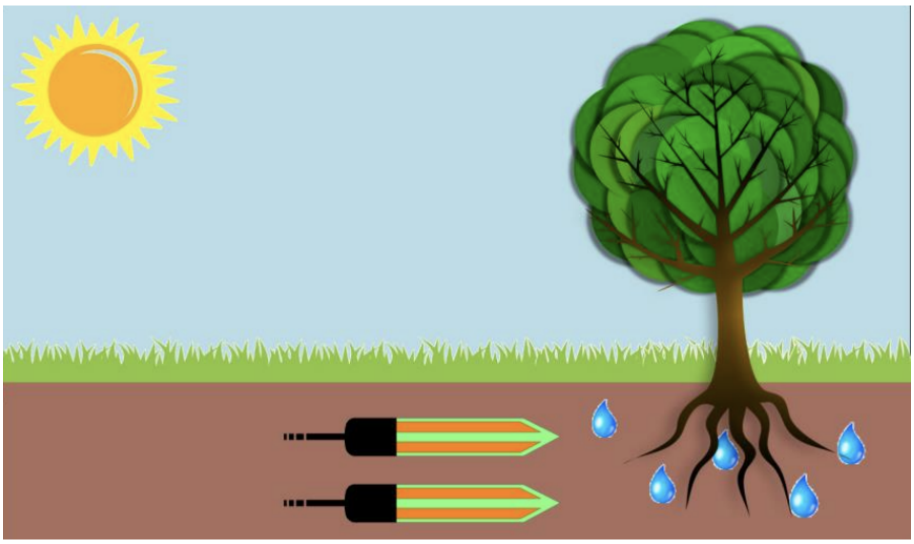

FIGURE 3.8: Soil moisture correct placement.

3.3 Data collection

In order to measure and store the data from the sensors, a data logger is required. For this experiment, a device called senseBox:mini has been used as a data logger [16]. The SenseBox serves as a versatile environmental monitoring station, which can be connected to the internet and transmit the collected data to a server. There are several versions of Sensebox, senseBox:mini is one of them. This compact device comes with a variety of sensors that transform it into a mini weather station, capable of detecting and monitoring various environmental parameters.

FIGURE 3.9: The senseBox:mini data logger [16].

It includes the BME680 sensor connected to an I2C-Wire port, making it a comprehensive tool for environmental monitoring. Moreover, it is able to accommodate other sensors using the different ports it has. The truebner SMT50 is one of them, also connected to an I2C-Wire port. Also, it features an OLED screen, a display for data visualization. The device itself is an open-source sensor board known as the SenseBox MCU and includes a Wi-Fi module that allows for internet integration and remote data transfer.

To facilitate user-friendly programming, the SenseBox provides a Blockly graphical programming interface. Users can program the device using this system, which displays sensor data on the display. Although some technical background may be helpful, the design attempts to be user-friendly for beginners. Another feature of the SenseBox is its ability to work with the OpenSenseMap platform. OpenSenseMap is a platform where data from senseBoxes and other environmental sensors can be registered, managed, and shared. This makes it simple to retrieve data from the sensors and location tracking of the device.
In total six senseboxes are used in the experiment, each one has a BME680 sensor and truebner SMT50 sensor connected to it. For each sensebox, a station is created on OpenSenseMap. There are six stations Box 0, Box 1, Box 2, Box 3, Box 4 and Box 5. The description of each Box is the following:

- **Box 0**: Environmental sensor on top of panel (on vegetation), Soil moisture and temperature sensor in Rf upper.
- **Box 1**: Environmental sensor on bottom HDPE, Soil moisture and temperature

sensor in Rf lower.

- **Box 2**: Environmental sensor on top roof tile (conventional roof), Soil moisture and temperature sensor in a mix of Rf/Rw upper.
- **Box 3**: Environmental sensor on bottom roof tile (conventional roof), Soil moisture and temperature sensor in a mix of Rf/Rw lower
- **Box 4**:Environmental sensor on top roof tile (green roof), Soil moisture and temperature sensor in soil
- **Box 5**: Environmental sensor on bottom roof tile (green roof), Soil moisture and temperature sensor in Rw.

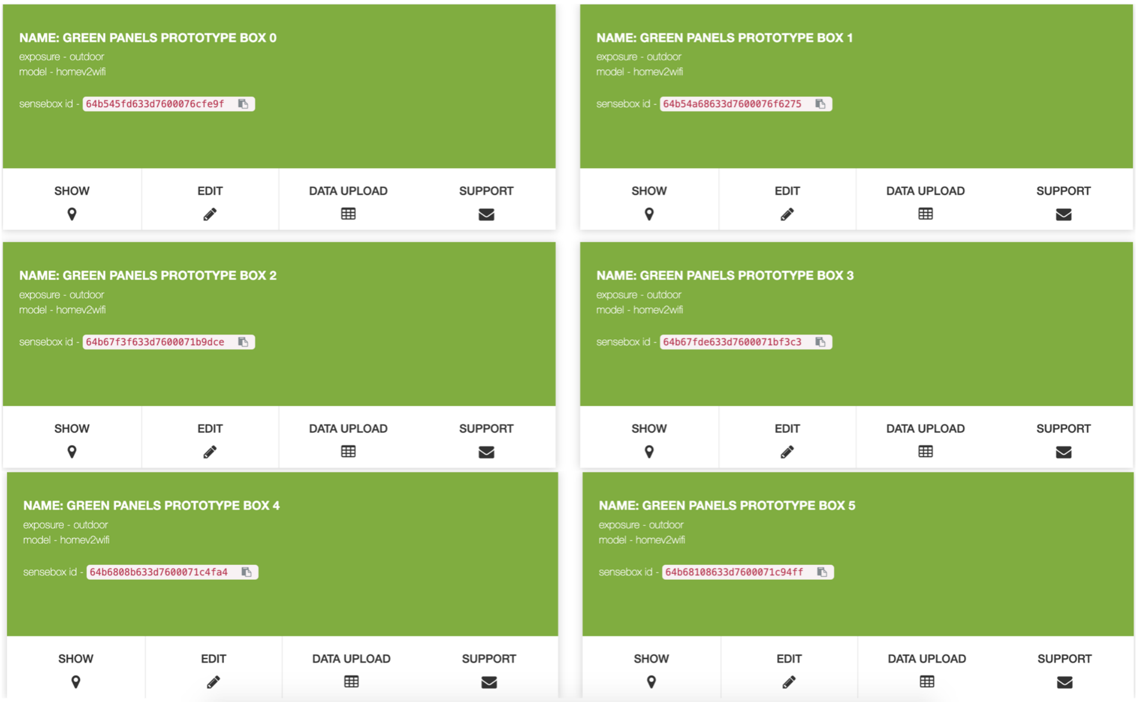

FIGURE 3.10: Sensebox stations on Opensensemap.

3.3.1 Data validation

In order to obtain validated results, several aspects need to be considered and controlled for the methods used to be optimal. The following aspects are:

- Sensor calibration and placement: Regularly calibrate truebner SMT50 and BME680 sensors to ensure accurate readings. Ensure that the sensors are placed in close locations on the roofs to minimise errors due to sensor positioning.
- Replication: To increase the validity and reliability of the results, replication of the experiments and measurements under various conditions is essential. It helps in the reduction of randomised errors.
- Statistical analysis: Use appropriate statistical techniques to analyze the data collected from sensors and experiments, accounting for variations.

Moreover, comparing the data captured by the sensors with the data of the weather station installed in Enschede could increase reliability.

3.4 Data analysis techniques

This section outlines the statistical techniques used to analyze the data.

3.4.1 Statistical test

The t-test is a method used to determine if there is a difference in the mean values of two groups[17]. It is beneficial when working with data samples from populations following a normal distribution. The central concept behind the t-test is to evaluate whether the means of these two groups are statistically different. This involves comparing the difference in means with the variability observed in the data. By calculating a t-statistic and comparing it to a value from the t-distribution, we can decide whether to reject our assumption, also known as the null hypothesis. Typically this null hypothesis assumes no difference between the groups. Rejecting it suggests that there indeed exists some distinction between them. The t-test is considered a reliable tool in statistics and research to help validate hypotheses derived from studies and experiments.

The t-score is a measure that indicates the difference between two groups compared to the variation within each group. A higher t-score indicates a distinction between the groups, while a lower score suggests greater similarity. When conducting a t-test, a higher t-value suggests that the results are more likely to be reproducible.

To determine the significance of the t-value, we rely on p-values, which estimate the probability that the observed data in the sample occurred by chance. These p-values range from 0% to 100%, indicating how reliable the data is. Lower values indicate a likelihood of results. For example, a p-value of 0.01 indicates a 1% chance that the experimental results happened by luck.

Thus, to perform a t-test on the data captured from the Soil Moisture and Temperature Sensor (Truebner SMT50) and the Environmental Sensor (BME680), the main goal would be comparing the means of the measurements between roof with Green Panels and conventional roof.

3.4.2 Assumptions

Before conducting a t-test, certain assumptions must be checked first. The data should follow a normal distribution, which can be checked using histograms. Also, ensure data is correctly sorted by time and check missing values.

3.5 Limitations and Delimitations

The SenseBox:mini and openSenseMap system can be a powerful tool for environmental monitoring and open data science. However, like any technology, it does have certain limitations and delimitations.

Limitations:

- Accuracy of Sensors: The sensors in the SenseBox:mini are relatively affordable, making the device accessible to many. However, they may not be as precise or accurate as a professional environmental sensors. This could lead to less accurate data being uploaded to openSenseMap. Accuracy of both sensors is mentioned in the appendix.

- Dependence on Network Connectivity: The functionality of SenseBox:mini depends on having a stable Internet connection to upload data to openSenseMap. In areas with poor connectivity, data transmission might be inconsistent or impossible.
- Weather Resistance: The SenseBox:mini may not be as robust to weather conditions as some other outdoor monitoring systems. It should be protected from extreme weather conditions, which could limit its deployment in certain environments.
- Limited Parameters: While the SenseBox:mini can measure a range of environmental parameters, its capabilities are still limited by the type and number of sensors it contains. If you're interested in monitoring a parameter that isn't included in the default SenseBox:mini, you may need to purchase and integrate additional sensors.
- Power Supply: Depending on the location choice, ensuring a consistent power supply to the SenseBox:mini could be challenging.

Delimitations:

- Target Audience: The SenseBox:mini is primarily designed for educational use, rather than professional environmental monitoring. Although this does not exclude its use in more formal settings, it does influence the design of the system, the sensors that are used, and the support that is provided.
- Geographic Limitations: As an open data project, openSenseMap's utility is dependent on the geographic distribution of its sensors. While anyone can contribute data from a SenseBox:mini, if sensors are primarily concentrated in a few areas, this will limit the representativeness and utility of the data for broader analyses.
- Data Ownership and Privacy: As an open data project, data uploaded to openSenseMap is publicly available. This is a delimitation in the sense that it may limit the types of projects for which SenseBox:mini and openSenseMap are suitable, particularly if data privacy is a concern.
- Technical Skill Required: While the SenseBox:mini is designed to be easy to use, some technical skill is still required for its assembly and setup, as well as for interpreting the data it collects. This could limit its use among those without the necessary technical background.

Despite these limitations and delimitations, they can still serve as a valuable resource for researchers interested in environmental monitoring and open data.

3.6 Timeline

Data is gathered for a period of 5 days. The sensors are programmed to measure data every 60 seconds. Thus, all the data is gathered every minute in each hour of each day. In total, each sensor has 90 data points.

