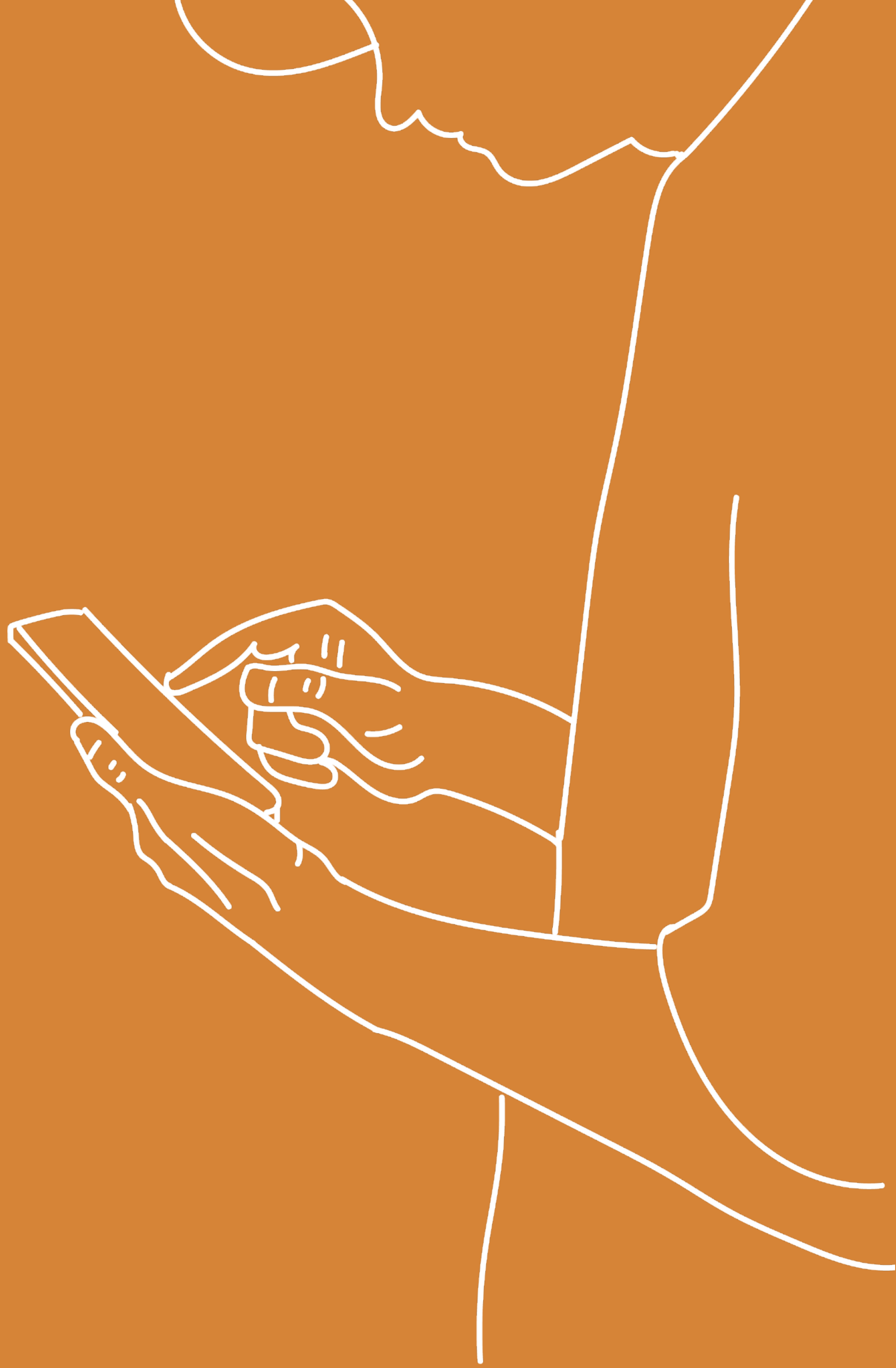
Validating Ultrasound Plant Sensor Data through the Perceptions of Growers



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In collaboration with
Plense Technologies

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Preface

For my thesis, I was determined to explore a topic within the agricultural sector. My passion for plants, sustainability, and design has always driven my academic interests, yet I never saw how these could be combined until I connected with my chair, Jotte. She encouraged me to explore the projects on the website of the TU Delft AgTech Institute, where I encountered several inspiring initiatives.

One project, called Plantenna, captured my attention. The concept of using sensor technology to capture sounds produced by plants fascinated me. I reached out to Plense Technologies, the spin-off of this project, to inquire about the possibility of a graduation project. I was very glad that there was an opportunity.

I would especially like to thank Thijs and Berend from Plense Technologies for giving me the space to formulate the subject of my thesis and for contributing with great enthusiasm. You and the entire team have been incredibly kind and helpful over the past months.

Moreover, I would like to express my gratitude to Jotte and Jacky for their invaluable expertise, but above all, for the inspiration they provided throughout this project. Your guidance introduced me to a new perspective, rooted in systems thinking. I am grateful that you gave me the opportunity to explore this new approach at my own pace.

Furthermore, I would like to thank all the experts and growers who made time to answer my questions, walk me around the greenhouse, and test my ideas and concepts. Every encounter gave me inspiration and knowledge for my thesis. Without you this project would not have been possible.

Lastly, I want to thank my family, boyfriend, and friends for their support throughout the project, and for giving me moments to relax, clear my mind, and celebrate milestones along the way.

Abstract

The project focuses on validating ultrasound plant sensor technology through grower insights. The primary goal is to understand how growers monitor their crops, using terms like "vegetative," "generative," "strong," and "weak." Additionally, we aim to gather their reasoning behind certain plant assessments. By correlating these insights with data from ultrasound sensors, we hope to provide interpretable information that growers can use in their cultivation practices.

Making cultivation more efficient for growers is crucial to the challenge of producing enough food for the world's growing population. By using technology that supports growers, we can help them scale up their operations and ultimately produce more food.

We conducted interviews to investigate how tomato growers monitor their crops. Usability testing was also performed to design an intuitive, straightforward way for growers to share their insights. The result of this effort is an app that collects growers' subjective plant assessments efficiently.

