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**Optimization of Human Processes in A Greenhouse
Aeroponic Potato Farming System Using 3D
Simulation And Virtual Reality**

School of Technology and Innovation
Master's thesis in Industrial Management
Programme

Vaasa 2024

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ABSTRACT:

As global demand to industrialize food production increases, Aeroponics farming emerges as a sustainable approach to yielding higher food growth with minimal resources. This thesis addresses two aspects for advancing industrial-scale aeroponic potato farming; Optimizing human process flow and configuring an effective layout in a greenhouse farm. The first research question addresses how human processes and task affects productivity in an aeroponic greenhouse farm and how it can be enhanced, by monitoring workflow patterns and identifying bottlenecks. The second question explores layout configurations suitable for large-scale aeroponic potato farm produce. Through different layout comparisons, this study identifies the optimal layout configuration that maximises practicality, facility effectiveness, space utilization and work efficiency.

This study is simulation-based using 3D designs and virtual reality. The method used in this thesis is based on Discrete Event Simulation (DES) a modelling technique that represents the behaviour of a production system by simulating individual events that occur at certain points in time.

A proposed solution is creating an aeroponic greenhouse farm layout using DES software, inserting 3D elements and configuring some human process modelling. The first layout is vertical having longer aisles and having an efficient workflow process. The second layout takes a horizontal shape with shorter aisles making work efficient and easy to manoeuvre.

The findings offer valuable insights into how the right layout configuration can improve workers' efficiency. Results showing basic human performance of both greenhouse farm layout and simulation can be viewed using virtual reality glasses.

The result demonstrates that the use of 3D modelling and simulation is beneficial in optimizing process flow and visualizing layouts when incorporated with VR to inspect models via immersive experience.

KEYWORDS: Aeroponic potato farm, 3D modelling and simulation, process modelling, Virtual reality

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Abbreviations

3D	Three Dimensional
ABS	Agent-Based Simulation
AGV	Automated Guided Vehicles
AI	Artificial Intelligence
BIM	Building Information Modelling
CAD	Computer-Aided Diagram
CC	Creative Common
CEV	Controlled Environment Farming
DES	Discrete Event Simulation
DSR	Design Science Research
DT	Digital Twin
ECCLES	Engineered Closed Circle Environmental
ECLESS	Environmental and Life Support System
FPRO	Finnish Patent and Registration Office
ICT	Information Communication Technology
IE	Industrial Ecology
IoT	Internet of Things
LAI	Leaf Area Index
NB	Nota Bene
NFT	Nutrient Film Technique
OLP	Offline Programming
PCT	Patent Cooperation Treaty
RAM	Random Access Memory
RD	Research Design
SDS	System Dynamics Simulation
UI	User Interface
USAD	The United States Department of Agriculture
VC	Visual components
VR	Virtual Reality
VR	Virtual Reality
WIPO	World Intellectual Property Organization
XR	Extended Reality

Acknowledgment

I would like to thank Dr. Rayko Toshev for his steadfast supervision and guidance throughout this research. I would also like to thank Prof. Rainen Hermans for granting me the opportunity to be a part of the research project through this thesis.

To my fiancée, Roosa who has always been a source of comfort in reassuring me things will get better, to all my sisters who held me in their prayers and supported me with words of reassurance. And to my brother Charles Agu for believing in me, I sincerely appreciate you all.

Vaasa, November 2024
Beluolisa Agu

1 Introduction

Farming has been a part of human means of survival since the beginning of time, over the past few decades, the agricultural sector has witnessed an advanced transformation with the integration of technology, particularly through greenhouse farming, simulation, and precision farming techniques. This technological advancement has gained a significant presence in cultivating high-value quality crops, introducing new farming techniques such as hydroponic and aeroponic farming. This farming technique is increasingly sought after in fine dining establishments for its superior quality and unique growing conditions. Aeroponics, a method where plants grow in an air or mist environment, presents a promising solution to traditional agriculture challenges like limited arable land and resource inefficiency (Barak, 2020)

Farmers are gradually inculcating aeroponic farming, but face challenges to implement this farming technique since it requires some technical knowledge. The designing of a greenhouse aeroponic farm using visual components is the backbone of this thesis; Here this paper will focus on the layout of a greenhouse aeroponic farming system strictly for the production of aeroponic potatoes farming using the Aeropod technology offered by Aeropod OY similar to the National Aeronautics and Space Administration (NASA's) space agricultural farming as a groundbreaking technology in the harvesting of genetically identical potato varieties using space technology. NASA's innovative efforts in space agriculture have established the groundwork for progress in aeroponic farming methodologies (Massa et al., 2016). NASA's aeroponic devices were initially created to assist in extended space missions and to optimize crop farming in restricted and resource-constrained settings. These technologies have been modified for usage on land, offering significant knowledge about sustainable farming methods. (Massa et al., 2016)

This thesis will design the human process flow and analyze the efficiency of the overall greenhouse farm agronomy process.

Aeroponics farming is not a new technology, however, the approach that Aeropod Oy has developed is new to both aeroponic and hydroponic farming, claiming a 5-patent

family (World Intellectual Property Organization WIPO| The Patent Cooperation Treaty PCT & Finnish Patent and Registration Office), (Hermans, 2022). This approach also integrates the use of 3D simulation to scale up the facility size for higher potato cultivation based on production per ton and greenhouse capacity. The facility is intended to produce fine varieties of potatoes for fine dining and retail per specific kg for individual consumption.

1.1 Research area

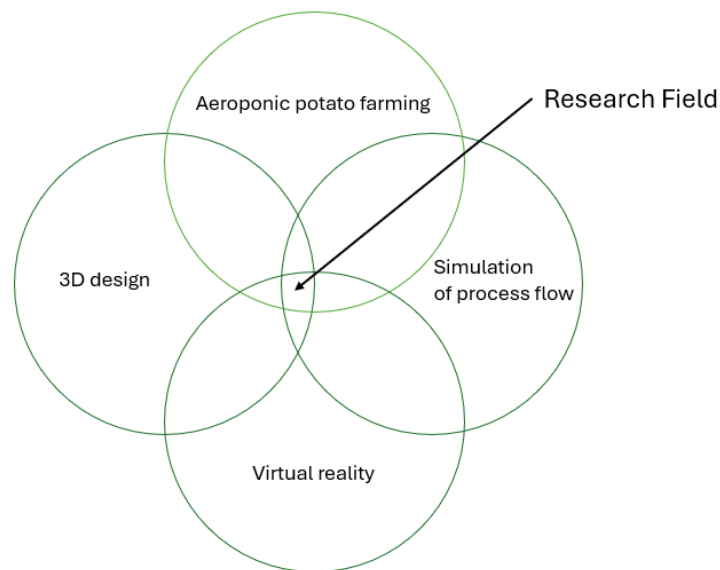


Figure 1. Definition of the research area

This research gives valuable information to Aeropod OY on the design layout and process flow to help make informed decisions for their new greenhouse farm. With the advances in the agricultural sector, large-scale aeroponic potato farming needs more insight to optimize nutrient delivery, scalability, IoT integration, and the possibility utilizing 3D design using Virtual Reality (VR) head gears. VR solutions make it possible to quickly preview and have a realistic first-person experience when planning industrial facilities. The research area of this thesis focuses on human resource efficiency in the greenhouse farm. The major dealbreaker is the use of simulation tools and VR to observe a concise representation of the processes happening inside the facility.

1.2 Research gap

Most research on aeroponic farming focuses on crop produce such as vegetables, fruits, and herbs but has a low focus on tuber produce. On the other hand, most aeroponic farming is vertically designed and is not practical for tuber produce nor efficient for a larger consumption market.

1.3 Research onion framework

An important part of this research methodology will be Saunders's research onion. Saunders (2007) developed a research technique and framework for future studies, focusing on the "research onion" model. This model evaluates its suitability for future studies outlining seven sequential processes that follow a constructive pattern for creating a research methodology and design, starting with defining the philosophical standpoint. The research onion framework is designed in a way that the application step moves from the outer core to the inner core formulating a logical research structure. The outermost layer is the research philosophy, followed by the next layer, the approach to theory development. The next layer focuses on Methodological choices, the fourth layer deals with strategies, the fifth is the time horizon, and the final layer is the research techniques and procedures (Saunders et al., 2019)

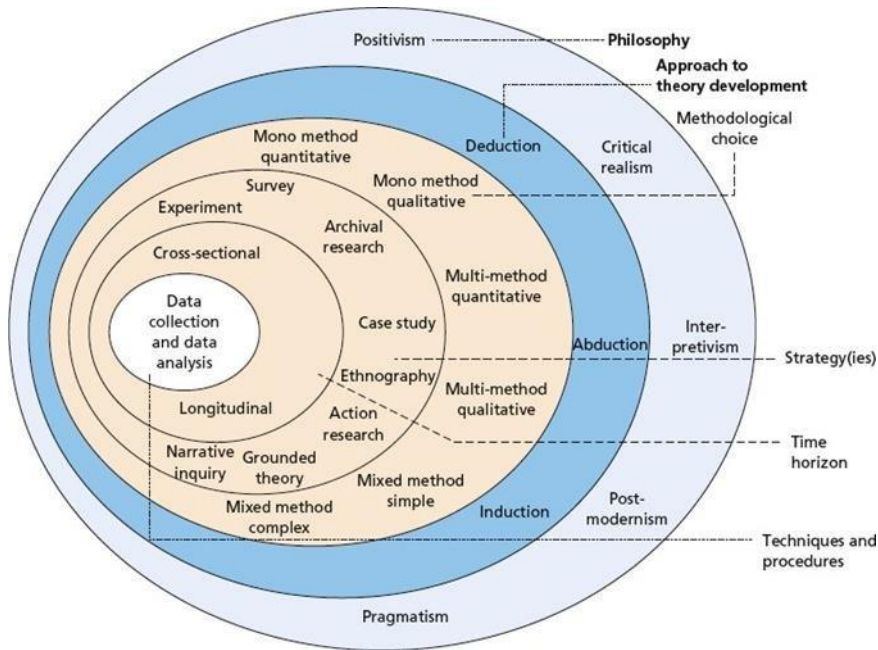


Figure 2. Structure of research onion (Saunders et al., 2007)

1. Research philosophy

The first layer of the research onion; Research philosophy, which refers to a set of attitudes and assumptions on the acquisition of knowledge. There are three forms of research philosophies: axiology, ontology, and epistemology. Axiology deals with values and ethics, while ontology is about fundamental beliefs about reality. Ontology includes objectivism and constructivism, while epistemology studies how we acquire knowledge about reality (Saunders et al., 2019). Choosing the appropriate methodology for specific research can pose a significant challenge. Research designs address the selection of research questions, identification of relevant data, determination of data collection methods, and analysis of the obtained results. Phenomenological philosophy offers valuable ideas on how to analyze and understand personal experiences (Saunders et al., 2019).

Since the world is made up of tangible entities and our perception is limited to sensations and images, Pragmatism is suitable as it prioritizes actionable outcomes over theoretical insights, allowing researchers to design solutions that directly depict the working conditions in the greenhouse farm.

2. Approach to the theory development

The second layer of the research onion; Approach to the theory development, this explores the concept of buildability through three research approaches which are deduction, induction, and abduction. (Saunders, et al., 2019). This thesis will follow both deductive approaches that start with reviewing the literature of past studies and evaluating it with the current situations moving on to pattern reconciliation with process flow and automation in the VR space. This focus will help ascertain the functionality of the final result gathering different themes and patterns.

3. Methodological choices

The third layer; Methodological choice. According to Saunders (2016), research onion outlines six methodological choices, Mono method quantitative, Mono method qualitative, multi-method quantitative, Multi-method qualitative, Mixed method simple, and Mixed method complex. This thesis methodology aligns with the research question and objectives and harmonizes all the Design Science Research (DSR) and its artifacts.

4. Strategies

The fourth layer of the research onion; Strategy. This thesis will follow a DSR approach to validate the theoretical framework, Design Science research methodology will be employed using methods, construct, and instantiations artifacts. An empirical investigation will be conducted to understand the proposed simulation approach. This will involve socio-technical theory components (structure, people, technology, and task) approach and monitoring performance under different operational conditions.