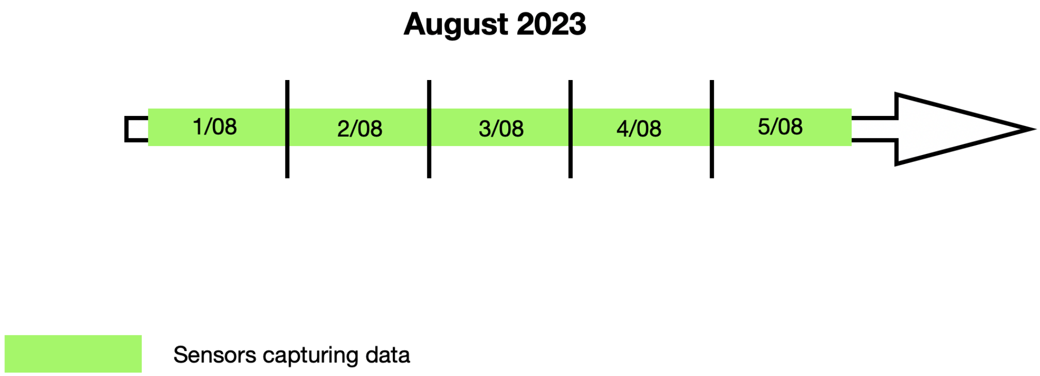

FIGURE 3.11: Timeline of the experiment.

Chapter 4

Result

4.1 General Results

In this section, the results from the statistical analysis will be presented based on the data gathered from the sensors.

4.1.1 BME680 sensor data

To ensure that the data from the BME680 sensor is sufficient and accurate, the temperature, humidity and air pressure data of the BME680 sensor is plotted with the weather station data to enable visual comparison.

Figures 4.1 and 4.2 show that the sensors of Box 0 and Box 2 had a deviating start. Moreover, it is notable that the sensor of Box 0 has the highest and lowest temperature recordings. It is also observable that the sensors of Box 2 have always had the lowest humidity over time.
On the other hand, the sensors of Box 1, Box 3, Box 4 and Box 5 and the weather station have had close or similar readings regarding temperature and humidity.

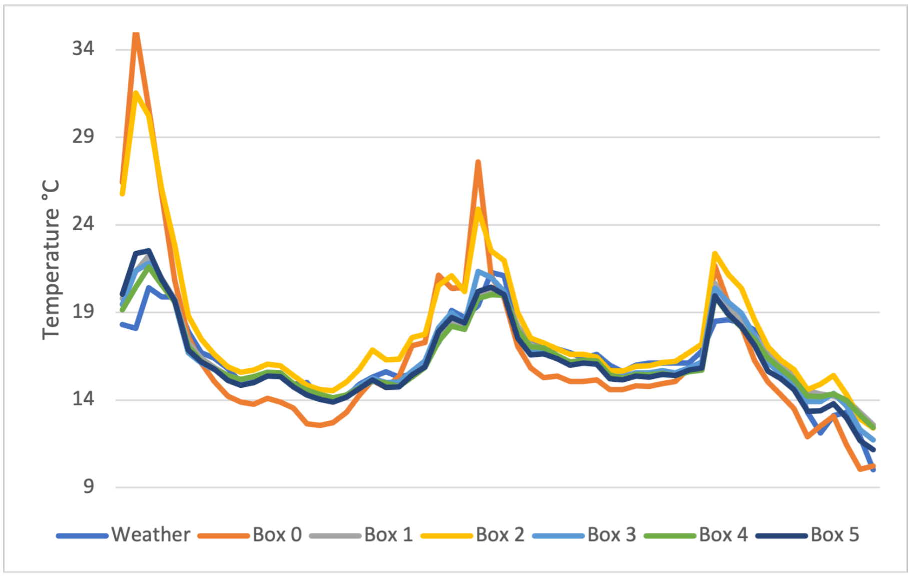

FIGURE 4.1: Temperature data of different senseboxes and weather station.

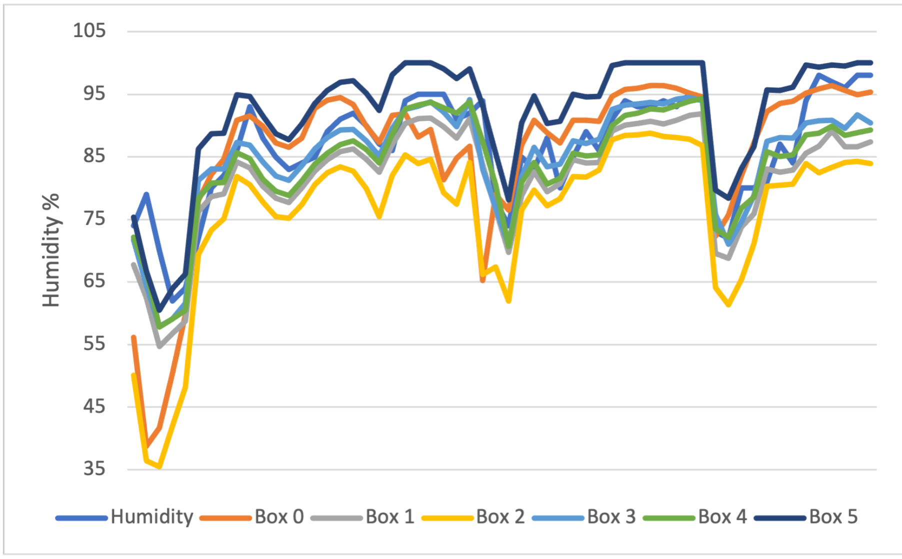

FIGURE 4.2: Humidity data of different senseboxes and weather station.

For the air pressure, it is shown in figure 4.3 that all the sensors had similar readings, and only the one of the weather station has higher air pressure. This is understandable because all the sensors are in the same elevation (exact location), and the weather station is at a different location, with a different elevation.

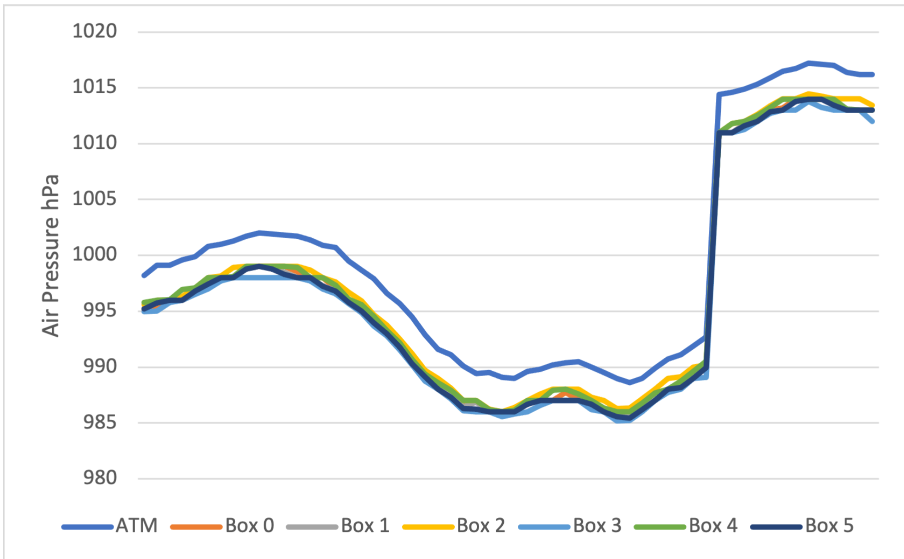

FIGURE 4.3: Air pressure data of different senseboxes and weather station.

4.1.2 Truebner SMT50 sensor data

For the data from the Truebner SMT50 sensor data, the soil moisture and soil temperature of each sensor on the substrates is plotted together.

Figure 4.4 shows that all substrates have more or less the same temperature. There are no significant deviations. For the soil moisture, Box 4 has the highest moisture. Conversely, Box 3 and Box 2 have the lowest moisture, with Box 2 having no moisture, as shown in figure 4.5. Box 0, 1, and 5 have close moisture percentages over time.

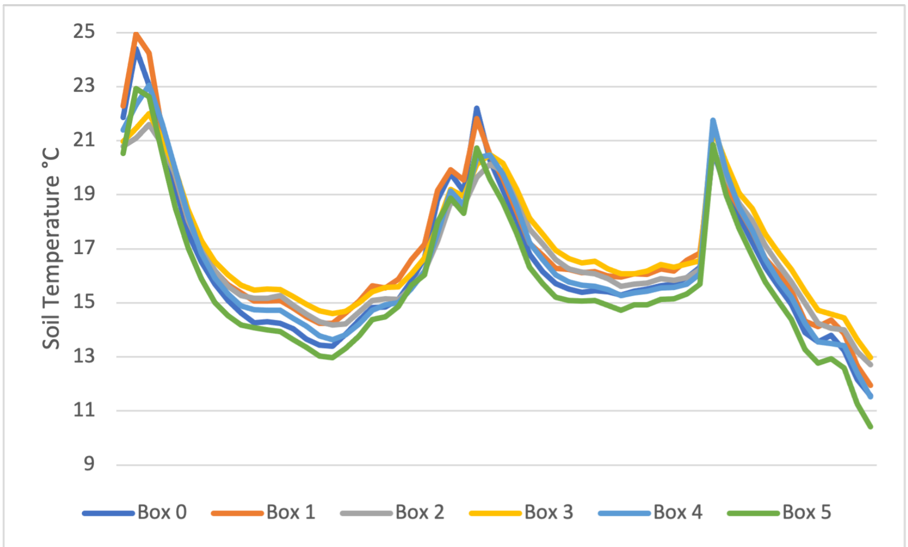

FIGURE 4.4: Soil temperature data of different substrates.

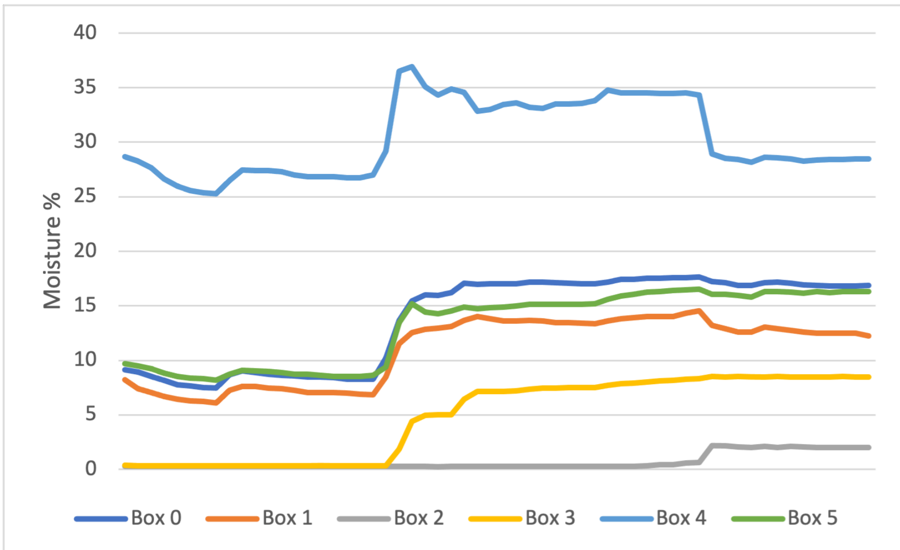

FIGURE 4.5: Soil moisture data of different substrates.

4.2 t-Test Results for Temperature

In this section, the results from the t-test analysis will be presented based on the different temperature data of sensor in different locations.