The next crucial step is to begin collecting data through the app to see if there's a common truth in the growers' insights. If such a pattern is found, the growers' assessments can be correlated with the ultrasound sensor data, and ultimately provide actionable insights back to growers in the terms they frequently use: "vegetative," "generative," "strong," and "weak."

Ultimately, these actionable insights would be combined with other data types to generate tailored advice for the grower. An exploration will be done to determine how this could take shape.

Glossary

Assimilates/assimilating
Assimilates are the building blocks (organic compounds) formed by the plant via the process of photosynthesis. Assimilating refers to the process of forming these building blocks.

Generative growth
Generative growth is used by growers to describe that the plant is putting its energy, into the development of its flowers and fruits, rather than in the development of the green parts of the plant.

Het Nieuwe Telen (HNT) (translation: The New Way of Cultivation)
Plant empowerment is a key concept within the movement of Het Nieuwe Telen. This approach was one of the first advancements in data-driven cultivation. Initially, Het Nieuwe Telen focused on the use of climate sensors to monitor and control the growing environment, rather than directly using plant sensors.

Plant Empowerment
This is the approach that focuses on understanding and optimizing the physiological processes of plants by looking at the three plant balances: energy, water, and assimilates. Plant sensors have the potential to monitor the physiological processes, using the data to give growers advice in cultivation.

Plant sensor
This is a sensor that monitors the physiological processes of the plant, such sap flow, soil moisture, and photosynthesis efficiency.

Plensor
This is the name of the sensor that Plense Technologies is developing.

Strong growth
Strong growth is used by growers to describe that many assimilates are produced.

Vegetative growth
Vegetative growth used by growers to describe that the plant is putting its energy, or sending assimilates, into the development of the stem and leaves, rather than in the development of its flowers and fruits.

Weak growth
Weak growth is used by growers to describe that the plant is not assimilating enough.

Contents

1 Introduction

1 Introduction

1.1 Context

As the world's population is expected to reach 9.8 billion by 2050 (United Nations, n.d.), there is an immense pressure to ensure everyone with sufficient food. Food production methods must be rethought to increase production, while keeping the limits of the earth in mind. The Netherlands, as world's second-largest food exporter (Reiley, 2022), plays a significant role in addressing this challenge.

Besides scalability and sustainability challenges, Dutch growers also face labour shortages, altogether making the profession less attractive for todays and potential growers. These difficulties have led some growers to stop their business, resulting in a declining number of growers over time, but also in the amount of agricultural knowledge. This increases the pressure on the remaining growers to meet the rising food demand.

Technology offers promising solutions to address these issues. Automated systems can take over tasks traditionally performed by humans, such as monitoring crop health conditions, which can reduce labour requirements and allow growers to scale up production more efficiently.

Beyond playing a role in tackling labour and scalability issues, technology can also play a significant role in reducing the environmental impact of cultivation. Emerging plant sensors have the potential to monitor real-time plant health. If this data is combined with other data types (e.g. climate, soil, or labour data), actionable insights could be given to the grower on how to cultivate more precisely. This will optimize yield, minimize resource, and spare the grower time in his decision-making process on how to cultivate next.

Figure 1: The team of Plense Technologies

1.2 Plense Technologies

This thesis is carried out in collaboration with Plense Technologies, a start-up co-founded by Berend de Klerk and Thijs Bieling (see Figure 1). Plense is a spin-off from the Plantenna project, which is a collaborative initiative, including the universities of Delft, Eindhoven, Wageningen, and Twente (4TU, n.d.). Their vision is to sustain everyone with sufficient food, keeping the limits of the earth in mind. They want to do this by integrating sensors into the plant and measure local environmental conditions, giving the grower actionable insights based on this data.

Plense Technologies shares this vision and currently explores how ultrasound technology can be used to monitor crops real-time, give actionable insights accordingly, and ultimately give the grower advice (see Figure 2).

Ultrasound technology has become increasingly affordable in recent years, making it a cost-effective alternative to other plant sensors. This enables the broader implementation of such sensors in the greenhouse. Moreover, it is expected that the ultrasound sensor will be able to measure multiple aspects of plant health and growth, possibly replacing the need of other types of plant sensors out there.

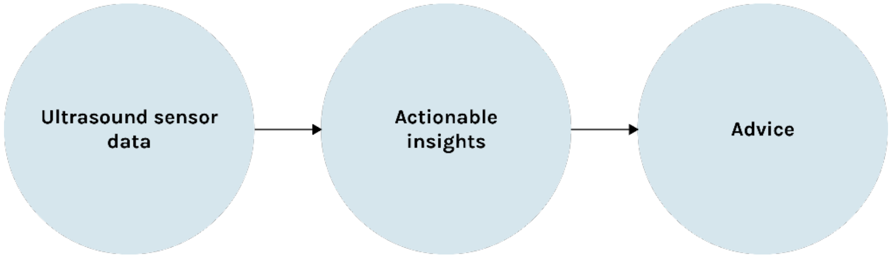


Figure 2: Vision of Plense Technologies

1.3 Problem Definition

Currently, plant sensors like that of the ultrasound sensor, hold potential to improve agricultural practises, however there are still a lot of challenges related to these sensors and the outcoming data. The plant sensor data is complex and not yet interpretable. Additionally, it is not yet known how this new data can be integrated with other types of data to eventually provide the grower with actionable insights and advice.

The plant sensor data of the ultrasound sensor of Plense Technologies is even more complex (see Figure 3). For example, with a stem diameter sensor, the stem diameter is being measured. In contrast, the ultrasound sensor's output is less straightforward. It is not yet fully understood what health and growth aspects of the plant are measured. It is known that the sensor will be able to capture sounds that the plant makes when under stressful conditions, but it is not known what they mean.