5. Time horizon

The fifth layer of the research onion; Time horizon, described by Saunder et al., (2019) possesses two types of time horizons, longitudinal and cross-sectional. Bryman & Bell, (2015) described that the cross-sectional time horizon method is used to examine a

specific phenomenon within a particular period, while longitudinal time horizon focuses on the continuous collection of data occurrence over a time period (Saunders, et al., 2019). This thesis will gather data over a cross-sectional time horizon, monitoring the behaviour of the human process to ascertain clear and accurate simulation.

6. Techniques and procedures

The last layer of the research onion; Techniques and procedures is used to gather informative data. The thesis will employ an interpretive method, focusing on the previous research design process. The study will also use qualitative data analysis methods such as primary and secondary data, discourse analysis, narrative analysis, and interpretive phenomenological analysis. These methods are used to identify shortcomings in current practices and arrive at a given finding.

1.4 Research questions

The fundamental objective of this thesis is to optimize human processes in a greenhouse aeroponic potato farming system using simulation and virtual reality. In other words, the use of a 3D simulation tool will be employed for this research to gather parameters such as cost, and process flow time. The greenhouse facility is designed to provide a first-hand representation of the actual greenhouse facility, such as Digital Twin (DT), using VR gears to get the actual perspective. Based on the thesis objectives, the following research questions will be answered in the **Result** of this thesis.

1. How can the human process flow in aeroponic farming be optimized?
2. What layout configuration supports industrial scale greenhouse aeroponics potato farm?

1.4.1 Limitations

This thesis will investigate different intra-logistics process flow with humans, the design concepts, and accessibility using Visual Components (VC) software. The software's usability will be briefly explained in this research paper.

This research will not show a simulation of the germination process of the potatoes. No elaboration on the planting, nurturing, or greenhouse effect using 3D simulation will be covered in this thesis.

Due to the nature of this research, which focuses on 3D design and simulation, some details are generalized, and some parameters are not represented in full detail. The layout is represented in an open design without roofing and solar panels.

This research is intended to elaborate on the greenhouse layout, efficiency, and design functionality using simulation. Only one aisle of the greenhouse farm will be simulated; other areas, including the loading dock, service area, packaging area, and entrance, will not be simulated, however, a 3D representation will be visualized.

1.4.2 Structure of the thesis

This thesis is developed on a five-chapter structure which will follow a sequential research order, firstly, an overall Introduction that covers the research background, questions and objectives including limitations. Following is chapter two, a **Literature review** that introduces and investigates the literature of the thesis including key definitions, related topics, theories, and an insight into the overall fundamental concept of the research. Chapter three **Methods** discusses the research methodology used in this research, the chapter is an extension of the research method used. The **Result** This chapter elaborates on a detailed visual analysis obtained during the research. It also focuses on 3D design, simulation, applications, processes, and operations. **Conclusion** comprises

of the constructive summary from all previous chapters that draw a useful conclusion on the research study area, and suggestions for future studies.

2 Literature review

2.1 Potatoes farming

The potato, native to the South American continent, thrived as a wild plant around 7000-9000 years ago. Its origins can be traced back to Lake Titicaca in the Andes Mountains. Potatoes can be found in various environments, from deserts to high-rainfall forests. Potato trading began in northern Peru around 1-600 AD. The term "papa" was popularized by Spaniards (Singh & Rana, 2014)

Potato farming in the Andean highlands relies on the continuous selection and multiplication of seeds (Van der Ploeg, 2002). According to Chiurciu et al., (2020) potato cultivation in the European Union is crucial for human sustenance, with the majority being the white potato. From 2010 to 2018, Chiurciu et al., (2020) examined cultivation and marketing parameters, total production, average production, sale prices, and primary importers and exporters. Poland, Germany, and France experienced growth in 2018, while Denmark achieved the highest average production value. The Netherlands, France, and Germany held the top positions as global exporters, while Belgium, the Netherlands, and Spain were primary importers (Chiurciu et al., 2020).

Finland experienced the most severe drought in 20 years due to high temperatures and minimal precipitation across North and Central Europe. This led to a decrease in crop production, particularly in the Nordic and Baltic countries. However, progress was made in EU law to reduce unfair trading practices in the food supply chain. The EU's farm policy agenda for 2019-2020 was expected to focus on reform recommendations for the Common Agricultural Policy while Rieger et al., (2023) argues that the agricultural sector's importance in promoting economic security is increasing due to social-economic changes and global economic expansion. Harmonizing agricultural policy with economic security involves safeguarding national interests, promoting sustainable growth, and modernizing the economy. Research reveals that the European Union's economic security is directly influenced by its agricultural policy success. These countries with high

economic security and moderate agricultural policy funding, such as Germany, Denmark, Ireland, Luxembourg, the Netherlands, Finland, and Sweden, show similar trends. Brexit remains a controversial topic, with the UK's departure deal between London and Brussels pending. Niemi (2019) argues that the US's trade battle with China has confused in the global food market, with tariffs on US agricultural products causing US expansion in Europe. The evaluation of 2018 and 2019 focuses on organic produce, Finnish meat industry competitiveness, agricultural investments, and the restructuring of the European Union's Common Agricultural Policy.

2.2 Aeroponic farming systems

Aeroponics is a soilless farming method that offers speed, and cost efficiency. It allows farmers to control root zone nutrients, water regimes, and environmental conditions, providing complete access to the roots throughout the crop's life (Fasciolo et al., 2023). The growing demand for water resources and food supply has led to the development of innovative farming methods, such as hydroponics, aeroponics, and aquaponics. These systems use mineral nutrient solutions to grow plants in soilless or aquatic environments, increasing yields and water conservation. These systems also reduce the use of harmful agrichemicals, making them a promising alternative for sustainable food security (AlShrouf, 2017).

Aeroponic farming is superior in aeration, water use efficiency, seasonal independence, disease-free propagation, and large-scale farming. Commercially successful for propagation, seed germination, seed potato farming, tomato cultivation, leaf crops, and micro-greens (Fasciolo et al., 2023)

2.2.1 Aeroponic potatoes farming

According to Tunio, (2020), Malawi ranks fourth in food production compared to cassava, sweet potato, and maize. The common propagation method is through tubers. However,

shade treatment negatively impacts plant growth, and nutrient uptake. Studies explore the interactions between season, shading, and root zone cooling (Naik et al., 2022)

Aeroponics can promote seed availability of healthy potato seed, allow easy identification and rouging of diseased plants, and enjoy accelerated growth due to improved aeration and optimal nutrient uptake (Tunio, 2020)

Conventional methods for producing potato seed have not been successful in preventing infections and resulting in lower crop yields. Aeroponics, a method that uses tissue culture and micropropagation, can quickly generate pathogen-free potato seed tubers (Borah, 2023). This technology can boost income and lower seed harvesting costs, making it more affordable for growers in impoverished nations. However, research on the quality of aeroponic seeds and their growth capacity is limited (Borah, 2023)

2.2.2 Conventional farming vs. Aeroponic farming

The conventional mini tuber production system faces challenges such as low multiplication rates and non-homogenous tuber size distribution. An aeroponics system has been developed to overcome these issues, allowing multiple harvests with an average yield of 20-50 mini tubers per plant (Çalışkan et al., 2021). Factors such as cultivar, planting density, mist solution nutrient composition, spraying interval, and lighting also affect tuber number and size. The mini tuber agronomy performances of three potato cultivars (Hermes, Marabel, and Sante) were compared at different planting densities (Çalışkan et al., 2021). In 2012, Movahedi et al., (2012) compared two propagation methods for potato mini tubers produce; Aeroponics and soil systems. The mini tubers were grown in aeroponics and soil systems, with stem length, root length, stem diameter, and yield measured. Both Movahedi et al., (2012) and Çalışkan et al., (2021) reports showed that the number of tubers per plant increased with decreasing planting density, with the aeroponic system having a higher yield per plant. The aeroponics system led to increased stem length, root length, stem diameter, and yield; The average tuber weight was higher in the conventional system, with a tuber yield/m² ranging from 5.9 to 9.3 kg/m², about

twice as high as in the conventional system. Cultivar Agria and Marfona were the most favorable genotypes, with Marfona showing higher yield and quality characters (Çalışkan et al., 2021)

The table below gives a comparison between aeroponics farming and hydroponics farming, both farming techniques are similar to each other, but have subtle differences, however, neither method requires the use of chemical fertilizers or pesticides. Both methods don't require the use of soil and are environmentally friendly compared to traditional farming.

Table 1. The difference between aeroponics farming and hydroponics farming

Aspect	Aeroponics	Hydroponics
Method of Nutrient Delivery	Plants receive nutrients from a mist sprayed onto their roots.	Plants may be suspended in water full-time or fed by an intermittent flow of water.
Design and Methodology	Farms are completely controlled and enclosed environments with crops growing suspended in air.	Farms are completely controlled and enclosed environments with crops in nutrient-rich water.
Plant Growth and Health	Plants grow in a sealed environment, reducing bacterial exposure. Roots are suspended for aeration and oxygen intake.	Plants grow in a sealed environment, reducing bacterial exposure. Roots come into direct contact with nutrient-rich minerals, increasing growth.
Environmental Impact	Uses 99% less land than traditional farming, 98% less water, 85% fewer food miles, and fewer nutrients.	Similar reductions in water and nutrient usage compared to traditional farming.

2.3 Simulation

A simulation of a system refers to the functioning of a model that can be altered and experimented with, allowing for inferring properties about the actual system or its sub-system. It is used to assess the effectiveness of a system, whether existing or proposed, under various configurations and over extended periods of time. Simulation is employed before modifying an existing system or constructing a new one to minimize the risk of failure, eliminate bottlenecks, avoid under or over-utilization of resources, and optimize system performance.

Discrete Event Simulation (DES) is a less complex method, but easier to execute and is used in a diverse range of scenarios. Human decision-making is necessary at every stage of a simulation study, except for executing simulations. Most simulation software programs can efficiently perform this task. Experienced problem formulators, simulation modelers, and analysts are essential for successful simulation research (Carson, 2005). Simulating the creation of manufacturing systems offers a diverse range of advantages for the firm. Discrete event simulation (DES) can be utilized as a technique to assess production change. Design of Experiments, DES facilitates the execution of research and tests, analysis of hypothetical situations, and development of preventive measures. It improves both products and processes at every stage, allowing for seamless operations without disrupting an ongoing production system. Furthermore, the simulation of production systems allows organizations to assess their existing architecture or strategize for future ones, as well as analyze throughput times, material handling, resource allocation, and supply networks. Furthermore, to evaluate potential enhancements before implementing them in an actual setting (Flores-Garcia et al., 2016)

Types of simulation

1. Discrete Event Simulation (DES) is a modelling technique that represents the behaviour of a production system by simulating individual events that occur at certain points in time. These events can include the arrival of a product, a machine malfunction, or a change in production capacity. DES simulations are effective in

identifying bottlenecks, enhancing production rates, and enhancing product quality (Flores-Garcia et al., 2016)

2. System Dynamics Simulation (SDS) is a modelling technique that represents the behaviour of a production system by capturing the interdependencies between several feedback loops. These loops can include the relationship between production capacity and inventory levels, among others. SDS simulations are effective in optimizing inventory levels, minimizing lead times, and enhancing overall system performance. (Flores-Garcia et al., 2016)
3. Agent-based Simulation (ABS) is a simulation method that represents the activities and interactions of particular agents, such as individuals or machines, within their environment. ABS simulations are a valuable tool for enhancing resource allocation, minimizing wait times, and enhancing overall system performance. (Flores-Garcia et al., 2016)
4. Monte Carlo Simulation is a method that employs random sampling and probability distributions to replicate the behaviour of a production system. Monte Carlo simulations are a useful tool for assessing the effectiveness of various production scenarios, identifying possible dangers, and optimizing the allocation of resources. (Flores-Garcia et al., 2016)
5. Process Flow Simulation is a modelling technique that represents the movement of materials and products throughout a production system, encompassing industrial processes and transportation routes. Process flow simulations are a valuable tool for identifying bottlenecks, optimizing production rates, and enhancing product quality. (Flores-Garcia et al., 2016)

2.3.1 Simulation on greenhouse farming

A greenhouse is a transparent structure that uses solar irradiance to create a favourable microclimate for plant growth. It protects plants from external environments and helps increase production and quality. Greenhouse systems have applications in crop farming, crop drying, aquaculture, soil solarization, and poultry (Choab et al., 2019). About 115 countries use agricultural greenhouses for commercial vegetable farming. This work reviews developments and research on more dynamic greenhouses, focusing on key design parameters, and applications under different simulation environments (Choab et al., 2019)

In the late 1900's during an experiment in the simulation of the energy balance of a greenhouse, an electronic computer program was employed to replicate the energy equilibrium of a greenhouse, computing solar radiation flows and simulating thermal radiative, sensible, latent, and conductive heat flows. Subsequently, the model was employed to forecast the heating and cooling needs of different greenhouse characteristics under varying environmental conditions. The results demonstrated the model's accuracy in predicting values for different treatments, highlighting its potential in forecasting greenhouse energy requirements (Kimball, 1973)

According to Fitz-Rodríguez et al., (2010), Greenhouse crop-growing techniques exist in a variety of climates around the world. These structures use a variety of components, forms, and glazing materials to generate ideal circumstances for plant development, with each suited to unique environmental requirements. An interactive simulator was shaped to help people understand and teach greenhouse dynamics better. Based on energy and mass balance principles, this web-based simulator allows users to choose from a variety of greenhouse designs, weather conditions, and operational techniques. Its objective is educational, demonstrating the physics of greenhouse systems and environmental management. Users can evaluate how different designs behave and what systems are required to maintain desired conditions by running simulations across various climates and

seasons in four geographical areas. The simulator delivers accurate estimates of greenhouse dynamics during a 28-hour period.