Initially, the collected temperature data of sensors placed in different locations are compared to the weather station. Box 0,1,2,3,4 and 5 are all individually compared to weather temperature using t-test. The most important variables from the t-test are the mean, variance, t-Stat and p-value, shown in table 4.3. Mean 1 and variance 1 corresponds to the series of Box and mean 2 and variance 2 corresponds to the weather station.

	Mean 1	Variance 1	Mean 2	Variance 2	T-stat	P-value
Box 0 - weather station	16.61	23.00	16.37	4.95	0.34	0.73
Box 1 - weather station	16.49	4.83	16.37	4.95	0.27	0.79
Box 2 - weather station	17.94	14.99	16.37	4.95	2.67	0.01
Box 3 - weather station	16.44	5.49	16.37	4.95	0.16	0.87
Box 4 - weather station	16.36	4.21	16.37	4.95	-0.04	0.97
Box 5 - weather station	16.24	5.95	16.37	4.95	-0.31	0.76

TABLE 4.1: Box 0,1,2,3,4 and 5 compared to weather temperature using t-test.

Moreover, sensors that are placed at the same locations (top roof tile and bottom roof tile) for roof with green panels and conventional roof are also compared using t-test.

	Mean 1	Variance 1	Mean 2	Variance 2	T-stat	P-value
Box 2 - Box 4	17,941	14,985	16,358	4,209	2,752	0,007
Box 3 - Box 5	16,443	5,490	16,240	5,953	0,459	0,647

TABLE 4.2: Box 2 and Box 3 compared to Box 2 and Box 5 using t-test, respectively.

From figure 4.6, it is clear that there are difference in temperature between the two data, with Box 2 always being warmer. On the other hand, for Box 3 and Box 5 the data gathered is similar, shown in figure 4.7

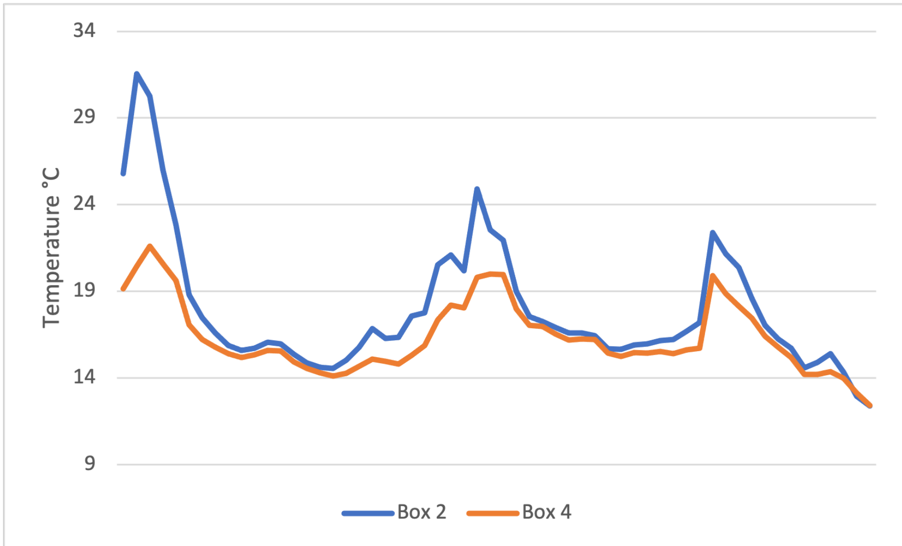

FIGURE 4.6: Temperature data of Box 2 and Box 4.

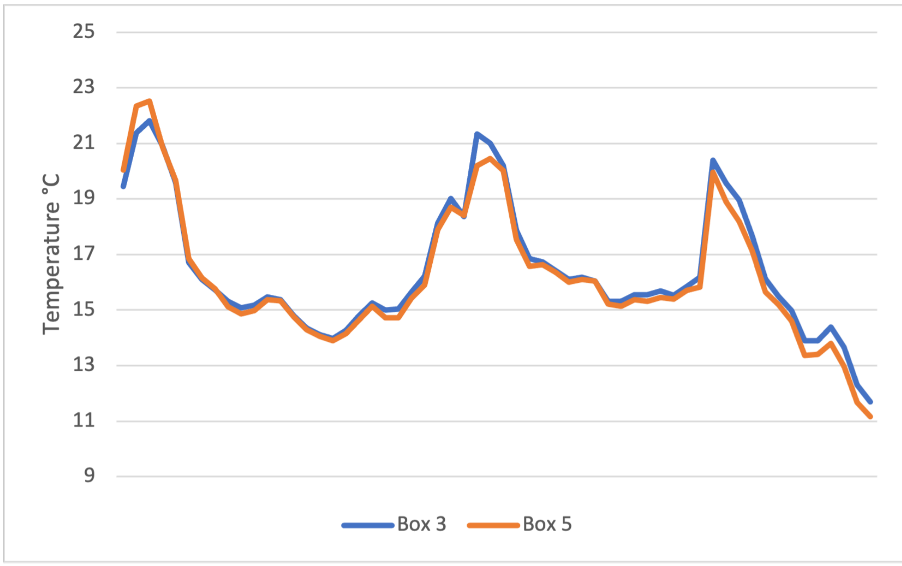

FIGURE 4.7: Temperature data of Box 3 and Box 5.

4.3 t-Test Results for Soil temperature

In this section, the results from the t-test analysis will be presented based on the different soil temperature data of different substrates used.
The collected soil temperature via sensors placed in different substrates are compared to the soil. Therefore, the temperature of Rf,Rw, soil and the mix of Rf/Rw substrates are all compared to the weather temperature using t-test. Same as before, the most important variables from the t-test are the mean, variance, t-Stat and p-value, shown in table 4.3. Mean 1 and variance 1 corresponds to the series of Box and mean 2 and variance 2 corresponds to the weather station.

	Mean 1	**Variance 1**	**Mean 2**	**Variance 2**	**T-stat**	**P-value**
Box 0 - weather station	16.385	7.689	16.374	4.949	0.023	0.982
Box 1 - weather station	16.923	7.041	16.374	4.949	1.207	0.230
Box 2 - weather station	16.640	4.764	16.374	4.949	0.649	0.518
Box 3 - weather station	17.042	4.742	16.374	4.949	1.635	0.105
Box 4 - weather station	16.446	6.864	16.374	4.949	0.160	0.873
Box 5 - weather station	15.811	7.214	16.374	4.949	-1.229	0.221

TABLE 4.3: Box 0,1,2,3,4 and 5 compared to weather temperature using t-test.

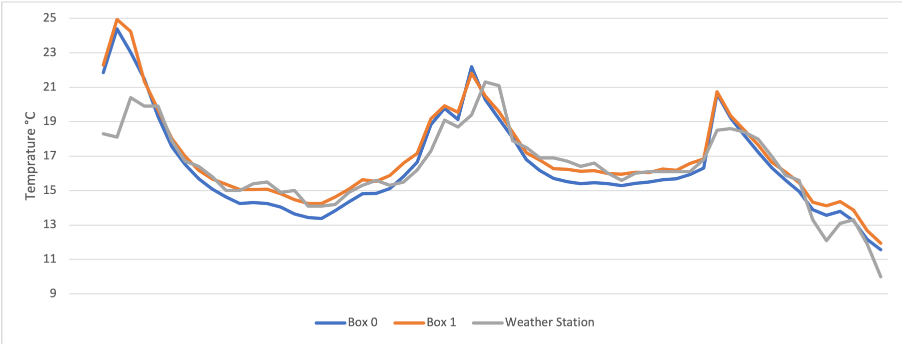

FIGURE 4.8: Rf upper and lower temperatures compared to weather temperature

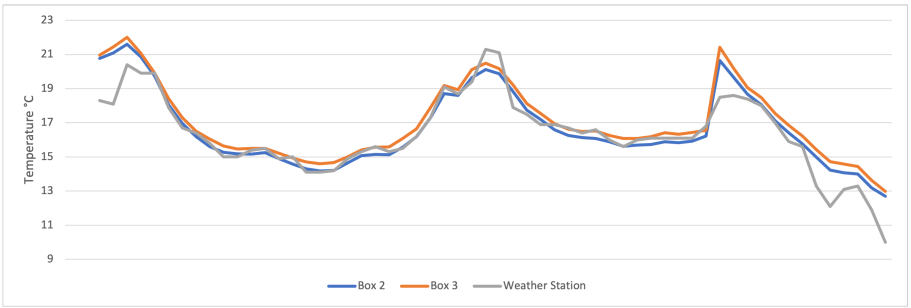

FIGURE 4.9: Mix of Rf/Rw upper and lower temperatures compared to weather temperature

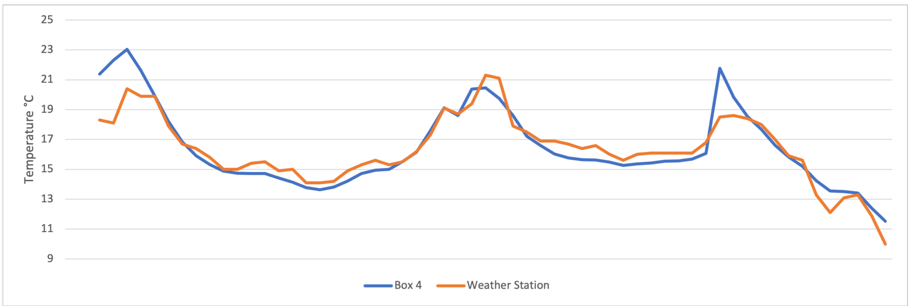

FIGURE 4.10: Soil temperature compared to weather temperature

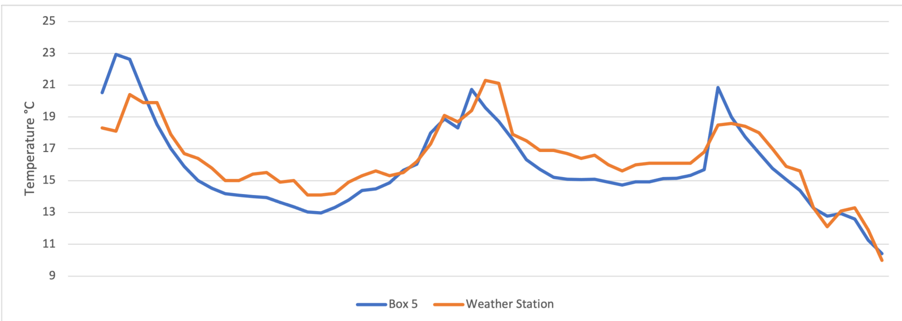

FIGURE 4.11: Rw temperature compared to weather temperature

Chapter 5

Discussion

This section examines the results based on the t-test comparisons for the temperature and soil temperature data. For each test, descriptive statistics and hypothesis testing are assessed, from which statistical and substantive conclusions can be drawn.

5.1 Temperature t-test

Box 0 - Weather

The mean temperatures between on top of vegetation (Box 0) and the weather are quite close to each other, with Box 0 having a mean temperature of 16.61°C and the weather having a mean temperature of 16.37°C. Moreover, the variance in temperatures is higher in Box 0 compared to the weather. The calculated t-statistic is 0.343, which is less than the critical t-value of 1.98 for a two-tailed test. The two-tailed p-value is 0.732, which is much greater than the standard α level of 0.05 used to denote statistical significance. Given the high p-value, it fails to reject the null hypothesis that there is no difference in means between Box 0 and Weather. This suggests that there is not a statistically significant difference between the mean values of your two groups. In effect, this means that the temperatures recorded in Box 0 do not significantly differ from the general weather temperatures based on the sample data.