Plense aims to collect ground-truth data, defined as reliable measurements of plant conditions, to validate the measurements of the ultrasound sensor. This includes quantitative metrics such as stem diameter (e.g., 12mm) and other physiological parameters relevant to tomato plant health and growth. By comparing the ultrasound signals with this ground-truth data, Plense will develop models to identify potential relationships between the sensor's output and specific plant conditions. However, this plant sensor data also lacks understanding

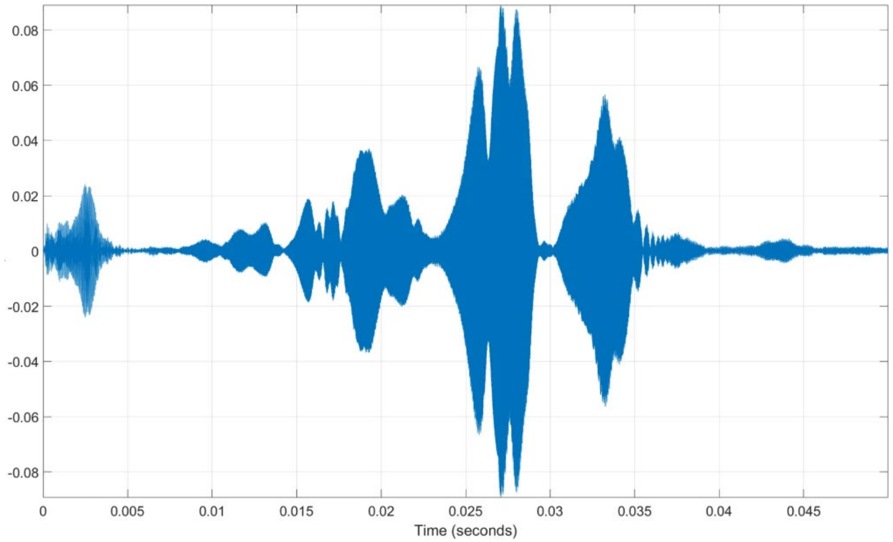


Figure 3: Ultrasound signal

1.4 Research question

The primary research question guiding this thesis is:

How can ultrasound plant sensor data provide actionable insights for the grower?

1.5 Project scope

This case will be researched on making the ultrasound plant sensor data actionable for the Dutch tomato growers first, because tomatoes are the most produced vegetable in the Netherlands (Statista, 2024). Moreover, tomato growers of the Netherlands are early adopters of greenhouse technologies, which means making the technology applicable for the Dutch tomato grower is a logical first stage in its development.

1.6 Project approach

The project follows the double-diamond method (see Figure 4), which is divided into four iterative stages: Discover, Define, Develop, and Deliver.

The Discover phase covers the necessary background knowledge (Chapter 2) required to understand the project. This includes definitions and concepts related to plant health and growth, the requirements for plant monitoring, current monitoring technologies, and an explanation of ultrasound sensor technology. Through this research, we identified a knowledge gap: there has been little focus on the expertise that growers bring to cultivation. To address this, a research design was developed in Chapter 3 to explore the grower's role in cultivation, with the results presented in Chapter 4.

In Define (Chapter 5), we outline the project direction and establish the design goals.

The Develop stage (Chapter 6) involves generating ideas to solve the design problem, and in Chapter 7, the best ideas are combined and conceptualized.

Finally, Chapter 8 presents the Deliver phase, where the final concept is introduced. Chapter 9 then explores the future potential of this concept.

The thesis concludes by answering the main research question and evaluating the design based on its desirability, viability, and feasibility.

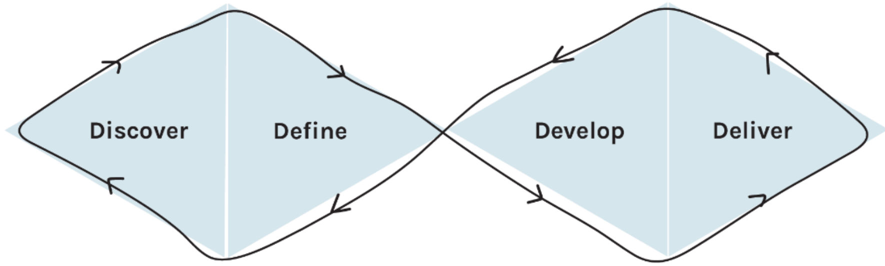


Figure 4: The double-diamond method

2 Background

2 Background

This chapter provides the necessary background knowledge for the rest of the thesis.

2.1 Fundamentals of plant health and growth

2.1.1 Defining plant health, growth, and stress

Plant health

In literature, plant health often does not have a clear definition. There are roughly two approaches in determining plant health: a positive and a negative approach. The positive approach describes plant health as the ability of the plant to function to the best of its genetic potential (Agrios, 2005). The negative approach states the plant is healthy, if it is in the absence of diseases (Boorse, 1977). The negative approach takes out the complexity of plant health, which cannot be solely dependent on the absence of diseases. This absence does not guarantee the plant is healthy. Environmental conditions and the availability of nutrients are also very determining in whether a plant is healthy or not. For this thesis the positive approach is more fitting, because the concept of the Three Plant Balances (Paragraph 2.1.2) also explains the plant to be healthy when all the three plant balances, both individually and amongst each other, are in balance. The plant can only perform at its best potential, when the plant balances are in equilibrium.

Plant growth

In contrast, plant growth is more easily expressed than plant health. It is commonly expressed as an increase in fresh weight, which includes both the dry matter and the water content of the plant (Geelen, Voogt & Van Weel, 2021). Hilty, Muller, Pantin, and Leuzinger (2021) share a similar definition of plant health, giving that growth is quantified in terms of biomass accumulation, which is a process that typically takes days or weeks to become noticeable (Hilty et al., 2021). Sometimes growth is expressed as an increase in dry weight (Geelen et al., 2021).

Plant health and growth are interrelated

Moreover, plant health and growth are interrelated but different concepts. A healthy plant generally indicates good growth, and conversely, good growth suggests a healthy plant. However, this relationship is not always straightforward. Plant health can be seen as a snapshot (datapoint) of a plant's status at a particular moment, while growth represents its trajectory (trend) over time. When a plant consistently shows signs of health, it contributes to cumulative growth over time. However, solely looking at growth does not provide a complete picture of how healthy a plant truly is. For instance, a plant might increase in weight due to heat stress, which can cause its green parts to retain water, stagnating growth. This may result in the plant appearing to grow while it is not healthy.