A study led by Pawlowski et al., 2009 investigates climate control methods in Venlo-type greenhouses in China's subtropical environment using the KASPRO model. Results show that the model accurately predicts greenhouse air temperature, humidity, and canopy transpiration rates in both summer and winter. The study also found that the most significant biomass production occurs in winter when the average air temperature is 19.7°C, achieved by setting daytime and nighttime air temperatures at 23°C and 18°C, respectively. The optimal energy-efficient biomass production is achieved by maintaining a daily average air temperature of 18°C and a Leaf Area Index (LAI) of 3 in winter (Pawlowski et al., 2009). Subsequently, Wageningen University & research reinvented KASSIM, a tool developed using KASPRO, which provides an interactive greenhouse simulation model, allowing Dutch educators to create innovative curricula using LED technology. It also supports the horticulture sector, including farmers, study groups, and in-company training, and offers comprehensive documentation on Groen Kennisnet (GKN).

Controlled Environment Farming (CEV) is a growing technology in agriculture, focusing on aeroponics, an air-based process for growing crops without soil. The system can be designed on an open-source Raspberry Pi board and can be used locally and over the internet, aiming to achieve maximum optimization, control, quality, and automation in an aeroponics-based greenhouse (Mithunesh et al., 2015)

2.3.2 Digital Twin

A Digital Twin (DT) is a tool for connecting manufacturing equipment in a smart factory. It allows for data analysis, monitoring, problem prevention, and future planning. (Arnarson, 2019). Digital Twin (DT) technology has become a key research direction in intelligent manufacturing, but its application for product life cycle management is still in its theoretical stage. (Singh et al., 2021). A DT is a virtual replica of a physical object that

exchanges real-time data, enabling real-time monitoring, design, planning, optimization, maintenance, and remote access. Stark et al., (2017) argue that a digital twin is essentially a digital replica of an object or process. It is created using several sensors to enable real-time monitoring of its performance. It is expected to grow exponentially in the coming decades due to Industry 4.0, which introduces autonomous, intelligent, and networked industrial systems. (Jones et al., 2020)

The Digital Twin concept has seen increased interest, but definitions vary across industry and academia. (Zheng et al., 2019). Pang et al. (2021) explains that physical products in the real world or physical environment serve as the basis for creating a digital twin. Contrary to popular belief, the physical entity encompasses not only the thing itself but also its surrounding environment. (Pang et al., 2021) For instance, a simulation of a shopfloor would be incomplete without human engagement with the object. Some research shows the opposite, indicating that the term "physical product" specifically refers to the object itself. (Stark et al., 2017) (Grieves, 2014)

2.3.3 Digital twin in agriculture

Digital twins are revolutionizing various industries, offering unprecedented control over physical entities and facilitating complex system management. However, the adoption of digital twins in agriculture remains uncertain (Pylianidis et al., 2021)

DT is useful in smart farming, where farmers can create detailed virtual representations of their farm, including crop growth, soil makeup, and weather conditions through crop modelling and precision agriculture, and explores potential applications and challenges, such as data privacy and data integration (Peladarinos et al., 2023)

2.4 Virtual reality in greenhouse farming

The use of DTs in greenhouses has increased since 2018, Industry 4.0, the fourth industrial revolution, is revolutionizing various industries by utilizing Information

Communication Technology (ICT) to enhance sustainability and productivity. This includes advancements in artificial intelligence, cyber-physical systems, machine learning, Internet of Things (IoT), big data, and extended realities (XR). In agriculture, intelligent farming is a key stage, allowing farmers to remotely oversee their activities using digital representations that can be displayed through smartphones, computer monitors, or XR gear in the form of augmented or virtual reality (Slob et al., 2023)

Bruno et al., (2020) designed a Virtual Reality (VR) simulation of an inflatable modular greenhouse on Mars, to help astronauts sustain themselves while away from the planet. The VR technology simulates an immersive environment, allowing astronauts to control and monitor the greenhouse using Oculus Rift head-mounted displays and touch controllers (Bruno et al., 2020). The fundamental goal of a VR simulation is to provide training, nearness to the actual specification, and performance of what is being simulated.

In 1994 Milgram and Fumio Kishino, in “A taxonomy of mixed reality visual displays” introduced the concept of a virtuality continuum (Milgram & Kishino, 1994). Their research concept defines “mixed reality” as everything between the real environment and the virtual environment (Milgram & Kishino, 1994). This mixture, or over-lapping projection over the real environment could be called Augmented Reality (AR) (Muñoz-Saavedra et al., 2020) In order to engage with augmented reality (AR) simulations, a user needs specific equipment, such as goggles or a smartphone equipped with a camera, similar to the requirements for virtual reality (VR). While Augmented Reality has shown significant potential in the field of Digital Transformation for educating workers in high-risk occupations, it has also gained considerable popularity in social media platforms in recent years (Grishkin, 2023)

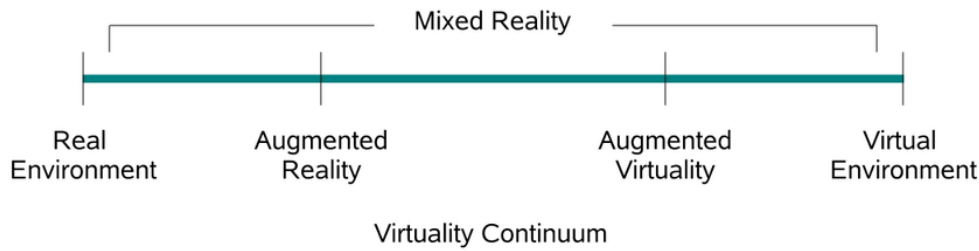


Figure 3. Reality-Virtuality continuum retrieved from: (Milgram & Kishino, 1994)

The virtual environment dimension is derived from the physical entity model. The model can be constructed using various methodologies: The method involves laser scanning, photogrammetry, and CAD modelling, which are then used to build either stationary or active digital representations. However, it is necessary to adhere to the principles of the physical world, including the laws of physics and human behaviour. (Pang et al., 2021)

2.5 Process flow

Manufacturing flow management is a crucial aspect of supply chain management, involving tasks for transferring goods and managing manufacturing flexibility. It requires planning and execution beyond the manufacturer's four walls to achieve the required degree of flexibility. This thesis provides a detailed description of the process, its interface with the shop floor operations, and effective implementations.

Advanced production management strategies in the construction industry require efficient information flows, including lean construction ideas and computer-aided visualization tools. Building information modelling (BIM) software systems can be used to facilitate process flow, enhancing transparency in the dynamic and distributed physical environment of the construction industry. These interfaces are crucial for implementing process transparency in the construction industry.

2.5.1 Process flow in agriculture

The industrialization of agriculture is transforming the food and fibre systems, from input supply to retail. This shift is driven by technological advancements and shifting end-use markets. The process flow in the agricultural sector aims to identify structural adjustments and realignments in agronomy and distribution system to supply different end-use markets efficiently. The analysis considers global markets and changes in the food industry, focusing on manufacturing approaches and negotiated coordination. This shift will replace impersonal open markets with negotiated systems, and information will greatly influence power dynamics and coordination (Boehlje et al., 1996)

Industrial Ecology (IE) aims to reduce environmental impact by examining the movement of matter and energy within and between the natural ecosystem and human industrial systems. The process focuses on transforming linear "throughput" material and energy flow into a cyclical "roundput" flow based on waste and renewables. In Finland, a key function was developed to integrate throughput material and energy fluxes into the round-put model, utilizing waste as a fuel and resource (Niutanen & Korhonen, 2003)

2.6 Simulation of systems

There are different types of production simulation, depending on the process, subject and outcome determines the type of production system to use. However, in this thesis, Discrete Event Simulation (DES) is employed as the DES model can be used in queueing systems, manufacturing processes, or a computer network. DES is effective in identifying bottlenecks, enhancing production rate, and enhancing product quality. Therefore, planning future changes.

2.6.1 Visual components simulation

In this section, the simulation tool used for this research is presented. Visual Component Premium 4.8 is the version used in creating and running the simulation. As stated as one of the limitations in (1.4.1) VC usability will be briefly explained in this section.

Visual Components (VC) is a software for simulating 3D manufacturing processes. It was established in 1999 and has its headquarters in Espoo Finland. The software is used to strategize, create, and authenticate production solutions and concepts before the actual production. VC supports Off-line Programming (OLP) technique for creating robotic control using simulation based on 3D visualization in a virtual environment. After the robot program is created and verified in the software, it can be transferred to the physical robot.(Visual Components, 2024). VC operates on a DES model which is advantageous regarding this thesis as the simulation in the VC space can be run for a time period. In the VC interface, human workers, machinery components, and tools can be simulated. External CAD files can be imported and run in the VC space as well.

In the VC 4.8 user interface (UI), features a left panel for an e-Catalog that allows users to search components and drag them into a 3D world for layout creation. the cell graph is used to keep track of the items shown in the 3D world. The top of the UI is reserved for tabs, these tabs contain various functionalities and features and increases the usability of the tool.

The Home screen tab has basic functions and tools for building simple layouts, including manipulation tools, measurement tools, and statistics. The Modelling tab is another useful tab in the top corner of the VC interface, it provides CAD tools for creating and modelling components to users' specifications. The editing of components allows for more realistic outcomes, such as making prototypes of the pods.

The geometry tab focuses on adapting 3D models for better performance and building 3D models for Aeropod forwarded with moveable links from 3D components.

3 Methods

This chapter examines the techniques used to optimize the efficiency in a greenhouse aeroponic potato farming system by utilizing 3D design, simulation and virtual reality. These methods focus on reviewing and organizing the knowledge from this thesis. One important goal of this study is to suggest a highly efficient resolution for the operational difficulties faced. To do this, it is essential to adopt a complete strategy that involves creating a precise process flow map, conducting meticulous data analysis, and simulating operations in the greenhouse environment.

In addition to achieving a desirable process flow, this paper will shed more light on the simulation's applicability to realistic usage. Therefore, it is mandatory to apply VR while simulating. The main software for carrying out this thesis is Visual Components (VC); the tools used will be Oculus and other VR kits from Meta and HTC Vive for getting actual dimensions for reference purposes.

3.1 Discrete event simulation

Data collection and analysis

Saunders et al., (2016) describe data as primary and secondary. One of the data collection and analysis objectives is to predict and make judgments based on the data outcome. Most analysis is done via software for large-scale data, **3.2** describes the steps for collecting, reviewing, and analyzing these data.

Primary data collection

The model diagram of the greenhouse structure containing the dimensions of the area, building, and structure is developed by Aeropod OY. In addition to this data are the design and process flow patterns. However, some modifications have been made with VC to align with the research objectives.

Secondary data collection

The fence, roof, and layout is recreated using VC, the trees, potatoes, and crates were created using tinkercad.com. The CAD file is imported to VC; Patterns, colours, shapes, and dimensions were adjusted on VC and scaled up to a physical lookalike representation. In 1.3, Saunders' research onion framework is explained extracting every layer and aligning them to how this paper will further proceed. That is the basis of the methodology and the framework this paper will follow. For the sake of clarity, Design Science Research methodology (DSR) will be employed.