Box 1 - Weather

The means of bottom HDPE panel (Box 1) and the weather are approximately 16.49°C and 16.37°C, respectively, which are very close to each other. The variances for the two variables are also quite close, 4.831 for Box 1 and 4.949 for the weather. Adding on, The calculated t-statistic is 0.273, which is less than the critical t-values for both the one-tail (1.658) and two-tail (1.981) tests. The p-values for one-tail and two-tail tests are 0.393 and 0.786 respectively, both higher than the α level of 0.05, referring to a lack of statistical significance. With the high p-value, it fails to reject the null hypothesis, which means that there is no statistically significant difference between the means of the two variables. Practically speaking, the data shows that the average weather conditions represented are relatively similar for both. Any difference can be due to a random variation rather than a systematic difference between them.

Box 2 - Weather

The mean temperatures between on top of roof tile on the conventional roof (Box 2) and the weather are approximately 17.94°C and 16.37°C, respectively. There is a notable difference. For the variances, Box 2 has a higher variance of 14.985 compared to the variance of the weather 4.949. The t-statistic comes out to be 2.673, higher than the critical values for both one-tail (1.658) and two-tail (1.981) tests. The one-tail p-value is about 0.0043, and the two-tail p-value is approximately 0.0086, both of which are below the α level of 0.05, indicating statistical significance. Reject the null hypothesis given the low p-values, confirming a statistically significant difference between the means of the two variables. Practically, it suggests a substantial difference in the weather conditions represented by the two variables.

Box 3 - Weather

The means of on bottom roof tile on the conventional roof (Box 3) and the weather are approximately 16.44°C and 16.37°C, respectively, which are very close to each other. The variances for Box 3 and weather are 5.490 and 4.949, respectively. The t-statistic is quite low with 0.163, which is lower than the critical t-values for both one-tail (1.658) and two-tail (1.981) tests. The calculated p-values for one-tail and two-tail tests are 0.435 and 0.871 respectively, both considerably exceeding the α level of 0.05, thus signals a lack of statistical significance. Given the high p-value, it fails to reject the null hypothesis suggesting no statistically significant difference between the mean values of the two variables.

Box 4 - Weather

The means of on top of roof tile on the green roof (Box 4) and the weather are approximately 16.36°C and 16.37°C, respectively, which are incredibly close to each other. The variances of the groups are comparable, with the values being 4.209 and 4.949 for Box 4 and weather, respectively. The t-statistic is -0.041, which is much smaller than the critical t-values for both the one-tail (1.658) and two-tail (1.981) tests. The one-tail p-value is 0.484 and the two-tail p-value is 0.967, both being much higher than the α level of 0.05 that implies to statistical significance. With the high p-value, keep the null hypothesis indicating that there is no statistically significant difference between the mean values of the groups. This suggests that the weather conditions represented are almost identical. The differences in mean values possibly coming from random variations.

Box 5 - Weather

The means of on bottom of roof tile on the green roof (Box 4) and the weather are approximately 16.24°C and 16.37°C, respectively, which are very close to each other. The variances for the two variables are slightly different, but still quite close, with respective values of 5.953 and 4.949. The t-statistic is -0.310, which is lower than the critical t-values for both one-tail (1.658) and two-tail (1.981) tests. The p-values for one-tail and two-tail tests are 0.379 and 0.757 respectively, both of which are above the α level of 0.05, indicating the lack of statistical significance. Given the high p-values, do not reject the null hypothesis. This suggests that there no statistically significant difference between the mean values of the two variables.

Box 2 - Box 4

The mean temperature of Box 2 is 17.94°C, which is higher than the mean temperature of Box 4 at 16.36°C. The variance in the temperature for Box 2 is much higher compared to Box 4. The calculated t-statistic is 2.752, which is greater than the critical t-value (1.981) for a two-tailed test. The two-tailed p-value is 0.0069, which is less than the α level of 0.05 used, to mark statistical significance. Reject the null hypothesis that there is no difference in the mean values between Box 2 and Box 4 due to the low p-value. This denotes that there is a statistically significant difference between the mean values of your two groups. In real-world terms, this suggests that there is a significant difference in the temperatures recorded in Box 2 and Box 4, with Box 2 being warmer on average.

Box 3 - Box 5

The mean for Box 3 is 16.44°C, slightly higher than the mean for Box 5, which is 16.24°C. The variances of the two variables are very similar, with the values being 5.49 and 5.95 for Box 3 and Box 5 respectively. The calculated t-statistic is 0.459, which is less than the critical t-values for both one-tail (1.658) and two-tail (1.981) tests. The two-tailed p-value is 0.6474, which is greater than the α level of 0.05 used to denote statistical significance. Given the high p-value, it fails to reject the null hypothesis that there is no difference in the mean values between the two groups. This indicates that there is not a statistically significant difference between the mean values of the two variables.

5.2 Soil Temperature t-test

Box 0 - Weather

The mean temperatures between soil temperature in Rf upper (Box 0) and the weather are quite close to each other, with Box 0 having a mean temperature of 16.38°C and the weather having a mean temperature of 16.37°C. Moreover, the variance in temperatures is higher in Box 0 with 7.689 compared to the weather with 4.949. The calculated t-statistic is 0.0228, which is much less than the critical t-value for both one-tailed and two-tailed test. The two-tailed p-value is 0.9818, which is much greater than the standard α level of 0.05 used to denote statistical significance. Given the high p-value, it fails to reject the null hypothesis that there is no difference in means between Box 0 and Weather. This suggests that there is not a statistically significant difference between the mean values of your two groups. In effect, this means that the soil temperatures recorded in Box 0 do not significantly differ from the general weather temperatures based on the sample data.

Box 1 - Weather

The means of soil temperature in Rf lower (Box 1) and the weather are approximately 16.92°C and 16.37°C, respectively, with Box 1 being slightly higher. The variances for the two variables are 7.041 for Box 1 and 4.949 for the weather, with Box 1 higher. Adding on, The calculated t-statistic is 1.2067, which is less than the critical t-values for both the one-tail (1.658) and two-tail (1.981) tests. The p-values for one-tail and two-tail tests are 0.115 and 0.30 respectively, both higher than the α level of 0.05, referring to a lack of statistical significance. With the high p-value, it fails to reject the null hypothesis, which means that there is no statistically significant difference between the means of the two variables. Practically speaking, the data shows that the average weather conditions represented are relatively similar for both. Any difference can be due to a random variation rather than a systematic difference between them.

Box 2 - Weather

The mean temperatures between soil temperature in a mix of Rf/Rw upper (Box 2) and the weather are approximately 16.64°C and 16.37°C, respectively. For the variances, Box 2 has a slighly lower variance of 4.763 compared to the variance of the weather 4.949. The t-statistic comes out to be 0.6492, less than the critical values for both one-tail (1.658) and two-tail (1.981) tests. The one-tail p-value is about 0.258, and the two-tail p-value is approximately 0.517, both of which are higher than the α level of 0.05, indicating no statistical significance. It fails to reject the null hypothesis given the p-values, confirming there is no statistically significant difference between the means of the two variables.

Box 3 - Weather

The means of soil temperature in a mix of Rf/Rw lower (Box 3) and the weather are approximately 17.04°C and 16.37°C, respectively, with Box 3 a bit higher. The variances for Box 3 and weather are 4.74 and 4.949, respectively. The t-statistic is 1.6346, which is lower but really close than the critical t-values for both one-tail (1.658) and two-tail (1.981) tests. The calculated p-values for one-tail and two-tail tests are 0.052 and 0.105 respectively, both exceeding the α level of 0.05, thus signals a lack of statistical significance. Given the p-value, it fails to reject the null hypothesis suggesting no statistically significant difference between the mean values of the two variables.

Box 4 - Weather

The means of soil temperature in a mix (Box 4) and the weather are approximately 16.45°C and 16.37°C, respectively, which are incredibly close to each other. The variance of Box 4 is higher, with the values being 6.863 and 4.949 for Box 4 and weather, respectively. The t-statistic is 0.1601, which is much smaller than the critical t-values for both the one-tail (1.658) and two-tail (1.981) tests. The one-tail p-value is 0.437 and the two-tail p-value is 0.873, both being much higher than the α level of 0.05 that implies to statistical significance. With the high p-value, keep the null hypothesis indicating that there is no statistically significant difference between the mean values of the groups. This suggests that the weather conditions represented are almost identical. The differences in mean values possibly coming from random variations.

Box 5 - Weather

The means of soil temperature in Rw (Box 4) and the weather are approximately 15.81°C and 16.37°C, respectively, with Box 5 being lower. The variances for the two variables are different, with respective values of 7.214 and 4.949. The t-statistic is -1.2293, which is lower than the critical t-values for both one-tail (1.658) and two-tail (1.981) tests. The p-values for one-tail and two-tail tests are 0.111 and 0.221 respectively, both of which are above the α level of 0.05, indicating the lack of statistical significance. Given the high p-values, do not reject the null hypothesis. This suggests that there no statistically significant difference between the mean values of the two variables.

Chapter 6

Conclusion

This research investigated whether there are significant differences in temperature readings across various settings compared to the general weather data. Using the data derived from statistical analysis, aside from the temperature recorded on the top roof tile of the conventional roof (Box 2) which demonstrated a statistically notable divergence, in most comparisons there was no statistically significant difference between the mean temperatures of various groups compared to general weather conditions, indicating a general trend of temperature uniformity in these areas. This was determined by comparing p-values greater than the standard α level, implying a failure to reject the null hypothesis. However, comparisons involving Box 2 presented a significant deviation with p-values less than the α level, highlighting a notable difference in mean temperatures and rejecting the null hypothesis. These findings demonstrate that, apart from Box 2, the locations studied mainly exhibit temperature homogeneity with the general weather, confirming the central inquiry of the research on mitigating extreme temperatures. Regarding soil temperature data, all substrates used when compared to the weather and each other, yielded high p-values, signaling a lack of statistically significant differences between the groups.

The Green Panels roof systems generally maintain temperatures close to the surrounding weather conditions, with most setups not showing statistically significant temperature differences when compared to general weather. This suggests that, in most cases, the green roof systems may not significantly contribute to reducing energy consumption and mitigating extreme temperatures, given that they align with existing weather conditions. However, the distinctive behavior of box 2, which exhibited a higher mean temperature, indicates potential areas where the system might have a significant impact on temperature regulation, thus having the green roof system can help reduce temperature. While the conclusion highlights the temperature and soil temperature data analysis, it does not delve into the specifics concerning water retention or management, including the impact on flood runoff peaks and precipitation transpiration. However, by understanding the soil moisture content data for each box with different substrates, a thorough analysis could provide insights into how the different Green Panels green roof systems can contribute to delaying flood runoff peaks and capture and transpire precipitation. When analyzed in tandem with precipitation data, the soil moisture content can indicate each setup's water retention and drainage characteristics, providing a basis to answer this research question.

Chapter 7

Recommendation

While the current research has delved deeply into the temperature and soil temperature dynamics across different settings, it leaves a substantial ground to further build upon. Given the distinctive trends observed in Box 2, it might be beneficial for practitioners and future researchers to focus on the following aspects:

- Understanding the distinctive temperature dynamics in Box 2: The research highlighted a significant deviation in the temperature profiles of Box 2 compared to others. Future studies should unravel the underlying causes of this divergence and propose modifications to optimize temperature control.

- Soil moisture content analysis: Alongside temperature analysis, a detailed study focusing on soil moisture content in different boxes can pave the way to understanding the capabilities of the Green Panels systems in mitigating flood runoff and optimizing precipitation transpiration.