Stress

If a plant is not healthy and not growing well, it might be considered stressed, although this definition isn't straightforward. Meinen, Van Hoogdalem, Geurts, and Dieleman (2022) explore the concept of stress in plants, explaining that stress arises from various stressors that disrupt the plant's internal balance. This disruption triggers a stress reaction, which serves as a mechanism to restore equilibrium. Stressors can include all external factors that alter the plant's response, such as excessively high humidity in the greenhouse or drought conditions.

While stress might seem something to avoid, it's important to recognize that it is not inherently negative. The duration and intensity of stress are key factors in determining whether the effects are positive or negative (Meinen et al., 2022). For instance, prolonged or intense stress can hinder a plant's ability to restore its internal balances, while moderate stress can enhance resilience. Understanding these nuances is crucial for optimizing growth and ensuring overall plant health.

2.1.2 Introducing the Three Plant Balances of Plant Empowerment

Plant Empowerment

This paragraph introduces the framework of the Three Plant Balances, a key concept of Plant Empowerment (Geelen et al., 2021). This framework offers a physiological perspective on plant health and growth, emphasizing the need to optimize these balances to enhance cultivation practices (Geelen, Voogt, & Van Weel, 2016). The Three Plant Balances consist of energy, water, and assimilates (see Figure 5). When these balances are disrupted, the plant may be

Figure 5: The Three Plant Balances (Geelen et al., 2021)

considered stressed; however, this stress can have both negative and positive implications.

The Energy Balance

This is the equilibrium of the energy that flows towards the plant and from the plant. The plant gets its energy input mostly from sunlight, for which a surplus of energy is needed for the plant to evaporate. This is directly the link of the energy balance to the water balance.

The Water Balance

The water balance is the balance between the water uptake and the water evaporation of the plant. Via the water system (vascular system) the roots suck up water combined with nutrients, carrying these to the different parts in the plant. The water is evaporated through the leaves, via stomata (like the pores in human). Evaporation plays a crucial role in maintaining plant health and growth. If in times of stress the evaporation rate of the plant slows down, or even stops, this also means less nutrients reach the different parts of the plant. This might cause a nutrient shortage, resulting in for example blossom-end rot (see Figure 6), which is a deficit in calcium (Janse, 1993a).

The Assimilate Balance

The assimilate balance refers to the equilibrium between assimilate production and consumption. The production of assimilates is primarily driven by photosynthesis. This process converts carbon dioxide, water, and visible light into glucose and oxygen. Glucose is an assimilate, which serves as a source of energy and building block for plant growth. Photosynthesis occurs during daytime, whereas respiration takes place continuously, both day and night. During respiration, assimilates such as glucose are broken down to release energy, which is essential for plant development. If there are not enough assimilates produced in comparison to the amount consumed, the plant will become weaker.

Figure 6: Blossom end-rot (Dick, 2021)

The role of stomata

Stomata (see Figure 7) control the gas exchange of the plant and directly affects the amount of photosynthesis that can take place, therefore playing a role in all the plant balances.

They absorb carbon dioxide during daytime and release oxygen during night-time. The amount of gas exchanged is mostly dependant on the degree to which stomata are open. This depends on climate conditions and the presence of pathogens.

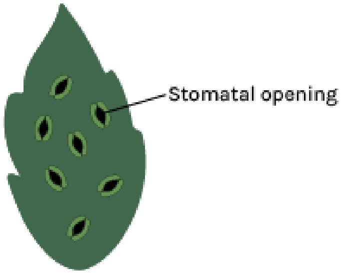


Figure 7: Representation of stomata on the leaf

Stomata tend to be open at humid conditions because then the chance of dehydration of the plant is lower, however, this also increases the risk of pests and diseases infiltrating the plant, like Botrytis (Dieleman et al., 2012). If humidity levels go above 93%, Botrytis can get into plants through small cuts or damp spots on stems (Köhl et al., 2007). Moreover, stomata they might let in fungi and bacteria (Bakker, 1991b).

In dry conditions the stomata tend to be closed, to avoid dehydration. They need to be open to keep on evaporating, whenever this gas exchange process is disturbed, the plant will not grow.

2.2 Plant health and growth requirements

This section provides a literature review on the plant health and growth conditions. This is necessary to understand the circumstances that are desired for plants to be healthy and grow optimally. The requirements will be divided into climate requirements and soil requirements (see Figure 8). For each requirement the primary balance will be given to which it belongs. This links these requirements to the Three Plant Balances as discussed in Paragraph 2.1.2).

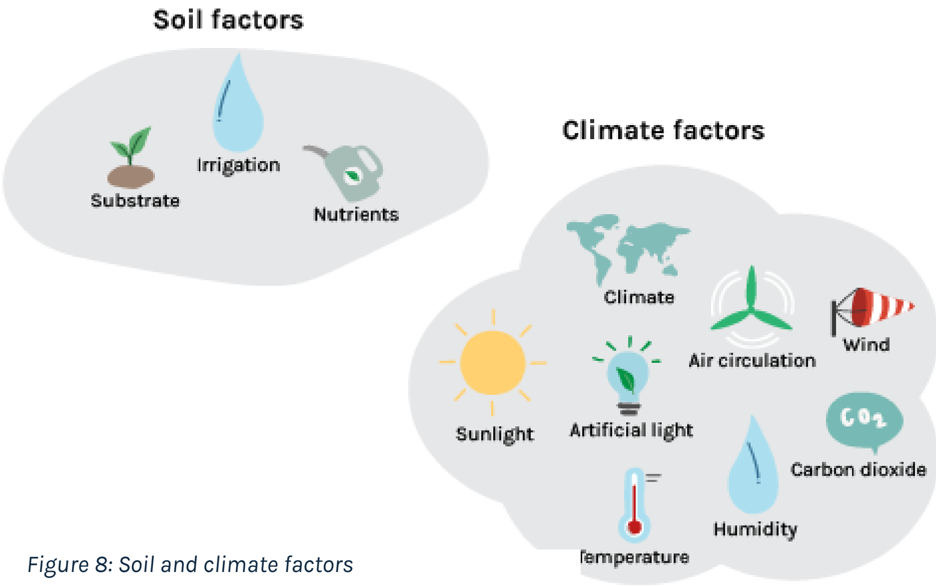


Figure 8: Soil and climate factors

2.2.1 Climate requirements

Light (Energy balance)

Geelen et al. (2021) state that weather determines 80% of the conditions within a greenhouse, with the remaining 20% fine-tuned by the grower using available tools. This can be explained by the fact that the maximum energy supplied via heating pipes (150 W/m^2) is far less than what the sun provides (500-800 W/m^2).