3.2 Design Science Research Methodology

Design Science (DSR) is a problem-solving paradigm that focuses on seeking solutions to real-world problems, DSR projects aim to expand the boundaries of humans and organizational capabilities by designing artifacts. These artifacts are represented by constructs, models, methods, and installations, these problems can arise from problem space. An example will be (people, organizations, socio-technical systems, technology, etc.). (Hevner, et al., 2004)

To achieve the goal of improving the efficiency of human processes in a greenhouse aeroponic potato farming system, this thesis will employ the DSR methodology, The DSR technique is well-suited for this research as it prioritizes the development and assessment of inventive creations to address realistic issues.

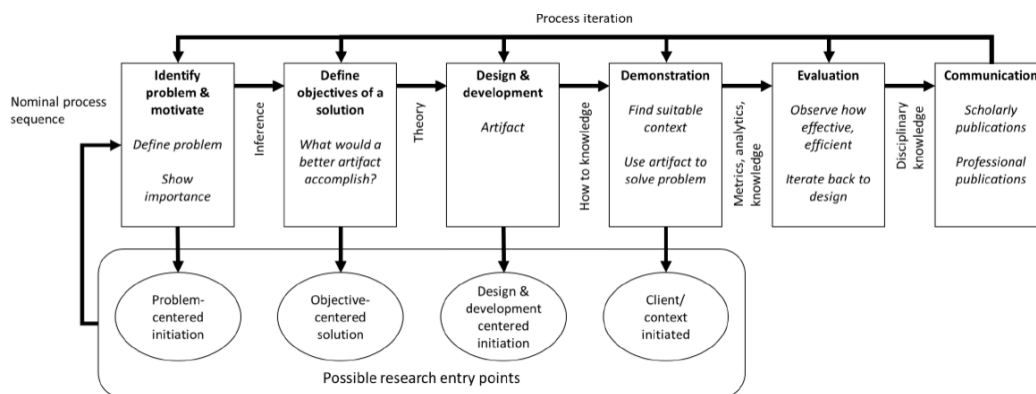


Figure 4. A Design Science Research Methodology for Information Systems Research (Peppers et al., 2007)

1. Identify Problems and motivate

The first stage which introduces the possible research entry point begins with identifying the challenges linked to enhancing human processes in a greenhouse aeroponic potato farming system. This involves recognizing inefficiencies in cost, process flow time, and harvesting lead time. The objective is to create a 3D design that functions as a digital twin (DT) of the greenhouse to enhance these operations. Acquire current information about aeroponic systems and the application of simulations in an agricultural setting. To achieve this step, examination of scholarly articles, industry reports, and case studies that examine aeroponic farming, greenhouse systems, and DT technologies are analyzed utilizing databases such as Google Scholar, and ScienceDirect. Next is to Identify the challenges encountered in the process of industrializing aeroponics techniques and expanding operations to an industrial scale (March, et al., 1995)

The main difficulties that must be tackled by the suggested simulation and VR technologies are optimizing space utilization, improving workflow efficiency, and minimizing operational expenses.

2. Define the objectives of a solution

The second process is to describe the goals that the simulation must accomplish to enhance the efficiency of the greenhouse. This encompasses the precise representation of the greenhouse conditions, the simulation of the aeroponic farming procedure, and the provision of a platform for virtual reality engagement. The next is to define the requirements for the simulation. The 3D tool's requirements involve functional and non-functional features including aeroponic setup modelling, environmental simulation, and real-time data analytics. It should also consider VR integration, user interface design, and scalability. Success criteria include cost reduction and process flow time improvement. A success metrics document will assess the tool's impact on operational efficiency and cost-effectiveness (Peffer, et al., 2007)

3. Design and development

The third process introduces the artifacts discussed at the beginning of this **Design Science Research Methodology**. This process involves creating a 3D simulation tool that functions as the decision tool for the greenhouse. This step involves creating a digital model of the greenhouse and integrating aeroponic farming including the process within the shop floor. The development phase encompasses the construction of the simulation model as well as the incorporation of VR elements. The research aims to create a 3D simulation for a greenhouse environment and aeroponic processes using platforms like Visual Component and Oculus. The tool will model the greenhouse structure, aeroponic systems, and operational scenarios, allowing for iterative testing and refinement. The individual items in the greenhouse layout will be detailed using Computer Aided Diagram (CAD) tools, incorporating 3D models of potatoes, leaves, plants, equipment, workflows, etc. The VR capabilities will be integrated, allowing users to navigate the greenhouse, manipulate controls, and observe processes in real time.

4. Demonstration

This is the last stage of the research entry that uses the design artifacts to solve problems. This process evaluates the efficacy of the 3D simulation tool in depicting the flow process and enhancing the efficiency of human operations in the greenhouse. This step demonstrates the tool's capability to simulate and assess various process flow scenarios and machine efficiency.

Perform simulation run testing:

This is to evaluate various operating settings and scenarios using the simulation tool. Specify many scenarios (such as pathways, human accessibility, and lighting conditions) to be replicated in simulations. Next is to execute the simulation for every scenario and document the performance results, afterwards, utilize the tool to conduct experiments with process tweaks and carefully observe the effects. Then collect data to analyze the impact of various operational methods on cost, process flow time, and harvesting lead time, showcasing the tool's ability to enhance efficiency in greenhouse operations.

Utilise VR gear to engage virtually:

Showcase the immersive potential of the simulation tool using VR. This involves the installation of VR equipment (such as Oculus or HTC Vive) assisting users as they navigate through the virtual greenhouse. This enables users to engage with the virtual environment by conducting activities such as examining human and machinery processes, plant development, modifying system parameters, and displaying data overlays. Next is to demonstrate a practical exhibition showcasing how VR may improve the general control and layout of the greenhouse processes, providing a direct and immersive experience of the possible enhancements.

Gather data on performance metrics:

This involves the collection of both quantitative and qualitative data regarding the performance of the tools. Next is to document quantitative measurements such as the duration of each procedure, utilization of resources, and financial consequences for each instance of simulation. Gather user input regarding the VR experience and the usability of the simulation tool. Lastly, is to create a dataset that offers valuable information on the tool's efficacy in enhancing the layout operations and gauging user satisfaction with the virtual reality interface.

5. Evaluation

The fifth process involves observation of the previous processes noting their effectiveness and efficiency, in this process, the 3D simulation tool will be accessed based on the predetermined criteria for success. This entails evaluating the precision of its greenhouse process modelling, the efficiency of its operational optimization, and the user-friendliness of its VR implementation.

This thesis phase aims to validate the accuracy of the simulation tool by comparing outputs with real-world data. It involves collecting operational data such as (current process flow times, etc) from greenhouse aeroponic systems and analyzing discrepancies. The simulated outcome's effectiveness and usability are evaluated through user feedback.

The goal is to evaluate the whole process and iterate any previous process not aligning with the research question while giving a comprehensive evaluation report detailing how the simulation tool has answered the research objectives. (Venable, et al., 2016)

6. Communication

The last step of DSR is the communication phase, the aim here is to document the research findings and comprehensively present convincing results (Peffer, et al., 2006). This includes discussing how the tool can be used to industrialize aeroponics farming scaling up greenhouse operations to an industrial level.

Documenting the research process, findings, and conclusions, including the development and execution of the simulation process. In the end, all findings are presented in this paper highlighting the process and impact of the tool. The research outcomes are shared with my supervisor, academic, the involved organization, and industry audiences, increasing visibility, receiving feedback, and contributing to agricultural technology and digital twin applications for further research.

NB. Each of these steps are essential for properly implementing the thesis utilizing the DSR methodology. By adhering to this comprehensive plan, the research will provide a valuable modelling tool and offer insights and practical ideas for optimizing human processes in a greenhouse aeroponic potato farming system using 3D design, simulation, and VR.

4 Result

This chapter presents the results categorized according to the research questions in gap and offers comprehensive insights into the potentials and drawbacks of implementing these technologies in agricultural practices. This chapter will be divided into several parts that best answer the research argument. The first part of the result chapter is focused on the case company Aeropod OY, which consists of historical background, greenhouse concept, general overview, previously implemented solutions, uniqueness of the technology, and the reason to expand to an industrial scale. In the next section, Visual components (VC) is presented including a walkthrough of the layout concept; In the next section, the process flow and simulation layout is created, and updated including changes to accommodate various process flows, this is followed by the VR sessions carried out while conducting this research to help identify possible areas for improvement. The results is presented using VR headsets to virtually view the greenhouse farm. Further in this chapter, the creation process of the model and outcomes of production simulation are presented, and then a final solution is drawn.

The nature of the research and technologies applied in this chapter is based on some specific tools, data collection, and analysis, these analyses is done using simulation, DT software, and 3D visualization. Tools used are VC, HTC Vive, and Oculus. In addition, tinkercad (through Creative Commons) is used to create some stock CAD models which are not available in VC, this includes the potatoes, plants, crates, and other little details in the greenhouse farm. The patterns, colours, shapes, and dimensions is adjusted on VC and scaled up to a physical lookalike representation.

4.1 Case company description

Aeropod OY is a small company based in Finland, that promises to revolutionize the growing of potatoes in a more sustainable and stress-free way. The company focuses solely on the agricultural sector. The term “Aeropod” is coined from the technology used in growing and nurturing aeroponic vegetable produce; This tuber produce is grown in a

pod embedded with sophisticated technology that has been developed with the incorporation of other partners such as Sitra, Elinkeino-, liikenne- ja ympäristökeskus, IOT Flow and Suomen siemenperunakeskus Oy.

Aeropod OY aims to provide year-round access to fresh, locally grown root vegetables. Developed in Finland over a decade ago, this technology seeks to liberate farming from seasonal limitations. Initially, the company carried out experiments that focused on cultivating air potatoes. However, the objective is to broaden the scope to include other root vegetables and crops, such as sweet potatoes and Indigenous Peruvian varieties (Aeropod, 2024).

Aeropod OY is leading the way in agricultural advancement with its groundbreaking innovation; The Air Potato. This distinctive produce is specifically cultivated to provide customers with a superior option to conventional potatoes, focusing on flavour, purity, and environmental sustainability. Aeropods' objective is to provide a stress-free gastronomic encounter by supplying potatoes that are as recently harvested and uncontaminated as if they were just plucked from the fields, without any ecological consequences linked to traditional farming techniques.

4.2 Product feature

Aeropod OY claims that one plant can produce 100 potatoes after harvesting, this is because the harvesting process does not destroy the plants leaving room for multiple harvesting. One downside remains that the tuber produces are small in size due to the lack of soil exposing it to gravitational pull.

In return, this farming practice will not replace traditional farming. The objective is the cultivation of luxury produce for fine dining. Below are the three main benefits Aeropod OY promises to attain.

Tasty: The Air Potato possesses a thin and delicate skin, akin to that of a freshly harvested potato in early summer, which is available throughout the year. The flavour and texture

of the product are continually preserved using innovative air farming techniques, guaranteeing a high-quality gourmet experience with each bite. (Aeropod, 2024).

Clean: Air Potatoes from Aeropod are cultivated in advanced and controlled settings, ensuring no toxic pesticides or plant protection chemicals are used. This process not only maintains the natural growth of the potatoes but also greatly diminishes the environmental impact through the utilization of advanced aeroponic farming, Aeropod effectively mitigates nutrient leakage into the ecosystem, hence fostering a sustainable approach to agriculture. (Aeropod, 2024).

Effortless: Aeropod Potatoes are harvested in a pre-cooked state, requiring no additional preparation before being cooked. These products do not need to be washed or peeled because they do not have traces of pesticides and other impurities both on the outside and within. Additionally, each package is accompanied by a recipe curated by a renowned chef, ensuring that preparing a delectable meal for any event is effortless. (Aeropod, 2024).

4.2.1 Previous Aeropod concept

(Figure 5) below is an actual representation of the growing condition of the potatoes, it shows a top view of the stems including the leaves, and the lighting conditions necessary to grow the tube, attached are support structures to keep the stems in place preventing them from falling off while keeping it upright to a desirable position. (Figure 6) shows the general conditions in the root system and how it appears. (Figure 6) also houses the automated nutrient sprayers, irrigation system, and a perfect temperature imitating that of an ideal traditional potato farming needed for the growth of the potato tubers.