- Comparative study with real-life implementations: To ensure the practical applicability of the findings, it is recommended to conduct comparative studies incorporating real-life data from Green Panels' green roof systems installations. This will help in understanding how laboratory results mirror real-world scenarios.

The current research has made a seminal contribution to establishing a preliminary understanding of the temperature dynamics in different settings characterized by different substrates. This exploration holds the potential to:

- Address gaps in the existing literature: It addresses a crucial knowledge gap by offering insights into the temperature and soil temperature patterns, setting the stage for detailed investigative studies.

- Inform practice: Practitioners looking to implement green roof systems can leverage the findings to inform their decisions, explicitly concerning the choice of materials and configurations that facilitate temperature homogeneity.

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Chapter 8

Appendix

8.1 Sensors information

Both the BME680 and Truebner SMT50 sensors are designed for reliable environmental and soil measurements. However, the specific accuracy of these sensors can depend on a variety of factors including how they are utilized, calibrated, and maintained. Here, I will give you an overview of the reported accuracies from their technical specifications and general information about each:

8.1.1 BME680 Environmental Sensor

- Manufacturer: Bosch Sensortec
- Applications: Designed to measure a range of environmental factors including temperature, humidity, pressure, and volatile organic compounds (VOCs).
- Accuracy: Temperature: Typically ±0.5°C, Humidity: Typically ±3% relative humidity, Pressure: Typically ±0.12 hPa, Gas Sensor (VOCs): The accuracy can vary significantly depending on the specific compounds being measured and the conditions of measurement.
- Remarks: It's known for providing high accuracy for temperature, humidity, and pressure measurements.
  VOC sensor needs careful calibration and is generally used to indicate air quality rather than providing precise concentrations of specific compounds.

8.1.2 Truebner SMT50 Soil Moisture and Temperature Sensor

- Manufacturer: Truebner GmbH
- Applications: It is primarily used in agriculture, horticulture, and environmental studies to monitor soil conditions.
- Accuracy: Soil Moisture: The manufacturer claims an accuracy of ±3% in mineral soils. The accuracy can be different in organic soils and depends on proper calibration. Temperature: ±0.5°C
- Remarks: It has a good reputation for providing reliable soil moisture and temperature readings. It is known to be durable and able to withstand harsh environmental conditions, including immersion in water.