Sunlight remains the gold standard for plant growth, as it outperforms artificial light sources like LEDs. Plants have evolved to adapt to natural sunlight conditions (Geelen et al., 2021). However, LEDs offer potential because they can produce different light spectrums. Specific light recipes might improve plant health and growth through the seasons or even make year-round cultivation possible for some crops. Nevertheless, Dieleman et al. (2020) highlight that this is challenging, as much of the research is conducted in climate chambers that lack the full spectrum of natural sunlight. Plants behave unnatural in the absence of sunlight. Dieleman et al. suggest integrating sunlight into LED lighting trials.

Despite the challenges, research shows that red light is essential for photosynthesis, while far-red light is crucial for stem and leaf development. However, the most important factor is the ratio between these light types. Additionally, although green light is less absorbed by leaves, it plays a key role at the crop level, as it penetrates more deeply into the canopy, providing light to lower or hidden parts of the plant, such as fruits. It is important to note that the effects of LED lighting vary significantly depending on the breed.

Not only the light spectrum matters, but also whether the plant receives direct or diffuse light. Kaarsemaker et al. (2005) investigated the benefits of direct versus diffuse light and found that direct light interception is generally more beneficial due to its higher intensity of Photosynthetically Active Radiation (PAR), which is essential for photosynthesis. However, inaccuracies in PAR sensor readings, influenced by factors like shadow screens, may have affected the results.

Lastly, Dueck et al. (2007) studied the impact of light exposure duration and intensity on tomato production in greenhouses. The results showed that tomatoes exposed to 18 hours of high-intensity light yielded the most, while those exposed to only 12 hours yielded the least. Interestingly, similar yields were observed between plants receiving 15

hours of high-intensity light and 18 hours of low-intensity light, both with the same light sum. This suggests that total light duration has a greater influence on productivity than intensity alone.

Temperature (Energy balance)

Shamshiri et al. (2018) delve into determining the optimal air and root-zone temperatures throughout the various stages of plant growth. They identify optimal temperatures ranging from 17 to 27 degrees Celsius for all growth stages (Kittas et al., 2005). However, it's important to note that these optimal temperatures can vary significantly depending on the specific breed.

Dieleman et al. (2009) emphasize that maintaining fluctuating temperatures during both day and night is essential. Higher temperatures during the day facilitate assimilation, while lower nighttime temperatures help conserve energy. However, extreme fluctuations can lead to issues such as leaf margin damage and fungal diseases. The typical temperature difference between day and night is between 5 and 7 degrees Celsius (Baudoin et al., 2013).

Humidity and vapour pressure deficit (VPD) (Water balance)

Humidity and vapor pressure deficit (VPD) are closely related in greenhouse cultivation. Humidity refers to the amount of moisture in the air, while VPD measures the difference between absolute humidity and the maximum moisture the air can hold. When humidity is high, VPD is low, indicating that plants tend to evaporate less. Conversely, when humidity drops, VPD increases, stimulating plants to evaporate more.

Dieleman (2008) investigated the effects of high humidity on plant yield and found that high humidity levels are not beneficial for production. Additionally, high humidity negatively impacts not only crop growth, but also fruit quality. Bakker's research (1990) demonstrated that high humidity can make tomatoes go bad faster.

Carbon dioxide (Assimilate balance)

Dieleman et al. (2009) found that tomato plants grew faster in a fully closed greenhouse, due to the increased level of carbon dioxide. Enough carbon dioxide was available for the plants to photosynthesize.

2.2.2 Soil requirements

Substrate

Substrate is the growth medium of the tomato plant, such as peat. Nowadays, there is an increasing demand amongst growers for alternatives of peat, which has been used for many years (LTO Nederland, 2024). There is not yet legislation forcing growers into this transition, however, there is an urge for this transition as it is expected that the substrate production must increase by a factor of 4 by 2050 to produce enough food for the increasing population (LTO Nederland, 2024).

Harvesting peat is not a sustainable practice. To use peat for purposes like agriculture, it must be drained, allowing oxygen to enter the soil. This oxygen promotes the breakdown of peat by microbes, releasing stored carbon as carbon dioxide and nitrogen, which significantly contributes to greenhouse gas emissions and climate change (Rydin & Jeglum, 2013; Joosten et al., 2016; Leifeld & Menichetti, 2018). The release of these gases is harmful to the environment.

Nutrients (Water balance & Assimilate balance)
Plants rely on a variety of essential nutrients for their growth and development, including calcium, magnesium, nitrogen, phosphorus, potassium, and sulphur (Maathuis, 2019). These nutrients play different roles in plant physiology and their importance may vary depending on the specific growth stage of the plant. Potassium, for example, helps the roots grow and calcium is to produce cells and helps the green parts of the plant (Stichting Tomatoworld, 2022a). Additionally, phosphate gives energy and stimulates growth of the whole plant (Stichting Tomatoworld, 2022b).

Water (Water balance)
In general, growers provide approximately 30% more water to plants than they need. This excess water is necessary to rinse the substrate mat, preventing the build-up of salts (West et al., 1979). The water that drains from the mat is collected through underground tubes for reuse later. Since this water contains nutrients, samples can be taken to analyse which nutrients the plants did not absorb, allowing or adjustments in nutrient combinations for future feedings.

Some growers monitor the water percentage in the mat daily. An "interingspercentage" of about 15% compared to the previous day is common (Valstar & Stargrow Consultancy, 2018). This means that each day, after watering, the amount of water in the substrate mat should decrease by 15% overnight. This method helps growers ensure that the plants have absorbed sufficient water.