Figure 5. Design concept, stem view and general growing condition of the leaves (Aeropod, 2024)



Figure 6. Design concept, growing chamber of potato tubers (Aeropod, 2024)

With the design concept being a success, Aeropod OY introduced the single pod in (Figure 7) the pod itself is a minimalistic rectangular design with a high-tech metallic look. The unit features two tiers of compartments, one is the surface area which houses the plant under a Light-Emitting Diode (LED) grow light which are positioned on the horizontal frame above the plant. The lower tier of the pod system is the housing chamber that contains Aeropod's high-tech aeroponic system and other essential components like the water system, and nutrient system essential for plant growth.



Figure 7. Final prototype Picture of the third-generation prototype (Aeropod, 2024)

4.2.2 Current greenhouse farm design

The (Figure 7) depicts the most recent prototype and final design of the pod, the concept of these pods is to be stacked vertically, side by side to create a long aisle of seamlessly flushed pods. This sequence will be replicated on the opposite side of the farm to create a pathway through which workers can carry out their duties creating a flow chain.

This research will focus on the expansion of these pods, creating an industrialized greenhouse Aeropod farm. Its new facility in (Figure 8) Shows a geometric floor plan view of the greenhouse facility which should be replicated into three buildings with details on its dimensions. The total land of the three buildings will cover a total area of 6696m² with each building having a length of 74.8m and a width of 27.8m as seen in (Figure 8) and (Figure 9), each building consists of a shop floor where the Aerodops are vertically stacked to each other with an aisle in the middle and replicated five more times, on the

North wing of each building, there is a loading dock, two packing area, cooler, cleaning room and service area. On the East wing (Figure 11) There is a restaurant reserved for freshly harvested potatoes for fine dining. Since the facility is located in Finland, the amount of sunlight is limited to only the summer period, this facility aims to reduce its energy consumption by generating energy harvested from the sun through its rooftop solar panels, it also houses its photosynthesis through the pods plant lightning having a closed roof instead of the traditional greenhouse glass roof.

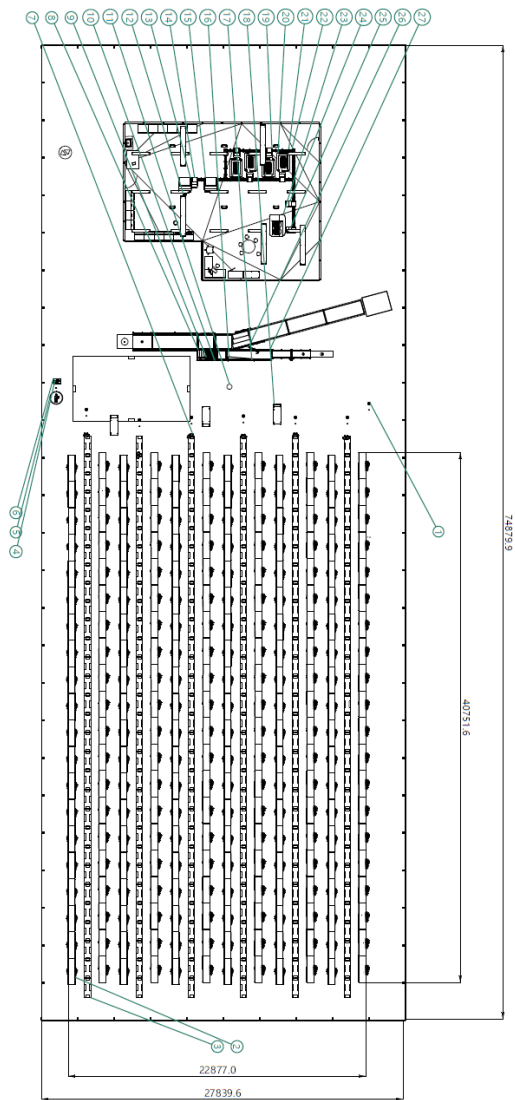


Figure 8. Floor plan of the greenhouse farm (Aeropod, 2024)

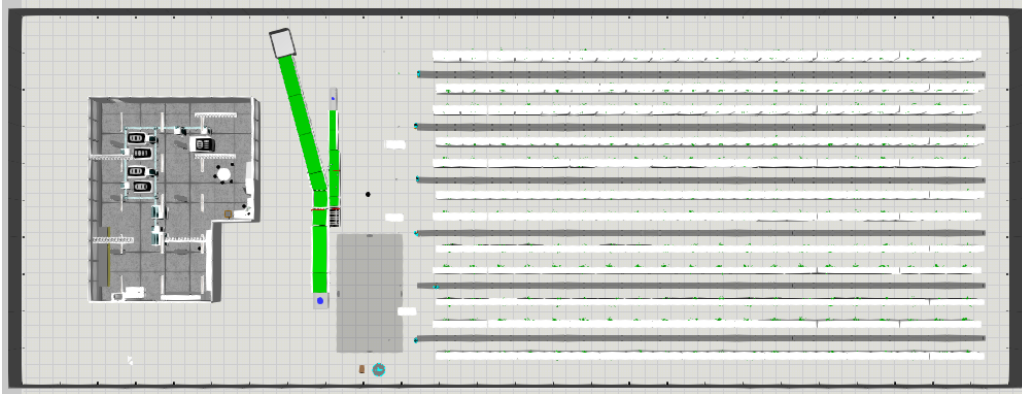


Figure 9. Singular full-scale greenhouse building design structure.

(Figure 9) shows the layout of the greenhouse farm having a box-making machine and offices, which as expected is to be replicated in designing the other two buildings on both sides (left and right). It also shows the side-by-side arrangement of the pods, the pathway, the spacing size, and the height of the wall spanning 6m.



Figure 10. Single greenhouse design building by (Aeropod, 2024)

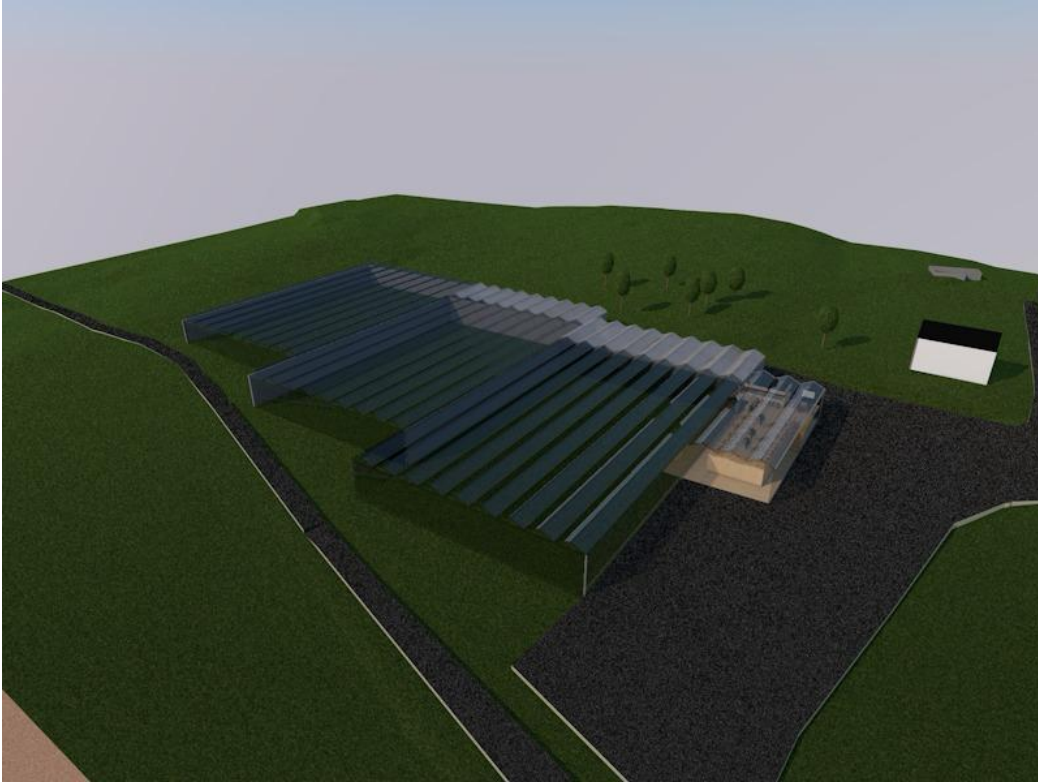


Figure 11. Aeropods greenhouse farm, design concept (Aeropod, 2024)

A 3D aerial view of the greenhouse facility is shown in (Figure 14). The image is provided by the company, the 3D image gives a representation of how the actual greenhouse farm is proposed to look upon completion. There are a few tweaks in the (Figure 14) image that will be redesigned upon the completion of this research, most notable will be the roofing style which will not be transparent but a solid rooftop and will be filled with solar panels on the South wing of the facility based on the position of the sun in Finland.

4.3 Simulation of Aeropod's greenhouse farm for layout optimization/process modelling

This section details the simulation and process workflow of Aeropod OY greenhouse farm facility using VC. The research phase is divided into several parts ranging from planning flow pattern, and space utilization up to the final design style. Simulation test times

are carried out together with Prof. Rayko Toshev and Raine Hermans (Dean of the School of Technology and Innovation, University of Vaasa) with a significant iteration of the process flows that lead to the final concept.

To simplify the model, the research is a combination of several components broken down into two major groups (Facility and process flow). These groups are a guide to the main components and Bill of Material (BOM) and the placement of the components in their respective places. At the end of the result a summary of the BOM according to each layout will be highlighted. Group one consists of six items for the process flow and group two consists of eleven items for the facility creation, categorized according to the design shopfloor specification. Subsequently, the groups were assigned names and numbers to help in identification. Some of the items were converted into 3D models and imported to VC.

Table 2. Process flow

Number	Name
1	Human resource
2	Process
3	Flow Group
4	Resource planning
5	Feeders
6	Path

Group 1. Process flow configuration

This group elaborates on utilizing VC's settings and configurations through process modelling which is the core functionality of this research. The process modelling is designed to resemble real-world events in practice. This process modelling consists of 5 steps. (Visual Components, 2023).

1. Layout design.
2. Define products, their visualization, structure, and properties.

3. Define processes, like machines, workstations, inventories, and buffers using task statements.
4. Define flow by creating sequences of processes that products must complete.
5. Run the simulation, collect KPIs, and make necessary changes to achieve your goals.

This section focuses on the most important of the 5 steps alongside the most notable feature of the simulation and then goes further to run the simulation collating performance, 2D drawing of the greenhouse farm, and other necessary indicators.

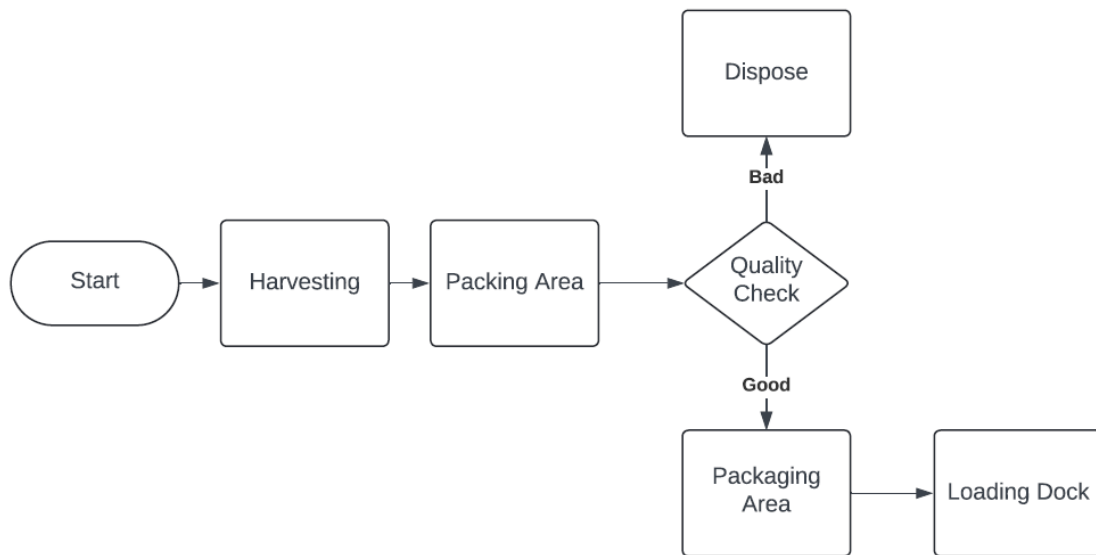


Figure 12. Process flow diagram of the human activity from the starting point to the loading dock

Human resource

Unlike the Traditional Human Resource (HR) that deals with employees' well-being, the human resource in VC refers to the workers on the shop floor who carry out specific tasks, the human resource is essential for ensuring smooth operations while monitoring the estimated time to carry out one task with the VC play button. It plays a crucial role in visualizing flaws in the handling of equipment or production in real time, most of these tasks are programmable using the human resource controller (Figure 14) which helps improve and implement workers' manoeuvring.