8.2 Sensor coding (Python)

The following code is an example of programming SenseBox for Box 0. The code can also be used for other boxes, by changing the SenseBox ID, and sensors ID.

```
/*
  senseBox:home - Citizen Sensingplatform
  Version: wifiv2_1.6.0
  Date: 2022-03-04
  Homepage: https://www.sensebox.de https://www.opensensemap.org
  Author: Reedu GmbH & Co. KG
  Note: Sketch for senseBox:home WiFi MCU Edition
  Model: homeV2Wifi
  Email: support@sensebox.de
  Code is in the public domain.
  https://github.com/sensebox/node-sketch-templater
*/

#include <WiFi101.h>
#include <Wire.h>
#include <SPI.h>
#include <senseBoxIO.h>

#include <Adafruit_GFX.h>
#include <Adafruit_SSD1306.h>
#include <Adafruit_Sensor.h>
#include <Adafruit_HDC1000.h>
#include <Adafruit_BMP280.h>
#include <Adafruit_BME680.h>
#include <VEML6070.h>
#include <SparkFun_SCD30_Arduino_Library.h>
#include <LTR329.h>
#include <ArduinoBearSSL.h>
#include <Adafruit_DPS310.h> // http://librarymanager/All#Adafruit_DPS310
#include <sps30.h>


// Uncomment the next line to get debugging messages printed on the Serial
                                        port
// Do not leave this enabled for long time use
// #define ENABLE_DEBUG

#ifdef ENABLE_DEBUG
#define DEBUG(str) Serial.println(str)
#define DEBUG_ARGS(str,str1) Serial.println(str,str1)
#define DEBUG2(str) Serial.print(str)
#define DEBUG_WRITE(c) Serial.write(c)
#else
#define DEBUG(str)
#define DEBUG_ARGS(str,str1)
#define DEBUG2(str)
#define DEBUG_WRITE(c)
#endif

/* ------------------------------------------------------------------------
                                        - */
/* --------------------------------Metadata-------------------------------
                                        - */
/* ------------------------------------------------------------------------
                                        - */
/* SENSEBOX ID  : 64b545fd633d7600076cfe9f
```

```
                                                */
/* SENSEBOX NAME: Green Panels Prototype Box 0
                                                */
/* ------------------------------------------------------------------------
                                                - */
/* ------------------------------End of Metadata---------------------------
                                                - */
/* ------------------------------------------------------------------------
                                                - */

/* ------------------------------------------------------------------------
                                                - */
/* ------------------------------Configuration-----------------------------
                                                - */
/* ------------------------------------------------------------------------
                                                - */

// Wifi Credentials
const char *ssid = ""; // your network SSID (name)
const char *pass = ""; // your network password

// Interval of measuring and submitting values in seconds
const unsigned int postingInterval = 60e3;

// address of the server to send to
const char server[] PROGMEM = "ingress.opensensemap.org";

// senseBox ID
const char SENSEBOX_ID[] PROGMEM = "64b545fd633d7600076cfe9f";

// Number of sensors
// Change this number if you add or remove sensors
// do not forget to remove or add the sensors on opensensemap.org
static const uint8_t NUM_SENSORS = 6;

// Connected sensors
// Luftfeuchte - BME680
#define BME680_CONNECTED
// Lufttemperatur - BME680
#define BME680_CONNECTED
// atm. Luftdruck - BME680
#define BME680_CONNECTED
// VOC - BME680
#define BME680_CONNECTED
// Bodenfeuchte - SMT50
#define SMT50_CONNECTED
// Bodentemperatur - SMT50
#define SMT50_CONNECTED

// Display enabled
// Uncomment the next line to get values of measurements printed on display
#define DISPLAY128x64_CONNECTED

// Sensor SENSOR_IDs
// Luftfeuchte - BME680
const char BME680_LUFTFESENSOR_ID[] PROGMEM = "64b545fd633d7600076cfea5";
// Lufttemperatur - BME680
const char BME680_LUFTTESENSOR_ID[] PROGMEM = "64b545fd633d7600076cfea4";
// atm. Luftdruck - BME680
```

```
const char BME680_ATMLUFSENSOR_ID[] PROGMEM = "64b545fd633d7600076cfea3";
// VOC - BME680
const char BME680_VOCSENSOR_ID[] PROGMEM = "64b545fd633d7600076cfea2";
// Bodenfeuchte - SMT50
const char SMT50_BODENFSENSOR_ID[] PROGMEM = "64b545fd633d7600076cfea1";
// Bodentemperatur - SMT50
const char SMT50_BODENTSENSOR_ID[] PROGMEM = "64b545fd633d7600076cfea0";

WiFiClient wifiClient;
BearSSLClient client(wifiClient);

unsigned long getTime() {
  return WiFi.getTime();
}

//Load sensors / instances
#ifdef HDC1080_CONNECTED
  Adafruit_HDC1000 HDC = Adafruit_HDC1000();
#endif
#ifdef BMP280_CONNECTED
  Adafruit_BMP280 BMP;
#endif
#ifdef TSL45315_CONNECTED
  bool lightsensortype = 0; //0 for tsl - 1 for ltr
  //settings for LTR sensor
  LTR329 LTR;
  unsigned char gain = 1;
  unsigned char integrationTime = 0;
  unsigned char measurementRate = 3;
#endif
#ifdef VEML6070_CONNECTED
  VEML6070 VEML;
#endif
#ifdef SMT50_CONNECTED
  #define SOILTEMPPIN 1
  #define SOILMOISPIN 2
#endif
#ifdef SOUNDLEVELMETER_CONNECTED
  #define SOUNDMETERPIN 3
#endif
#ifdef BME680_CONNECTED
  Adafruit_BME680 BME;
#endif
#ifdef WINDSPEED_CONNECTED
  #define WINDSPEEDPIN 5
#endif
#ifdef SCD30_CONNECTED
  SCD30 SCD;
#endif
#ifdef DISPLAY128x64_CONNECTED
#define SCREEN_WIDTH 128
#define SCREEN_HEIGHT 64
#define OLED_RESET 4
Adafruit_SSD1306 display(SCREEN_WIDTH, SCREEN_HEIGHT, &Wire, OLED_RESET);
#endif
#ifdef DPS310_CONNECTED
  Adafruit_DPS310 dps;
#endif
#ifdef SPS30_CONNECTED
  uint32_t auto_clean_days = 4;
  struct sps30_measurement m;
```

```
  int16_t ret;
  uint32_t auto_clean;
#endif


typedef struct measurement {
  const char *sensorId;
  float value;
} measurement;

measurement measurements[NUM_SENSORS];
uint8_t num_measurements = 0;

// buffer for sprintf
char buffer[750];

/* -------------------------------------------------------------------------
                                           - */
/* --------------------------End of Configuration---------------------------
                                           - */
/* -------------------------------------------------------------------------
                                           - */

void addMeasurement(const char *sensorId, float value) {
  measurements[num_measurements].sensorId = sensorId;
  measurements[num_measurements].value = value;
  num_measurements++;
}

void writeMeasurementsToClient() {
  // iterate throug the measurements array
  for (uint8_t i = 0; i < num_measurements; i++) {
    sprintf_P(buffer, PSTR("%s,%9.2f\n"), measurements[i].sensorId,
              measurements[i].value);

    // transmit buffer to client
    client.print(buffer);
    DEBUG2(buffer);
  }

  // reset num_measurements
  num_measurements = 0;
}

void submitValues() {
  if (WiFi.status() != WL_CONNECTED) {
    WiFi.disconnect();
    delay(1000); // wait 1s
    WiFi.begin(ssid, pass);
    delay(5000); // wait 5s
  }
  // close any connection before send a new request.
  // This will free the socket on the WiFi shield
  if (client.connected()) {
    client.stop();
    delay(1000);
  }
  bool connected = false;
  char _server[strlen_P(server)];
  strcpy_P(_server, server);
  for (uint8_t timeout = 2; timeout != 0; timeout--) {
```

```
  Serial.println(F("connecting..."));
  connected = client.connect(_server, 443);
  if (connected == true) {
    DEBUG(F("Connection successful, transferring..."));
    // construct the HTTP POST request:
    sprintf_P(buffer,
              PSTR("POST /boxes/%s/data HTTP/1.1\nAuthorization:
                                                  5c8c5d43478f2c871615e1

              %a622bfa737ced5631b9c5
              %1c8544008cf0d705c5471
              %\nHost: %s\nContent-Type: "
                   "text/csv\nConnection: close\nContent-Length: %i\n\n")
                                                        ,
              SENSEBOX_ID, server, num_measurements * 35);
    DEBUG(buffer);

    // send the HTTP POST request:
    client.print(buffer);

    // send measurements
    writeMeasurementsToClient();

    // send empty line to end the request
    client.println();

    uint16_t timeout = 0;
    // allow the response to be computed

    while (timeout <= 5000) {
      delay(10);
      timeout = timeout + 10;
      if (client.available()) {
        break;
      }
    }

    while (client.available()) {
      char c = client.read();
      DEBUG_WRITE(c);
      // if the server's disconnected, stop the client:
      if (!client.connected()) {
        DEBUG();
        DEBUG(F("disconnecting from server."));
        client.stop();
        break;
      }
    }

    DEBUG(F("done!"));

    // reset number of measurements
    num_measurements = 0;
    break;
  }
  delay(1000);
}

if (connected == false) {
  // Reset durchf hren
  DEBUG(F("connection failed. Restarting System."));
```

```
    delay(5000);
    noInterrupts();
    NVIC_SystemReset();
    while (1)
      ;
  }
}

void checkI2CSensors() {
  byte error;
  int nDevices = 0;
  byte sensorAddr[] = {41, 56, 57, 64, 97, 118};
  DEBUG(F("\nScanning..."));
  for (int i = 0; i < sizeof(sensorAddr); i++) {
    Wire.beginTransmission(sensorAddr[i]);
    error = Wire.endTransmission();
    if (error == 0) {
      nDevices++;
      switch (sensorAddr[i])
      {
        case 0x29:
          DEBUG(F("TSL45315 found."));
          break;
        case 0x38: // &0x39
          DEBUG(F("VEML6070 found."));
          break;
        case 0x40:
          DEBUG(F("HDC1080 found."));
          break;
        case 0x76:
        #ifdef BMP280_CONNECTED
          DEBUG("BMP280 found.");
        #elif defined(BME680_CONNECTED)
          DEBUG("BME680 found.");
        #else
          DEBUG("DPS310 found.");
        #endif
          break;
        case 0x61:
          DEBUG("SCD30 found.");
          break;
      }
    }
    else if (error == 4)
    {
      DEBUG2(F("Unknown error at address 0x"));
      if (sensorAddr[i] < 16)
        DEBUG2(F("0"));
      DEBUG_ARGS(sensorAddr[i], HEX);
    }
  }
  if (nDevices == 0) {
    DEBUG(F("No I2C devices found.\nCheck cable connections and press Reset
                                        ."));
    while(true);
  } else {
    DEBUG2(nDevices);
    DEBUG(F(" sensors found.\n"));
  }
}
```

```
void setup() {
  // Initialize serial and wait for port to open:
  #ifdef ENABLE_DEBUG
    Serial.begin(9600);
  #endif
  delay(5000);

  DEBUG2(F("xbee1 spi enable..."));
  senseBoxIO.SPIselectXB1(); // select XBEE1 spi
  DEBUG(F("done"));
  senseBoxIO.powerXB1(false);
  delay(200);
  DEBUG2(F("xbee1 power on..."));
  senseBoxIO.powerXB1(true); // power ON XBEE1
  DEBUG(F("done"));
  senseBoxIO.powerI2C(false);
  delay(200);
  senseBoxIO.powerI2C(true);
  delay(200);
  senseBoxIO.powerUART(true);

#ifdef DISPLAY128x64_CONNECTED
  DEBUG2(F("enable display..."));
  delay(2000);
  display.begin(SSD1306_SWITCHCAPVCC, 0x3D);
  display.display();
  delay(100);
  display.clearDisplay();
  DEBUG(F("done."));
  display.setCursor(0, 0);
  display.setTextSize(2);
  display.setTextColor(WHITE, BLACK);
  display.println("senseBox:");
  display.println("home\n");
  display.setTextSize(1);
  display.println("Version Wifi ");
  display.setTextSize(2);
  display.display();
  delay(2000);
  display.clearDisplay();
  display.setCursor(0, 0);
  display.setTextSize(1);
  display.println("Connecting to:");
  display.println();
  display.println(ssid);
  display.setTextSize(1);
  display.display();
#endif

  // Check WiFi Bee status
  if (WiFi.status() == WL_NO_SHIELD) {
    DEBUG(F("WiFi shield not present"));
    // don't continue:
    while (true);
  }
  uint8_t status = WL_IDLE_STATUS;
  // attempt to connect to Wifi network:
  while (status != WL_CONNECTED) {
#ifdef DISPLAY128x64_CONNECTED
    display.print(".");
    display.display();
```

```
#endif
    DEBUG2(F("Attempting to connect to SSID: "));
    DEBUG(ssid);
    // Connect to WPA/WPA2 network. Change this line if using open or WEP
    // network
    status = WiFi.begin(ssid, pass);
    // wait 10 seconds for connection:
    DEBUG2(F("Waiting 10 seconds for connection..."));
    delay(10000);
    DEBUG(F("done."));
  }

  // check the server time for the validation of the certificate
  ArduinoBearSSL.onGetTime(getTime);

  #ifdef ENABLE_DEBUG
    // init I2C/wire library
    Wire.begin();
    checkI2CSensors();
  #endif

  // Sensor initialization
  DEBUG(F("Initializing sensors..."));
  #ifdef HDC1080_CONNECTED
    HDC.begin();
  #endif
  #ifdef BMP280_CONNECTED
    BMP.begin(0x76);
  #endif
  #ifdef VEML6070_CONNECTED
    VEML.begin();
    delay(500);
  #endif
  #ifdef TSL45315_CONNECTED
    Lightsensor_begin();
  #endif
  #ifdef BME680_CONNECTED
    BME.begin(0x76);
    BME.setTemperatureOversampling(BME680_OS_8X);
    BME.setHumidityOversampling(BME680_OS_2X);
    BME.setPressureOversampling(BME680_OS_4X);
    BME.setIIRFilterSize(BME680_FILTER_SIZE_3);
  #endif
  #ifdef SCD30_CONNECTED
    Wire.begin();
    SCD.begin();
  #endif
  #ifdef DISPLAY128x64_CONNECTED
  display.clearDisplay();
  display.setCursor(30, 28);
  display.setTextSize(2);
  display.print("Ready!");
  display.display();
  #endif
  #ifdef DPS310_CONNECTED
    dps.begin_I2C(0x76);
    dps.configurePressure(DPS310_64HZ, DPS310_64SAMPLES);
    dps.configureTemperature(DPS310_64HZ, DPS310_64SAMPLES);
  #endif
  #ifdef SPS30_CONNECTED
    sensirion_i2c_init();
```

```
    ret = sps30_set_fan_auto_cleaning_interval_days(auto_clean_days);
    ret = sps30_start_measurement();
  #endif
  DEBUG(F("Initializing sensors done!"));
  DEBUG(F("Starting loop in 3 seconds."));
  delay(3000);
}


void loop() {
  DEBUG(F("Starting new measurement..."));
#ifdef DISPLAY128x64_CONNECTED
  long displayTime = 5000;
  int page = 0;

  display.clearDisplay();
  display.setCursor(0, 0);
  display.setTextSize(1);
  display.setTextColor(WHITE, BLACK);
  display.println("Uploading new measurement... ");
  display.display();
#endif
  // capture loop start timestamp
  unsigned long start = millis();

  //-----Temperature-----//
  //-----Humidity-----//
#ifdef HDC1080_CONNECTED
  addMeasurement(HDC1080_TEMPERSENSOR_ID, HDC.readTemperature());
  delay(200);
  addMeasurement(HDC1080_RELLUFSENSOR_ID, HDC.readHumidity());
#endif

  //-----Pressure-----//
#ifdef BMP280_CONNECTED
  float pressure;
  pressure = BMP.readPressure() / 100;
  addMeasurement(BMP280_LUFTDRSENSOR_ID, pressure);
#endif

  //-----Lux-----//
#ifdef TSL45315_CONNECTED
  addMeasurement(TSL45315_BELEUCSENSOR_ID, Lightsensor_getIlluminance());
#endif

  //-----UV intensity-----//
#ifdef VEML6070_CONNECTED
  addMeasurement(VEML6070_UVINTESENSOR_ID, VEML.getUV());
#endif

  //-----Soil Temperature & Moisture-----//
#ifdef SMT50_CONNECTED
  float voltage = analogRead(SOILTEMPPIN) * (3.3 / 1024.0);
  float soilTemperature = (voltage - 0.5) * 100;
  addMeasurement(SMT50_BODENTSENSOR_ID, soilTemperature);
  voltage = analogRead(SOILMOISPIN) * (3.3 / 1024.0);
  float soilMoisture = (voltage * 50) / 3;
  addMeasurement(SMT50_BODENFSENSOR_ID, soilMoisture);
#endif

  //-----dB(A) Sound Level-----//
```

```
#ifdef SOUNDLEVELMETER_CONNECTED
  float v = analogRead(SOUNDMETERPIN) * (3.3 / 1024.0);
  float decibel = v * 50;
  addMeasurement(SOUNDLEVELMETER_LAUTSTSENSOR_ID, decibel);
#endif

  //-----BME680-----//
#ifdef BME680_CONNECTED
  BME.setGasHeater(0, 0);
  float gasResistance;
  if ( BME.performReading()) {
    addMeasurement(BME680_LUFTTESENSOR_ID, BME.temperature - 1);
    addMeasurement(BME680_LUFTFESENSOR_ID, BME.humidity);
    addMeasurement(BME680_ATMLUFSENSOR_ID, BME.pressure / 100);
  }
  BME.setGasHeater(320, 150); // 320*C for 150 ms
  if ( BME.performReading()) {
      gasResistance = BME.gas_resistance / 1000.0;
       addMeasurement(BME680_VOCSENSOR_ID, gasResistance);
  }
#endif

  //-----Wind speed-----//
#ifdef WINDSPEED_CONNECTED
  float voltageWind = analogRead(WINDSPEEDPIN) * (3.3 / 1024.0);
  float windspeed = 0.0;
  if (voltageWind >= 0.018) {
    float poly1 = pow(voltageWind, 3);
    poly1 = 17.0359801998299 * poly1;
    float poly2 = pow(voltageWind, 2);
    poly2 = 47.9908168343362 * poly2;
    float poly3 = 122.899677524413 * voltageWind;
    float poly4 = 0.657504127272728;
    windspeed = poly1 - poly2 + poly3 - poly4;
    windspeed = windspeed * 0.2777777777777778; //conversion in m/s
  }
  addMeasurement(WINDSPEED_WINDGESENSOR_ID, windspeed);
#endif

  //-----CO2-----//
#ifdef SCD30_CONNECTED
  addMeasurement(SCD30_CO2SENSOR_ID, SCD.getCO2());
#endif

  //-----DPS310 Pressure-----//
  #ifdef DPS310_CONNECTED
    sensors_event_t temp_event, pressure_event;
    dps.getEvents(&temp_event, &pressure_event);
    addMeasurement(DPS310_LUFTDRSENSOR_ID, pressure_event.pressure);
  #endif

  #ifdef SPS30_CONNECTED
    ret = sps30_read_measurement(&m);
    addMeasurement(SPS30_PM1SENSOR_ID, m.mc_1p0);
    addMeasurement(SPS30_PM25SENSOR_ID, m.mc_2p5);
    addMeasurement(SPS30_PM4SENSOR_ID, m.mc_4p0);
    addMeasurement(SPS30_PM10SENSOR_ID, m.mc_10p0);
  #endif

  DEBUG(F("Submit values"));
  submitValues();
```

```
  // schedule next round of measurements
  for (;;) {
    unsigned long now = millis();
    unsigned long elapsed = now - start;
#ifdef DISPLAY128x64_CONNECTED
    display.clearDisplay();
    display.setCursor(0, 0);
    display.setTextSize(1);
    display.setTextColor(WHITE, BLACK);
    switch (page)
    {
      case 0:
        // HDC & BMP
        display.setTextSize(2);
        display.setTextColor(BLACK, WHITE);
        display.println(F("HDC&BMP"));
        display.setTextColor(WHITE, BLACK);
        display.setTextSize(1);
        display.print(F("Temp:"));
#ifdef HDC1080_CONNECTED
        display.println(HDC.readTemperature());
#else
        display.println(F("not connected"));
#endif
        display.println();
        display.print(F("Humi:"));
#ifdef HDC1080_CONNECTED
        display.println(HDC.readHumidity());
#else
        display.println(F("not connected"));
#endif
        display.println();
        display.print(F("Press.:"));
#ifdef BMP280_CONNECTED
        display.println(BMP.readPressure() / 100);
#else
        display.println(F("not connected"));
#endif
        break;
      case 1:
        // TSL/VEML
        display.setTextSize(2);
        display.setTextColor(BLACK, WHITE);
        display.println(F("TSL&VEML"));
        display.setTextColor(WHITE, BLACK);
        display.println();
        display.setTextSize(1);
        display.print(F("Lux:"));
#ifdef TSL45315_CONNECTED
        display.println(Lightsensor_getIlluminance());
#else
        display.println(F("not connected"));
#endif
        display.println();
        display.print("UV:");
#ifdef VEML6070_CONNECTED
        display.println(VEML.getUV());
#else
        display.println(F("not connected"));
#endif
```

```
        break;
      case 2:
        // SPS30_CONNECTED
        display.setTextSize(2);
        display.setTextColor(BLACK, WHITE);
        display.println(F("PM1&PM2.5"));
        display.setTextColor(WHITE, BLACK);
        display.println();
        display.setTextSize(1);
        display.print(F("PM1:"));

        #ifdef SPS30_CONNECTED
          display.println(m.mc_1p0);
        #else
          display.println(F("not connected"));
        #endif

        display.print(F("PM.25:"));
        #ifdef SPS30_CONNECTED
          display.println(m.mc_2p5);
        #else
          display.println(F("not connected"));
        #endif

        break;
      case 3:
        // SPS30_CONNECTED
        display.setTextSize(2);
        display.setTextColor(BLACK, WHITE);
        display.println(F("PM4&PM10"));
        display.setTextColor(WHITE, BLACK);
        display.println();
        display.setTextSize(1);
        display.print(F("PM4:"));

        #ifdef SPS30_CONNECTED
          display.println(m.mc_4p0);
        #else
          display.println(F("not connected"));
        #endif
          display.print(F("PM10:"));
        #ifdef SPS30_CONNECTED
          display.println(m.mc_10p0);
        #else
          display.println(F("not connected"));
        #endif
        break;
      case 4:
        // SMT, SOUND LEVEL , BME
        display.setTextSize(2);
        display.setTextColor(BLACK, WHITE);
        display.println(F("Soil"));
        display.setTextColor(WHITE, BLACK);
        display.println();
        display.setTextSize(1);
        display.print(F("Temp:"));
#ifdef SMT50_CONNECTED
        display.println(soilTemperature);
#else
        display.println(F("not connected"));
#endif
```

```
        display.println();
        display.print(F("Moist:"));
#ifdef SMT50_CONNECTED
        display.println(soilMoisture);
#else
        display.println(F("not connected"));
#endif

        break;
      case 5:
        // WINDSPEED SCD30
        display.setTextSize(2);
        display.setTextColor(BLACK, WHITE);
        display.println(F("Wind&SCD30"));
        display.setTextColor(WHITE, BLACK);
        display.println();
        display.setTextSize(1);
        display.print(F("Speed:"));
#ifdef WINDSPEED_CONNECTED
        display.println(windspeed);
#else
        display.println(F("not connected"));
#endif
        display.println();
        display.print(F("SCD30:"));
#ifdef SCD30_CONNECTED
        display.println(SCD.getCO2());
#else
        display.println(F("not connected"));
#endif
        break;
      case 6:
          // SMT, SOUND LEVEL , BME
        display.setTextSize(2);
        display.setTextColor(BLACK, WHITE);
        display.println(F("Sound&BME"));
        display.setTextColor(WHITE, BLACK);
        display.println();
        display.setTextSize(1);
        display.print(F("Sound:"));
#ifdef SOUNDLEVELMETER_CONNECTED
        display.println(decibel);
#else
        display.println(F("not connected"));
#endif
        display.println();
        display.print(F("Gas:"));
#ifdef BME680_CONNECTED
        display.println(gasResistance);
#else
        display.print(F("not connected"));
#endif

        break;
    }
    display.display();
    if (elapsed >= displayTime)
    {
      if (page == 4)
      {
        page = 0;
```

```
      }
      else
      {
        page += 1;
      }
      displayTime += 5000;
    }
#endif
    if (elapsed >= postingInterval)
      return;
  }
}

int read_reg(byte address, uint8_t reg)
{
  int i = 0;

  Wire.beginTransmission(address);
  Wire.write(reg);
  Wire.endTransmission();
  Wire.requestFrom((uint8_t)address, (uint8_t)1);
  delay(1);
  if(Wire.available())
    i = Wire.read();

  return i;
}

void write_reg(byte address, uint8_t reg, uint8_t val)
{
  Wire.beginTransmission(address);
  Wire.write(reg);
  Wire.write(val);
  Wire.endTransmission();
}

#ifdef TSL45315_CONNECTED
void Lightsensor_begin()
{
  Wire.begin();
  unsigned int u = 0;
  DEBUG(F("Checking lightsensortype"));
  u = read_reg(0x29, 0x80 | 0x0A); //id register
  if ((u & 0xF0) == 0xA0)            // TSL45315
  {
    DEBUG(F("TSL45315"));
    write_reg(0x29, 0x80 | 0x00, 0x03); //control: power on
    write_reg(0x29, 0x80 | 0x01, 0x02); //config: M=4 T=100ms
    delay(120);
    lightsensortype = 0; //TSL45315
  }
  else
  {
    DEBUG(F("LTR329"));
    LTR.begin();
    LTR.setControl(gain, false, false);
    LTR.setMeasurementRate(integrationTime, measurementRate);
    LTR.setPowerUp(); //power on with default settings
    delay(10); //Wait 10 ms (max) - wakeup time from standby
    lightsensortype = 1;                     //
  }
```

```
}

unsigned int Lightsensor_getIlluminance()
{
  unsigned int lux = 0;
  if (lightsensortype == 0) // TSL45315
  {
    unsigned int u = (read_reg(0x29, 0x80 | 0x04) << 0);  //data low
    u |= (read_reg(0x29, 0x80 | 0x05) << 8); //data high
    lux = u * 4; // calc lux with M=4 and T=100ms
  }
  else if (lightsensortype == 1) //LTR-329ALS-01
  {
    delay(100);
    unsigned int data0, data1;
    for (int i = 0; i < 5; i++) {
      if (LTR.getData(data0, data1)) {
        if(LTR.getLux(gain, integrationTime, data0, data1, lux));
        else DEBUG(F("LTR sensor saturated"));
        if(lux > 0) break;
        else delay(10);
      }
      else {
        DEBUG2(F("LTR getData error "));
        byte error = LTR.getError();
        Serial.println(error);
      }
    }
  }
  return lux;
}
#endif
```