2.3 Plant monitoring methods

Plant health and growth can not only be monitored via looking at the climate and soil, which is a somehow traditional cultivation method. Nowadays, emerging plant sensors, allow to measure plant health and growth by looking at the plant physiology. This section will first outline the parts of the plant that can be measured, whereafter an overview will be given on the technologies to monitor them. Concluding with the software platforms in the field to which sensors can be connected to give growers actionable insights.

2.2.1 Plant parameters

In Figure 9 an overview can be found on all the visual plant parameters out there. Figure 10 shows all the measurable parameters, often with a unit.

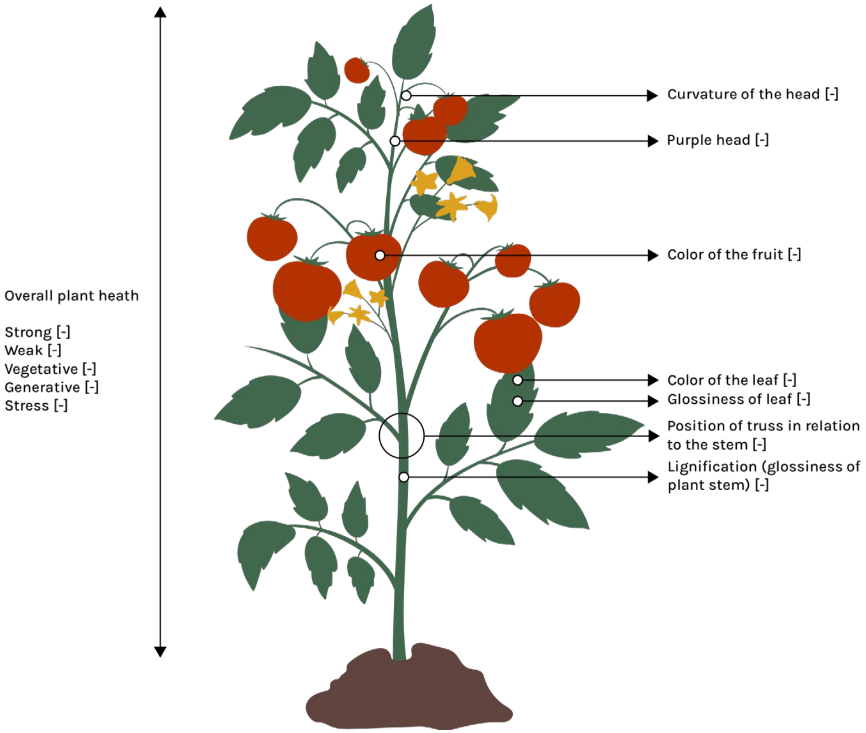


Figure 9: Overview visual plant parameters

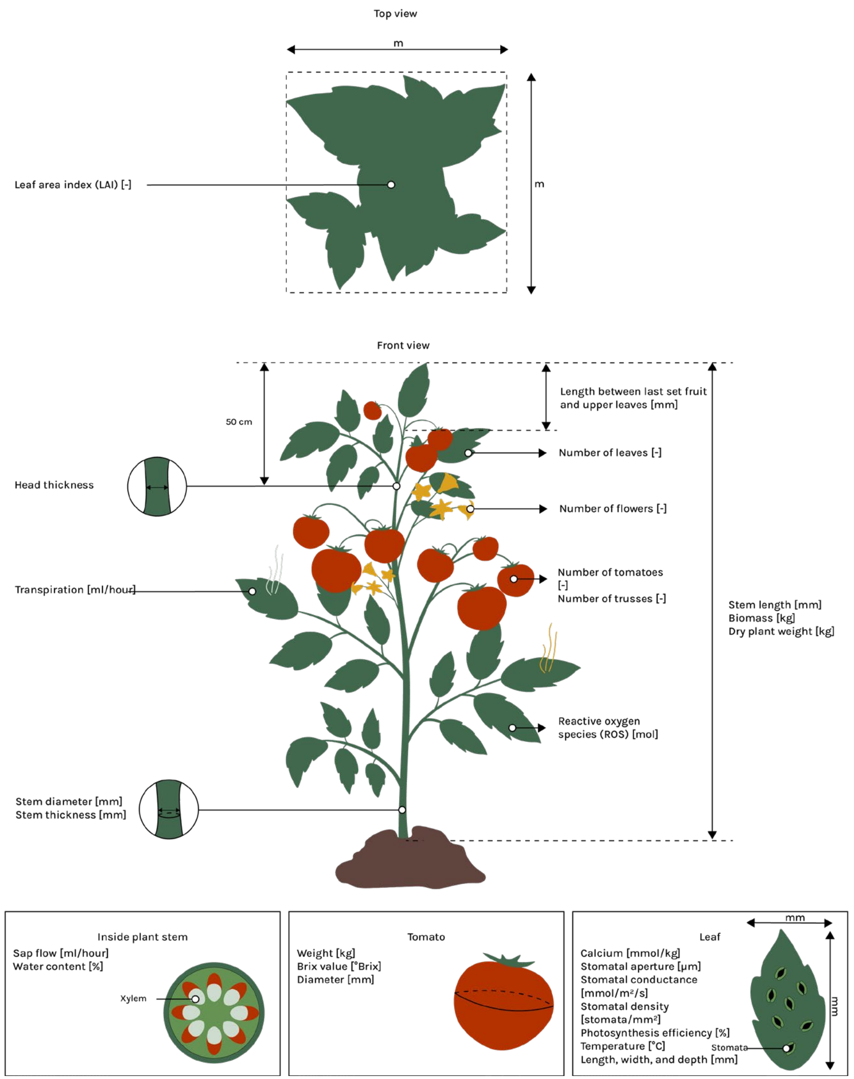


Figure 10: Measurable plant paramaters

2.2.2 Plant monitoring devices

Appendix A gives an overview of the plant monitoring methods available, including mostly high-innovative sensors that directly measure data from the plant.