Figure 13. Human resource

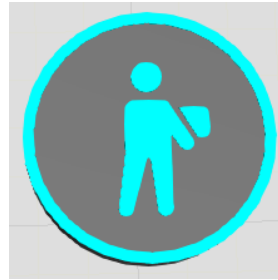


Figure 14. Human resource control

Process flow

Process flow is an interface in VC that breaks in steps how each process should be followed. At every step in the process flow, there is a linkage on how the process should be carried out, the most common process is to link a robot or a human with the help of a human resource button. Some complicated process flows can also be done with the processes table or the modelling tab.

Flow groups

Flow groups are a combination of different processes to make a singular but simultaneous flow. This means that different processes can be done on a different flow group, for the sake of clarity and simplicity.

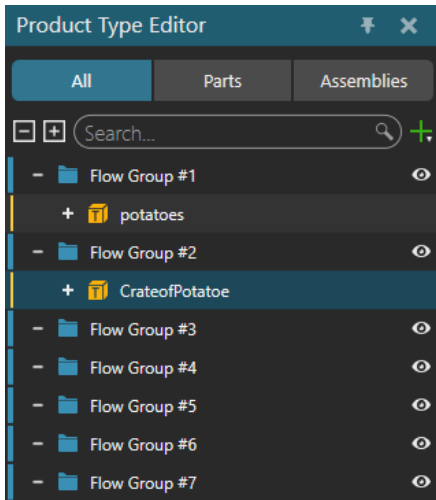


Figure 15. Flow groups

Processes and feeders

The processes refer to all the processes that have an action assigned to them like “feeder”, “flow-in” “flow-out” and others, these processes are a set of instructions outlined in an ordered step, reconfigured to reduce bottlenecks and facilitate efficiency. These actions are part of process modelling which aids in giving a favourable and smooth outcome.

The feeder feature in (Figure 16) is accessed from the e-catalogue dropdown menu, the purpose of the feeder in this research is to produce the boxes with harvested potatoes in them. In (Figure 20) feeders are attached to every pod. The concept is for the worker to identify where each pod is with the help of a path. This is done through the process modelling giving instructions on which pods are to be harvested first and so on.

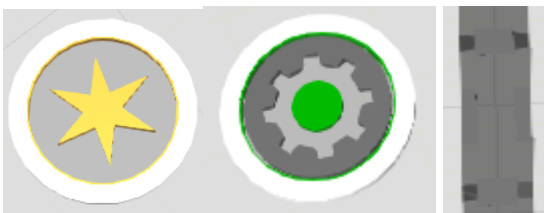


Figure 16. Feeders**Figure 17.** Pathway*Pathway*

A path is a walkway strategically placed inside the greenhouse farm that aids in directing either workers or Automated Guided Vehicles (AVG) on the right path to follow and how to navigate each path without colliding with other objects. The paths are also modelled with instructions to avoid collision.

Table 3. Bill of material for the greenhouse farm

Number	Name	Unit
1	Roofing Sheet	4
2	Solar panel	16
3	Fence	1 (40 unit)
4	Aeropods	120
5	Plant	120
6	Crete/ potatoes	140 / (ND)
7	trolley	8
8	Packing centre/	1
9	Service area	1
10	Cleaning area	1
11	Loading dock	1

Group 2. 3D design and layout configuration

The above (Table 3) gives an orderly arrangement of how the simulation is developed. Items are dragged and dropped in the VC 3D world. However, before these items were dropped in VC 3D world, some items were designed outside the VC 3D world. The Aeropods were geometrically designed using VC to mimic an actual physical representation.

The concept generation is to create a greenhouse layout. This process involves designing the first structural building getting the dimensions, and then adding all the components in Group 2 into the layout, Next is to arrange the components and propagate

Solar panel

A 3D model of a solar panel, the original design is obtained via (Free3d, 2024) imported, scaled, and modified via VC modelling. The installation of solar panels helps in greenhouse energy saving.

Roofing Sheet

The first thing that is designed in the layout is a roofing sheet. The raw design is an opaque plain polygon sheet which is designed and modified in VC. The single sheet is replicated 5 more times with the same length and 3 sheets are stretched on the width and placed in a “W” pattern resembling an actual facility roof. The 3D design is shown in (Figure 18).

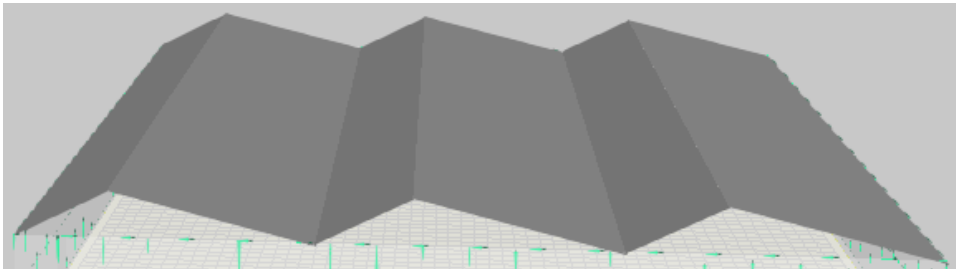


Figure 18. 3D roof design

Fence

(Figure 19) is a general fence from VC, scaled up to match the measurement in (Figure 10) taking account of the entrance.



Figure 19. 3D fence design

Aeropods

An Aeropod is a pod that houses the aeroponic system for air potatoes. As explained in 4.2) and seen in (Figure 7). This modelled system is created and modified in VC. On creating the aisle for these pods, one pod is scaled using the “pattern” function on the X-axis of 2400 (linear step) to a count of 20, and on the Y-axis of 400 (Linear step) to a count of 6. Meaning the X-axis had 20 pods without spacing. Replicating the same (5 times) on the Y axis but with a spacing of 1.3m.

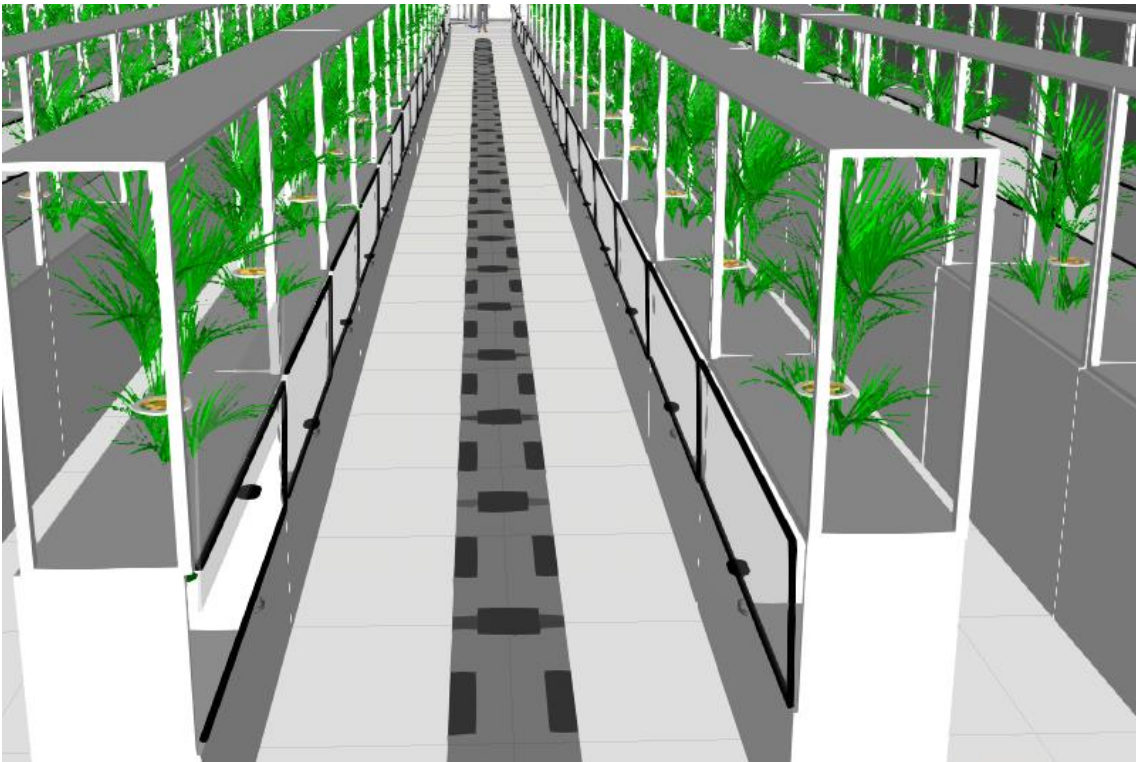


Figure 20. Aeropods with plants and process

Plants

The plant represented in this research is not an actual replica of a potato plant, due to the limited knowledge of the researchers in CAD, a palm tree obtained via Tinkercad (a creative common website) is used to replace the leaf part of the potato. The trees are then calibrated to match the height of one pod, and then propagated to all the pods on the X & Y axis.

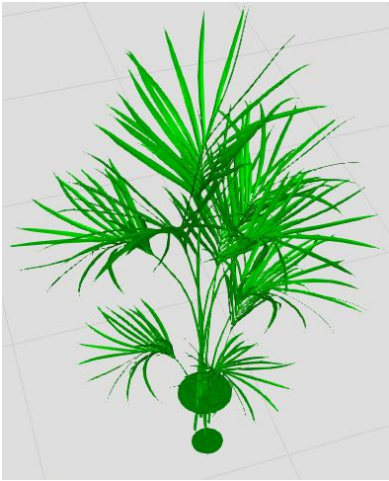


Figure 21. 3D plant concept

Crate/ potatoes and Trolley

The crate serves as temporary storage for the harvested potatoes, both the crates and potatoes were redesigned in Tinkercad and scaled up in VC. In the simulation, the crates are already loaded with potatoes inside for the worker to carry for final packaging. The Figure below represents freshly harvested potatoes in a crate.

The trolley is the major mode of transporting the potatoes in the crate to the next processing point. The trolley is generic in VC.

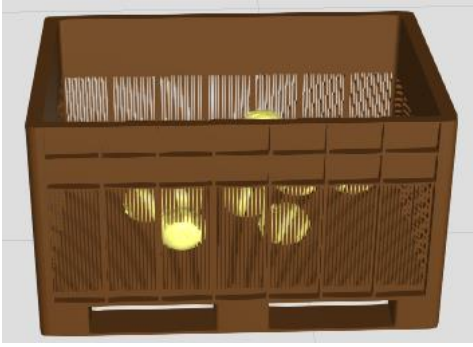


Figure 22. 3D Crate with potatoes

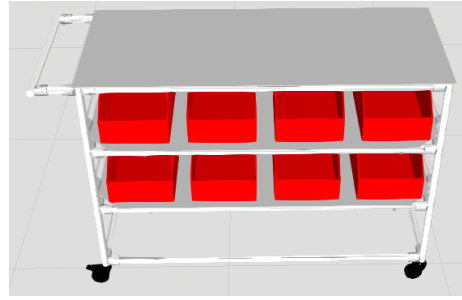


Figure 23. 3D Trolley

Packing centre

The packing centre is a section curved out from the “north wing” wall of the greenhouse structure. This space serves as a receiving, processing, packaging, and preparation centre in the greenhouse farm for the next process.

Service Area

The service area is a designated place that supports the service of employees. The service area will typically include restrooms, breakrooms, storage units, and some tools for the maintenance of the facility. This area is more like a staff relaxation centre.