8.3 Histograms

8.3.1 Temperature data

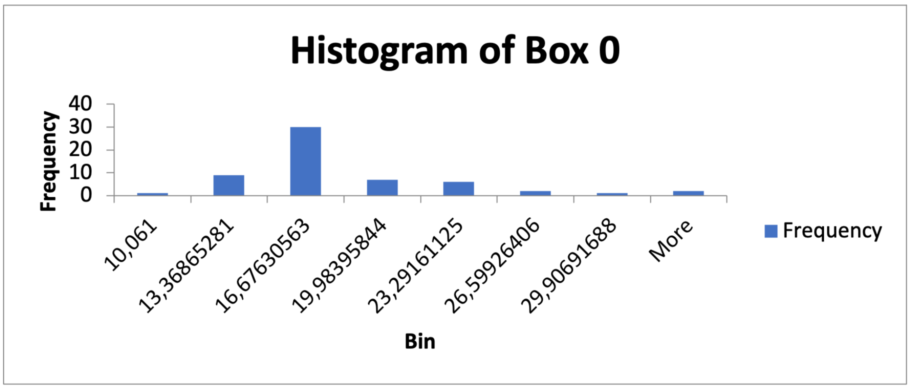

FIGURE 8.1: Histogram of temperature sensor of Box 0.

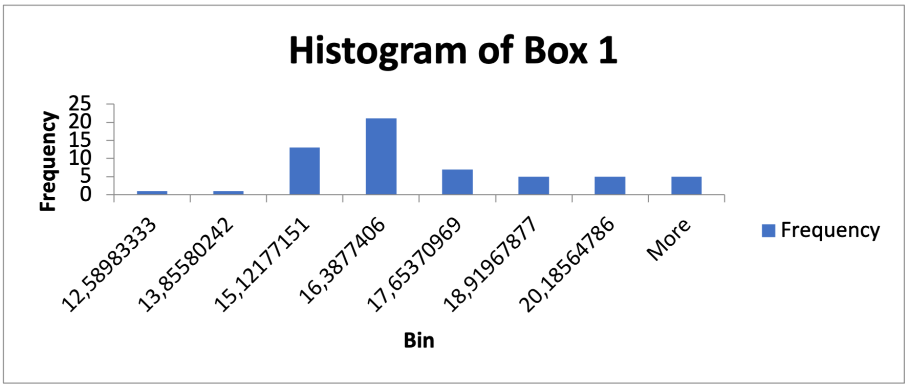

FIGURE 8.2: Histogram of temperature sensor of Box 1.

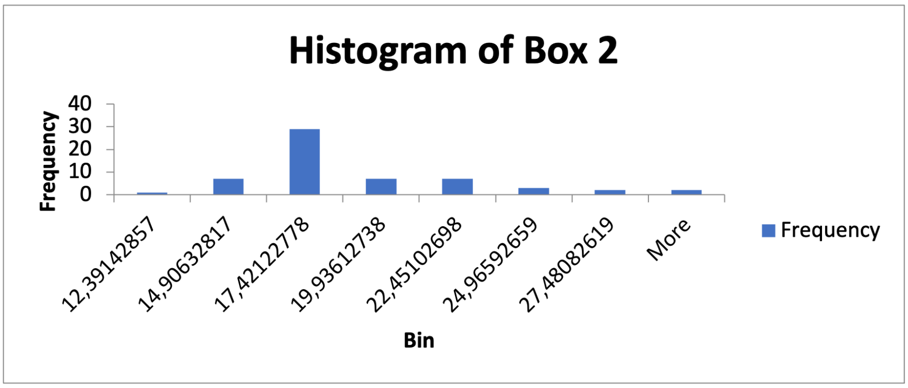

FIGURE 8.3: Histogram of temperature sensor of Box 2.

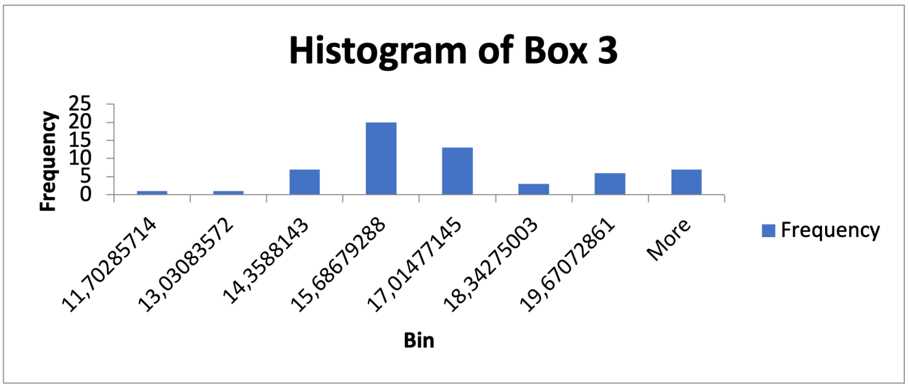

FIGURE 8.4: Histogram of temperature sensor of Box 3.