Remarkably, nothing yet is said on what the threshold values are for these measurements. For example, the CropObserver camera can detect several parameters of stomata, however, the opening is not yet found to which stomata are able to evaporate well, yet not being vulnerable for pathogens.

Moreover, it is for some parameters doubtful if an increase or decrease in the value is profitable. In some cases, this might be either way. For example, a stem diameter that is increasing can mean the plant is growing well and strong enough to carry the fruits, but this can also mean that the plant holds water as it experiences heats stress and is not able to evaporate.

Also, it is noticeable that there is not one device that is able to measure all the plant balances, or able to monitor plant health and growth on a more overarching level.

2.2.3 Software platforms

Eventually, data types of plant sensors, climate data, soil data, plant measurements, and probably more, should be combined in a hub. The following platforms do this and make actionable data derived from the data, which should inform the grower on making cultivation decisions.

Climate computers

The climate computer brings together all the data of the climate into one software platform (e.g. temperature, light, and carbon dioxide). The three largest companies in climate computer world-wide include Priva, Hoogendoorn, and Ridder. They put climate sensor in the greenhouse, connect them to the platform, and show how the climate conditions in the greenhouse, but also the irrigation develops. In the climate computer the grower is also able to give set points, for, for example, when the irrigation should start or how warm the climate in the greenhouse should be.

LetsGrow

LetsGrow has a platform to which climate sensors and plant sensors are connected. They are trying to give the grower advice on how to steer the greenhouse, based on this data.

BlueRadix

BlueRadix is a company that gathers a lot of data on the weather and climate conditions in the greenhouse, combines this with the strategy of the grower, and makes algorithms to predict how the temperature, humidity, and irrigation should look like in the coming one to two weeks.

They also are far in the step towards giving advice to the grower. This is a step that for example Source.ag has not been able to take yet.

Source

Source is a company that is gathering as much plant data as they can, to use the data in models to eventually provide and empower the grower in how to steer the greenhouse. They gather the plant data, by letting the grower fill in the measurements of the plant he normally would have filled in for his plant registration (see Appendix B to see how this form looks). A glimpse of the data Source measures can be found in Figure 11. This includes concrete measurable data such as the number of leaves, flowers, and fruits, but they do not yet collect the more tacit knowledge the grower possesses.

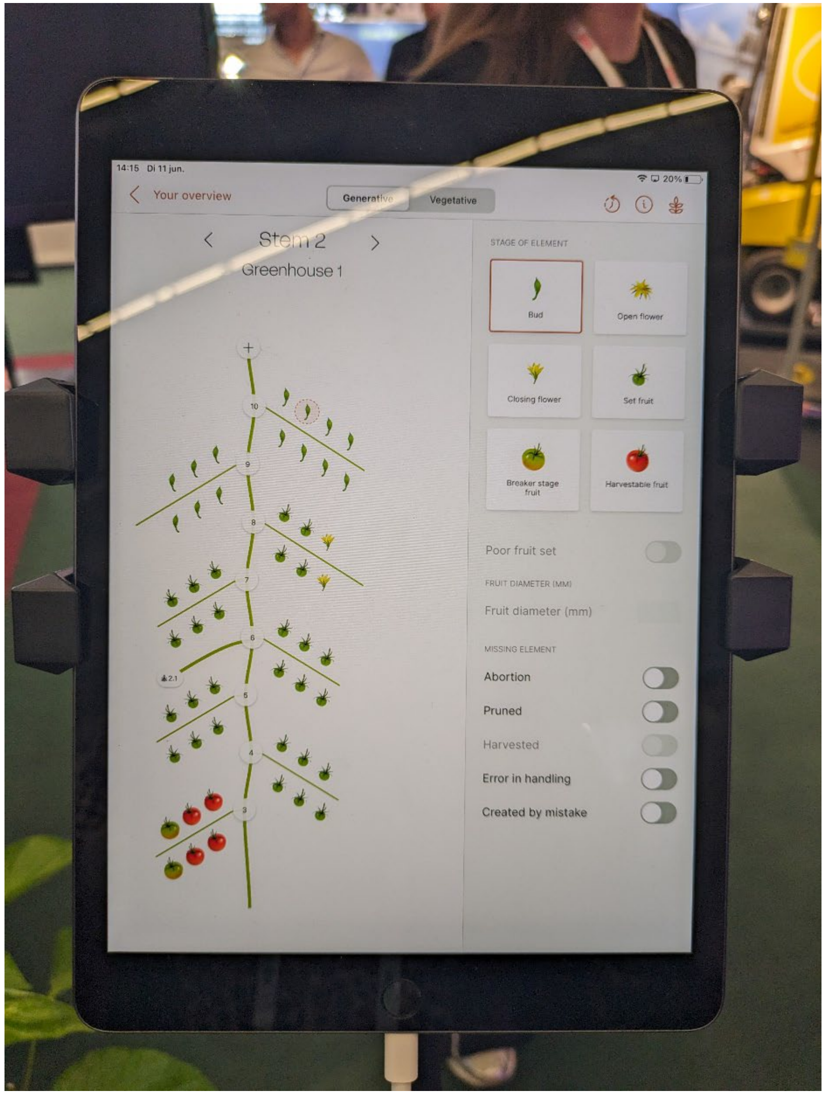


Figure 11: Platform of Source.ag

2.4 Plense's ultrasound sensor (Plensor)

2.4.1 Hardware

The ultrasound sensor of Plense is integrated into a housing with a clamping mechanism. The sensor is put on the lower part of the plant stem (see Figure 12). It is important that the ultrasound sensor is closely positioned to the plant stem, to avoid media disturbing the signal. Additionally, the sensor should be positioned closely to the plant stem for a range of stem diameters, which can differ a few millimetres from each other.

2.4.2 Ultrasound technology

Plants produce sounds

Plants produce sounds when they are stressed that cannot be heard within the hearing range of human. The sounds are the result of cavitation, which involves the formation of bubbles in the xylem vessel. This is the vessel in the plant stem through which the water flows. The sounds can be captured in a passive way, which is done by Khait et al. (2023), however, Plense does this in an active way.