Clean Room

The clean room is important in this greenhouse farm. It is right in front of the main entrance, and it is embedded with strict regulations to air quality, temperature, and humidity, strictly controlled to maintain low levels of contamination, such as microbes, chemical vapours, and dust. This room is equipped with air filtration, which is essential for the sterility within the greenhouse farm.

Loading dock

The loading dock serves as a service point where inbound and outbound supply is made. This is an area designated for the loading and unloading of products by truck.

4.4 Simulation Presentation

4.4.1 Initial Simulation

(Table 3) gives an orderly arrangement of how each item/material is brought to the 3D space in VC, some of these items were multiplied, stretched, geometrically exploded, and altered to give an actual design concept, one of the challenges faced in designing the greenhouse were the pods. The first design is a shelf at the bottom and a drawer stacked on top, it is later discovered that every shelf had a stock process node identifier, making workers go around without reaching the pod, A simpler solution is to merge a glass drawer on top of an ordinary drawer that had no process node. This resulted in the creation of the pods, the next is to duplicate it to Areopod Oy's final Prototype in (Figure 7). A feeder process node is attached to the drawer to a height of 650ft. Plants were added and placed inside the pod, trolleys were added, and Pathways were arranged along with workers that were strategically placed on every aisle. These were duplicated several times as seen in the beginning of this chapter. Then items from (Group 1) were configured and added.

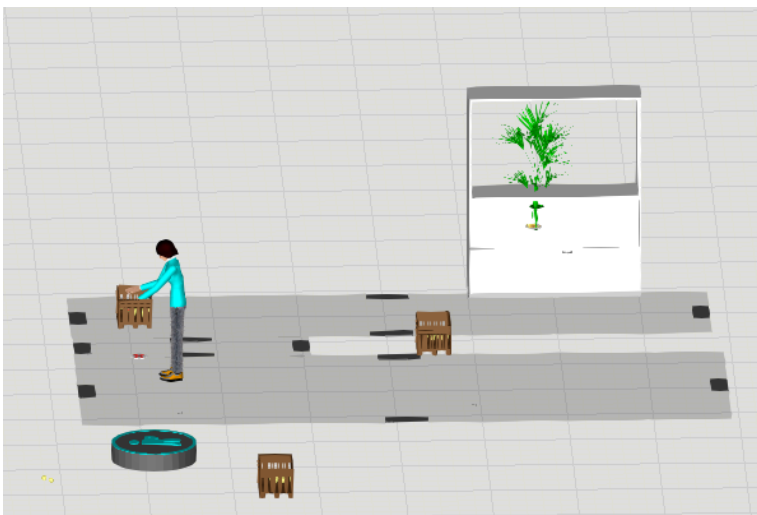


Figure 24. Testing a single Process flow simulation via process modelling

The first testing requires a simple design style with essential elements and tools to represent the simulation flow pattern as shown in (Figure 24). This involves simulating a single workflow and observing that the work patterns would align smoothly with that of the greenhouse design when scaled.

4.4.2 Initial layout Using Visual Component

Once every part of this research is connected and carefully placed in the right position, the model is played several times, looped, paused and remodelled. Then a final model is established, and the floor plan is visualized, and it is prepared for simulation as seen in (Figure 25).

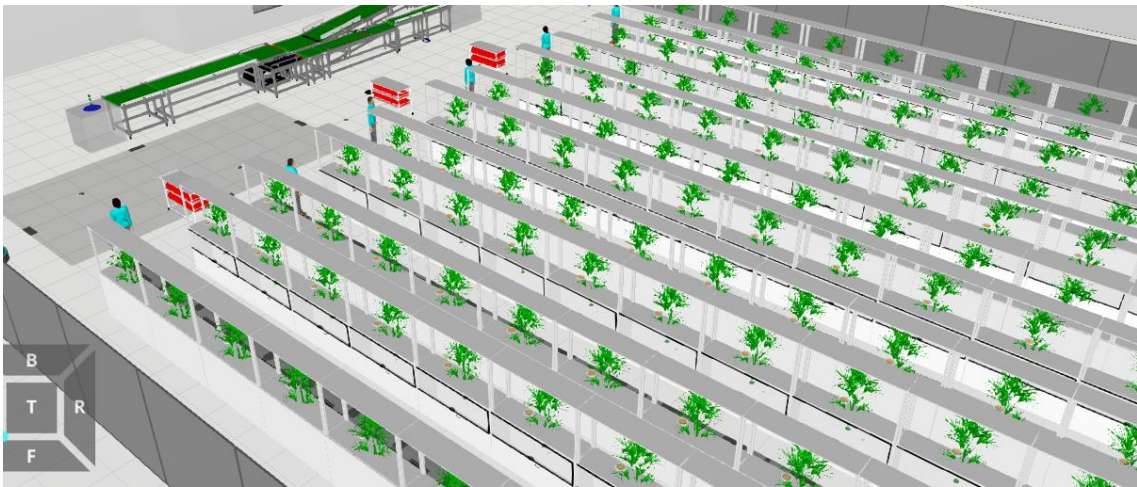
**Figure 25.** Layout configuration

Table 4. Bill of materials for initial floor plan (visual components)

ITEM	QTY	NAME
1	1	Transport Node
2	240	Plant
3	1	Pathway Area
4	15	Potatoe
5	1	Human Transport Controller
6	1	Empty Crate
7	1	Human (Otto)
8	1	EndBlock
9	1	Pusher
10	1	Sensor #2
11	1	NewComponent
12	2	ConveyorNavigator
13	1	LabDemoInput
14	1	LabDemo Decapper
15	1	LabDemo Centrifuge
16	1	Guide Bar
17	1	Sensor #1
18	3	Trolley with Boxes
19	4	LabDemo Analyzer
20	8	Analyzer
21	12	Lab Conveyor
22	4	LabDemoDivert
23	2	LabDemoEndStorageUnit #2
24	1	LabDemo Recapper
25	1	LabDemo Exit Storage
26	2	TurnPusher
27	1	Tip Bar

(Table 4.) Gives a direct representation of the BOM in (Figure 26) The generated BOM is obtained from VC's geometry tab and consists of significant items present in the greenhouse farm. There are some discrepancies in the quantities of items present as VC is unable to accurately give the exact quantity of human process, trolley, and transport nodes amongst others, but accurately identify every major item on the greenhouse farm.

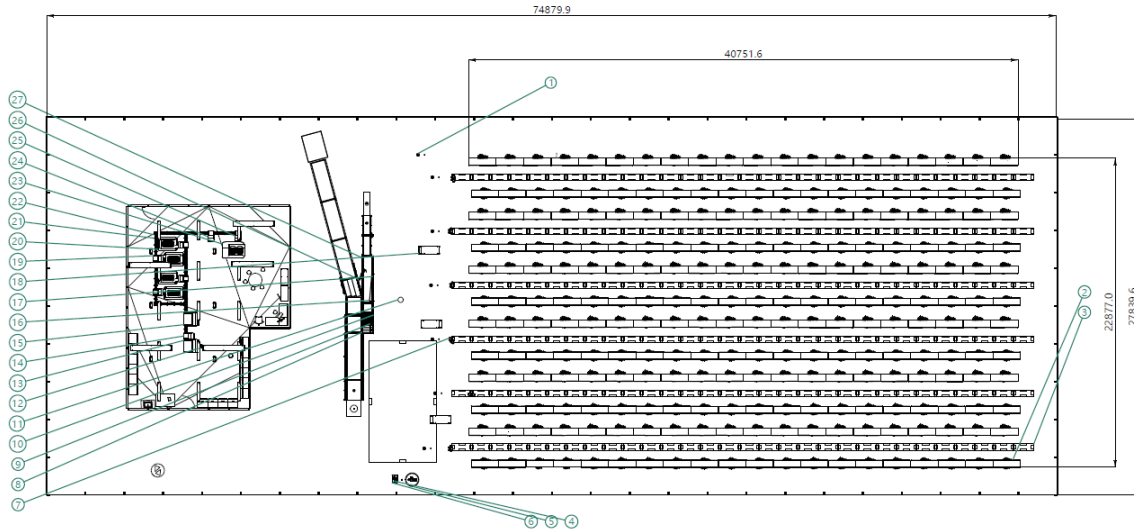


Figure 26. Initial floor plan, preview 1:0 scale

In addition, the simulation uses a time-based assumption and the timing in the simulation does not represent the real-time working conditions in the greenhouse farm. The simulation had a random run time of 2 minutes which is appropriate for a VR experience. Essential multimedia controls enable users to play the simulations, gather KPIs, make adjustments, and export the content in various formats.

4.4.3 Updated layout Using Visual Component

While designing the initial layout, the efficiency and length of the greenhouse became a challenge as the human resource had a long travel time along each aisle and efficiency became a problem. The updated design has the packing area, clean room, service area, packaging area, entrance, cooler, and loading dock on the north wing of the building while the aeropods sits on the southern wing of the greenhouse having operations similar to the initial layout in (Figure 25)



Figure 27. Updated Layout, scale 1:0

Table 5. Bill of materials for updated floor plan (visual components)

ITEM	QTY	NAME
1	1	Modular Troax Door
2	2	ModularTroaxFence
3	1	Cleaning Station
4	1	Sink Process
5	3	FEXA15.6-V1500S-F FORK
6	1	Truck freightliner N200314
7	116	Empty Crate
8	1624	Potatoe
9	1	Human Transport Controller
10	71	Feeder Process
11	71	Plant
12	1	Trolley with Boxes

(Table 5.) Represents of the BOM in (Figure 28). The generated BOM is obtained from VC's geometry tab and consists of significant items present in the greenhouse farm.

Similar to the initial floor plan, there are some discrepancies in the quantities of items present as VC is unable to identify human resources and give an exact quantity of other minor components such as shelves, chairs, and lamps amongst others, but accurately identify every major item on the greenhouse floor.

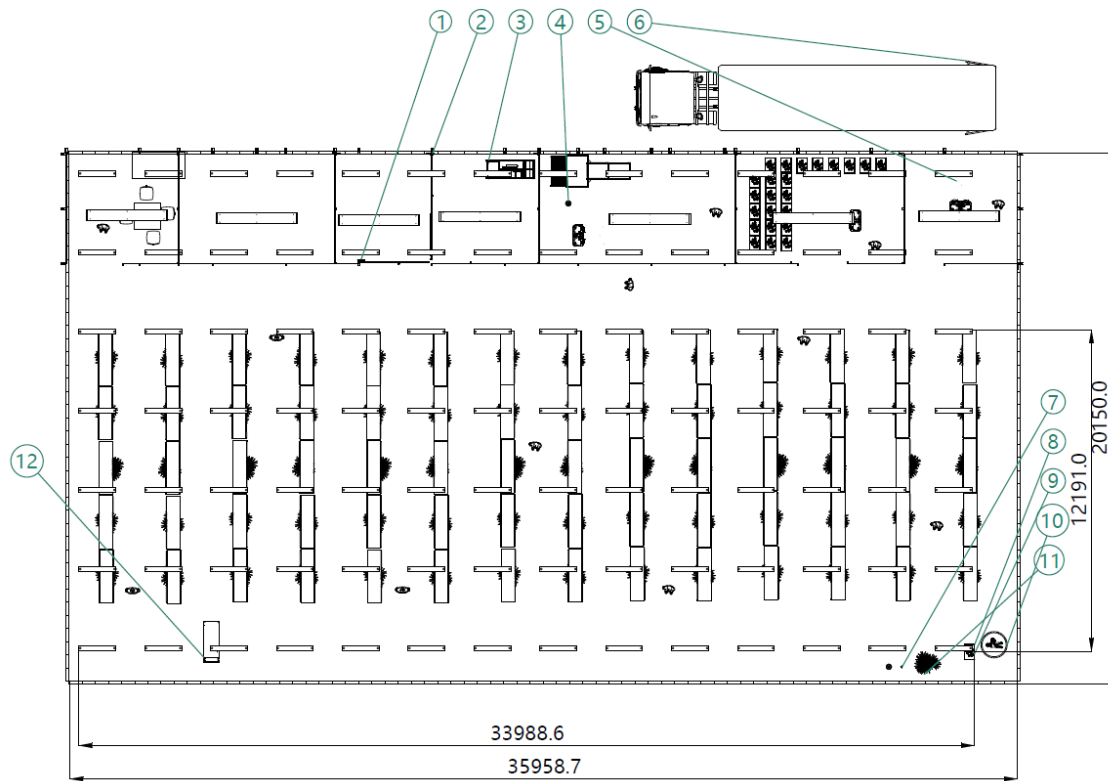


Figure 28. Updated floor plan, preview 1:0 scale

4.5 Streaming simulation to VR

Using a VR-supported tool to access VC can also help improve the design by allowing users to interact with the functionality of the pods.