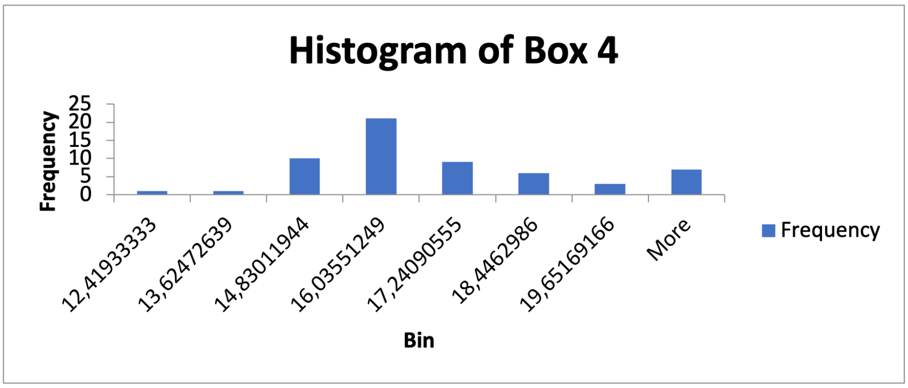

FIGURE 8.5: Histogram of temperature sensor of Box 4.

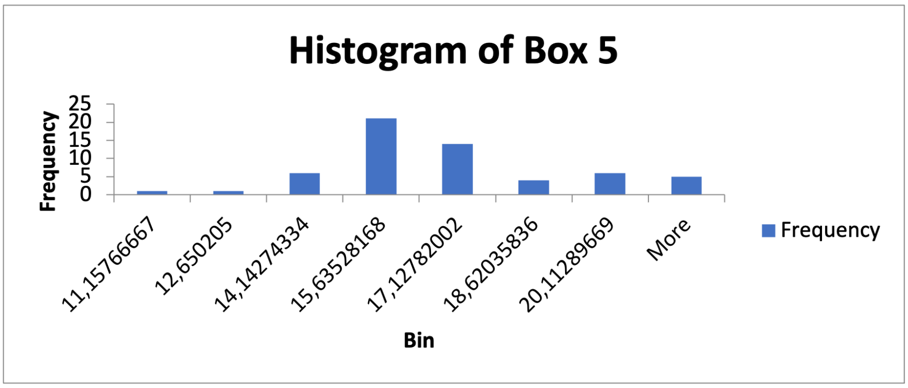

FIGURE 8.6: Histogram of temperature sensor of Box 5.

8.3.2 Soil temperature data

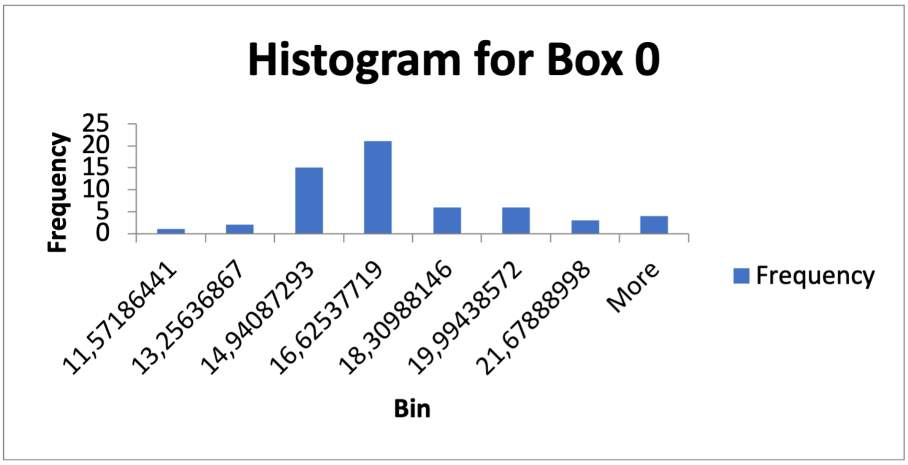

FIGURE 8.7: Histogram of soil temperature sensor of Box 0.

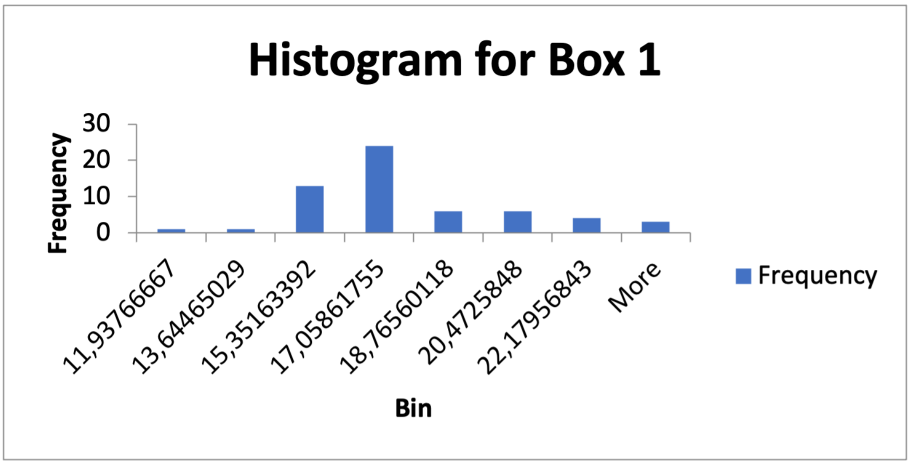

FIGURE 8.8: Histogram of soil temperature sensor of Box 1.

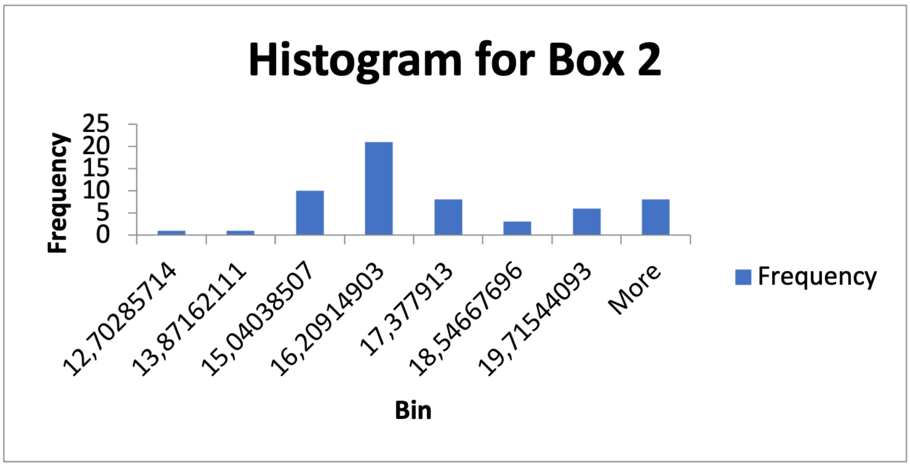

FIGURE 8.9: Histogram of soil temperature sensor of Box 2.

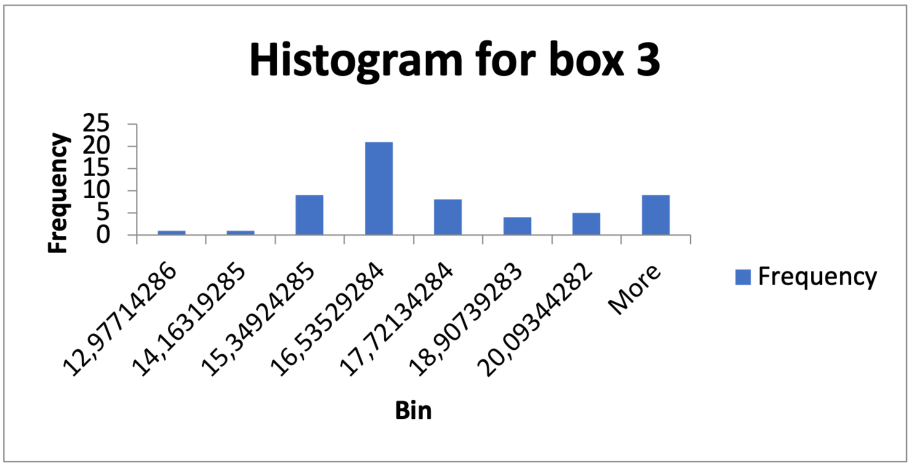

FIGURE 8.10: Histogram of soil temperature sensor of Box 3.

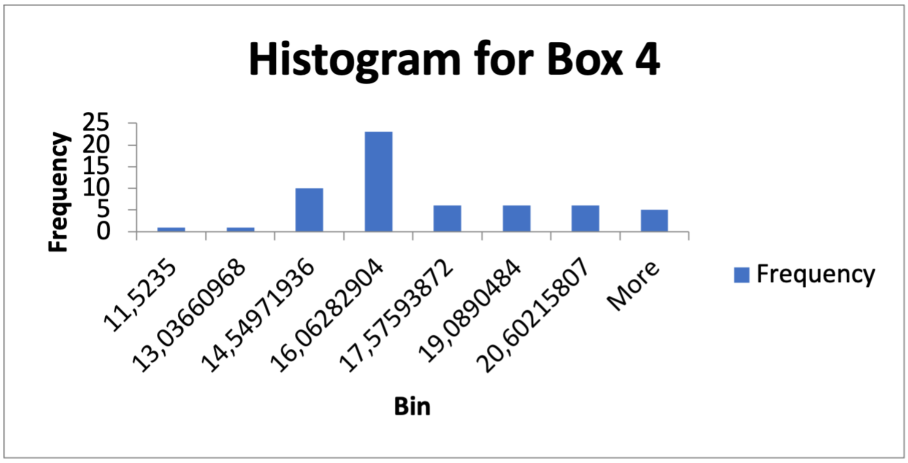

FIGURE 8.11: Histogram of soil temperature sensor of Box 4.

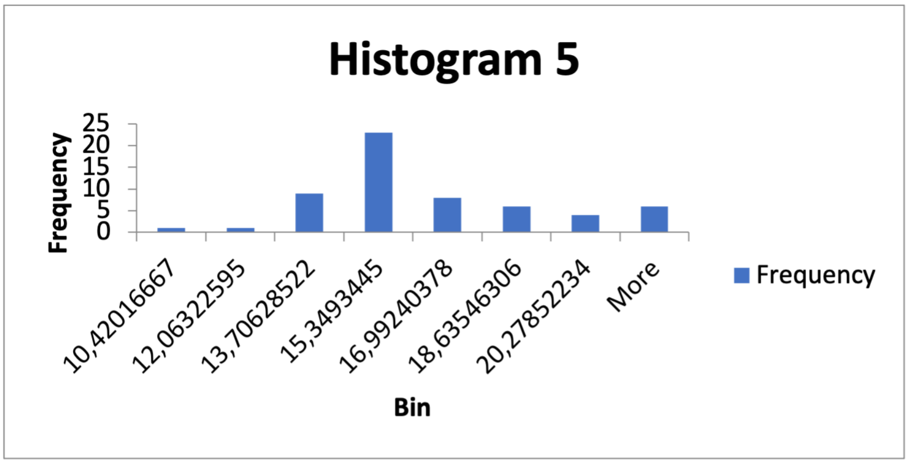

FIGURE 8.12: Histogram of soil temperature sensor of Box 5.

8.4 Excel sheets

The following folder contains an Excel workbook with data, and its respective statistical analysis.