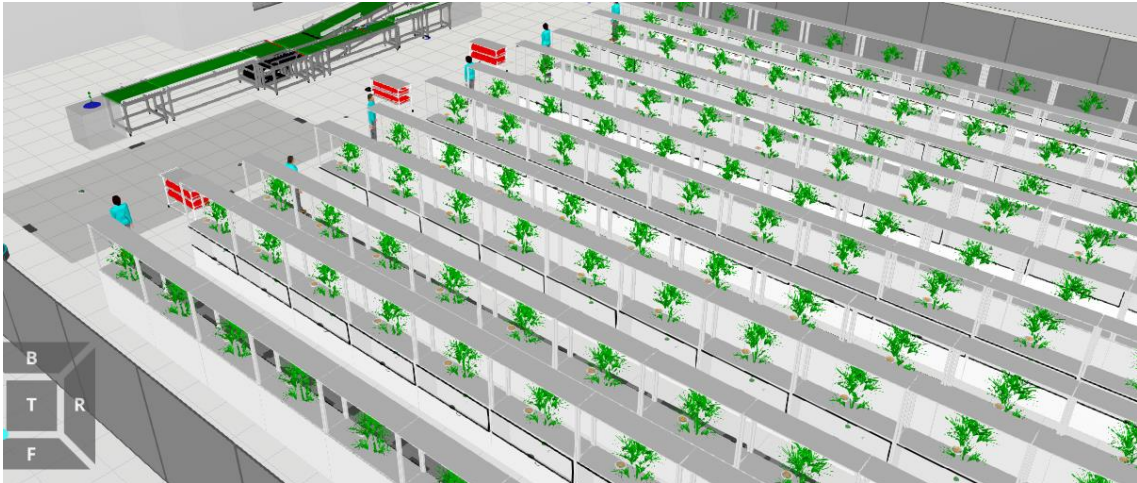


Figure 29. Layout of the greenhouse farm (Birds eye view)

For the purpose of stakeholders' inclusion and understanding of this research paper, the writer provides a comprehensive breakdown of the result aligning with the primary deliverables of the research which is, scaling up greenhouse aeroponics potato farming to an industrial level using 3D simulation concept in which it can be previewed on a VR headset on a 1:0 scale.



Figure 30. Layout 1

The use of VR in this research is important as it plays an insightful role in getting a personal visualizing moment to stakeholders. The (Figure 31) below shows the researcher using an HTC Vive VR system at the University of Vaasa's VR lab to give a clear

representation of being immersed in the simulation world; the VR view is simultaneously captured on the TV screen to give a personal view for the individual in the room to see without using the headset. The screen displays an overview of a work in progress on the greenhouse farm.

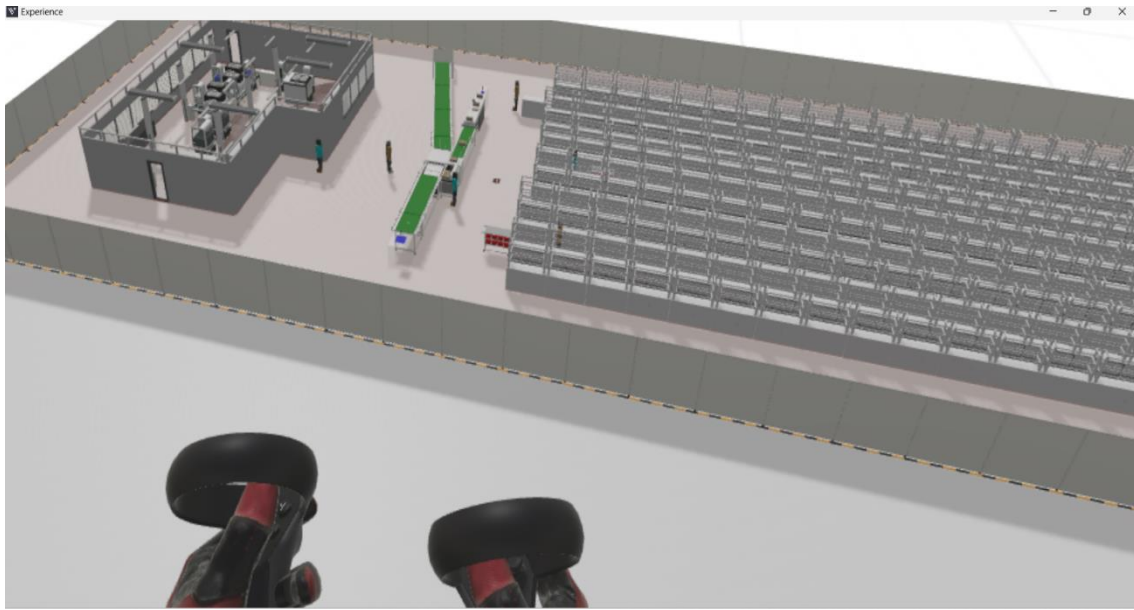


Figure 31. VR using HTC vive.

5 Conclusion

This chapter is projected to draw a conclusion on the key findings of this thesis. On the other hand, the research aimed to investigate the feasibility of scaling up greenhouse aeroponics potato farming using 3D simulation and optimizing the process flow in aeroponic farming. To achieve this, a comprehensive study is conducted on Aeropod, a leading Finnish company specializing in aeroponic potato farming. The result derived from this research shows a pictorial simulation representation of the DT of the Aeropod greenhouse farm. The process flow used is a direct representation of a DES modelling technique.

5.1 Key findings

While running the simulation, some findings were noted, one of which is the development of a greenhouse facility that is both modular and scalable. Another is the possibility of restructuring different layouts based on square area and land mass, another is that the VR experience provides a remarkable immersive view of workers' activities and shows major to minor loopholes in the layout configuration ready for immediate correction. Lastly is the process flow and how workers serve as a connections different processing parts of the greenhouse farm. It is evident that the singular pods might pose a challenge in the near future. An alternative will be to provide a singular pod that stretches to the end of the aisle divided into modular sections rather than singular pods stacked side by side that stretch to the end of the aisle. On the other hand, this facility utilizes a vertical arrangement of Aeropods, utilization of space facilitating walkable convenience amongst workers. Utilizing solar panels to enhance energy efficiency, and robust opaque roofing that does not support artificial illumination for photosynthesis, might stand as a limitation based on Finland's sun-deprived conditions. The 3D simulation approach aided in identifying bottlenecks and inefficiencies in the layout, allowing for necessary modifications prior to actual implementation.

Answering the research questions,

1. How can the human process flow in aeroponic farming be optimized?

By creating various process flow models, it is evident that the subsequent model will be better and more functional than the previous model. Creating an interchangeable walk path in the greenhouse layout will ensure that every part of the greenhouse design, including structural components and process flow, is optimized for efficiency and scalability. Concerning human resource performance, the solution lies in assigning each worker a task not overloading them. The creation of workers' idle time in the simulation process can help other sections (e.g., packaging center, loading dock, etc.) of the greenhouse farm perform better.

2. What layout configuration supports industrial scale greenhouse aeroponics potato farm?

planning an expansion utilizes various simulation tools such as Visual Components (VC). The simulation facilitates the development of an intricate blueprint for the greenhouse facility, demonstrating the potential for industrializing Aeropod's technology through the replication and expansion of the pod system. Possible solutions require duplicating the already existing floor plan and running several hours of simulation. In Addition, the updated layout Figure 27 in Result poses to be an ideal configuration for a future aeroponic farming system. It is also possible to propose that the application of DT technologies would enable a realistic representation of the functioning of the greenhouse farm.

Furthermore, the study demonstrated the significance of including sustainable methods, such as implementing energy-conserving strategies and utilizing non-hazardous chemicals and materials in the construction of the large-scale greenhouse. These aspects not only enhance the system's ability to handle the increased workload but also guarantee its compliance with the rising need for environmentally sustainable agricultural practices.

5.2 Managerial implication

In accordance with any given academic paper, most entities and manager tend to highlight the managerial implications they can learn and adapt their strategic business development decisions. Virtual optimization of human processes before any commissioning is one of the concerns of managers of different organizations based on the fact that the process flow plays a pivotal role in upscaling and increasing efficiency. The result of this research would go a long way in helping the agricultural sector considering 3D design and simulation. In accordance with this, using VR technology can help prevent errors allowing organizations to mark out loopholes in the process pattern and help organizations plan projects before real-life implementations are made. Managerial solutions for the specific problem lie in seeking an efficient way to design and implement an effective solution for the flow process in the agricultural sector leaning towards a smooth human flow and a sustainable future.

One crucial component observed during the simulation phase is the pods. Since the pods are singular and vertically attached to each other the cost of production will be multiplied by the total amount of pods placed vertically and then multiplied by their placement on the x-axis. In reality, each pod is to cost approximately €2,500 according to Raine Hermans (Patent holder for the Aeropod technology). However, scaling up the pods not by singularity but by material length measurement, the cost of production for one aisle on the y-axis containing 5 pods will cost €6,250 thereby halving the total cost per aisle. During the discussion on the implementation of the findings with Raine Hermans. He suggested that the 3D layout is in accordance with the design pattern of the greenhouse farm, but some of the proposed solutions have not been seen as most feasible just yet.

5.3 Limitations

Creating a smooth process flow layout in a greenhouse farm positively affects the overall efficiency. Inasmuch as the simulation is depicted in the result section, human productivity goes a long way in affecting the entire workflow. It is important to note that every

minute of idle time puts a limitation on productivity which is not shown in this research, this might be a result of tiredness, overworking, and lack of motivation.

The simulation does not take into account the ergonomics of workers. According to the Finnish Ergonomics Association.

“With the help of ergonomics, work tools, work environment, and other operating systems are adapted to meet human characteristics and needs. Ergonomics improves human safety, health, and well-being, as well as the smooth and efficient operation of systems”

Knowing that the ergonomics situation of workers is as important as their safety, supervision should be carried out regularly to avoid work-related accidents.

5.4 Recommendations for further research

Developing a 3D simulation requires lots of resources, experience, computing power, work time, and technical knowledge. Running a simulation of this scale requires quite a huge computing power. Although this simulation is conducted in VC 4.8 running on a Windows 10 Professional, intel core i5 processor, 64-bit Operating System, processor 4x3.1 GHz, and 8GB RAM, I however, experienced several software crashes during the simulation and severe freezing of the computer due to overloading it's memory. The overall outcome of this research did not advance as expected. Additionally, there is a need to master CAD design which I lacked as a skill set that limited my design skills resulting in me getting designs from third parties through some creative commons.

This thesis shows a simulation that merges facility design and the intra-flow process of potato produce. A notable improvement would be to gather data regarding monthly and yearly outputs. With more precision in data collection, a sophisticated simulation model can be developed. The targeted output rate was not reached with this simulation.

Therefore, a new layout design with highlighting these parameters should be considered after a more precise work time study.

A 3D layout simulation poses to be complex and is required to be built according to layout plan specifications, there is always the possibility to re-map a layouts into a more precise version which may involve adjustments in the aisle assignment and process flow of the farm produce which can be simulated to make a detailed version of the simulation. Flow time, failure rate, and variability study can be added into the simulation to observe different outcomes. It is also important to observe the working hours of individual workers to get a realistic simulation.

Further development can be made in the creation of a digital twin framework for the agricultural sector, especially greenhouse farming. Fully automated greenhouse facilities should be considered as AI (Artificial Intelligence) poses to play a better role in monitoring performance indicators factoring work shifts output ratio, cost, and process flow time.

With VR gears playing a major role in this thesis, there should be a need for an interaction between the human wearing the VR headset and what is being simulated. At the moment, when a VR headset is worn, it only gives an overview/ play time of the environment, and there are no functionalities for object and tool interactions (it is not possible to pick tools and observe their specification in your hand), example, knowing the diameter of a potato, knowing the height of a pod, or getting the measurement of a door frame, or knowing the distance between aisles. This information will be beneficial to stakeholders as corrections can be made while immersed in the VR space.

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