Active ultrasound technology

The active way of using ultrasound technology means that sound waves are sent through the plant stem (e.g. block waves), causing certain parts of the internal structure to resonate. The resonance frequencies the plant makes are picked up by the sensor. As some parts will resonate more than others, the outcoming signal will be a mix of several resonance frequencies. From these different ultrasound features can be extracted, such as peak amplitude and time of flight. This technology builds further on the research of Dutta et al. (2022), who have found connections between resonance frequencies, ultrasonic features xylem vessel geometry.

Making a robust ultrasound signal

The incoming signal from the Plensor is significantly influenced by the temperature of the surroundings. To filter this out, the temperature of the plant is measured with a thermographic camera. This data is then used to filter out the temperature influence, leaving only the plant measurement.

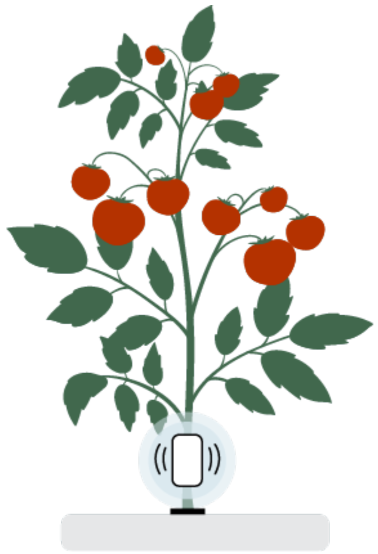


Figure 12: Plense's sensor (Plensor)

Data analysis

To analyse what the ultrasound signal means, ground-truth data will be collected of the plant. This is data known to be true, for example, a plant diameter of 16 mm. They are also busy with obtaining the stem diameter with a stem diameter sensor. At first, manually relations can be found between the ultrasound signal and the ground-truth data, later this will be automated via machine-learning models.

2.5 Knowledge Gap

The current methods of collecting plant health and growth data are largely quantitative and lack sufficient context, making interpretation challenging. This also includes for the data of the ultrasound sensor. While measurable plant parameters provide valuable information, they do not convey much insight into their implications for plant health and growth. This highlights the need for more qualitative insights to enhance data interpretability.

Additionally, there is currently no single sensor capable of detecting all three plant balances or monitoring general plant health and stress. While stomatal sensors show potential for measuring these factors, they lack established threshold values for effective interpretation.

The primary research gap identified is the insufficient focus on growers' expertise. Current monitoring technologies emphasize quantitative data but overlook the valuable insights that growers possess. By incorporating this knowledge, we could enrich the data of the ultrasound sensor, but also of other plant sensors and achieve a more holistic understanding of plant health and growth.

3 Research Design

3 Research Design

This Chapter gives an overview of the research design in finding out what role the grower can play in the field of plant sensor data.

3.1 Research Objectives

The research explores the role of the tomato grower in greenhouse cultivation. The following main research question was set up:

What is the role of the grower in greenhouse cultivation practises?

To answer this question the following sub-questions are leading:

1. What factors influence how the grower cultivates its crops (besides the crop's status)?
2. How does the grower sense the crop's plant health and growth status?
3. How does the grower see his role changing with arising greenhouse technologies?
4. Which methods/strategies does the grower use to control the crops or steer them towards the desired direction?
5. Which systems/tools are used to control the health and growth status of the crops?

3.1.1 Hypothesis

My hypothesis for the main research question is that the grower plays a substantial role in greenhouse cultivation, and that cultivation practises cannot yet be fully automated due to a lack of this practical knowledge.

3.2 Research Setup

Qualitative research was conducted, as this is the most fitting method to obtain the subjective knowledge of the growers.

3.3 Method

3.3.1 Interviews

Multiple interviews were carried out to explore the role of the grower in cultivation. Questions were asked with the sub-questions 1-5 in mind. These interviews were semi-structured, meaning a list of questions was set up to guide the discussion with room to deviate from it. During the interview short notes were taken, as well as quotes. The average interview took 1 hour.

3.3.2 Observational Research

Some growers offered a tour through the greenhouse, which gave more context on for example the layout of the greenhouse, the tools used to control the conditions in the greenhouse, and how the tomato plants grow. During the tour sometimes photos were taken and the information during the tour was later noted down.

3.3.3 Walk-Along

A walk-along was conducted with two growers to ensure the research was as close to the context and reality of how they monitor their crops as possible. This tour took approximately an hour. The goal of the research was to explore which terms growers use to describe plant health and growth, and which indicators they look at.

3.3.4 Expert Interview Delphy

An expert interview was conducted with a researcher from Delphy to gain deeper insights into the challenges growers face with greenhouse technologies. Delphy specializes in researching the implementation of greenhouse technologies and providing cultivation advice to growers.

The interview was particularly valuable since most of the growers visited had little to no experience using plant sensors and could not provide detailed information about their challenges. Delphy operates its own testing facility for technologies and actively collaborates with growers to test these innovations, making this interview highly relevant. Additionally, the researcher offered a tour of their Innovation Test Centre following the interview.

The interview was done with the researcher of Delphy, because almost none of the growers visited had experience with using plant sensors, so they could also not elaborate on their challenges. Delphy has its own testing location for technologies and actively test these with growers, therefore this interview was fitting. Moreover, after the interview a tour was provided through their Innovation Test Centre.

3.3.5 Expert Meeting Priva

A meeting of an hour with Priva focused on improving the quality of subjective assessments. Priva, which is shifting from providing data via climate computers to offering cultivation advice, discussed its 'Teler's View' project, where growers evaluated crop conditions based on a single photo. Approximately 5-10 growers participated in a bi-weekly session with cultivation experts, analysing the crop's status and desired state on a set of axes.

3.4 Participant Selection

Table 1 shows the participants selected for this research, together with their description, the data collection method, crop type, materials collected, contact moment, and the Appendix for more details.

The participants were selected to have a variety of tomato growers. The type of tomato grower can be found in the description of Table 1. More on the types of tomato growers can be found in Appendix C.

Not only tomato growers were selected, but also growers of the bell pepper and cucumber, to investigate the potential impact of this project on growers beyond the tomato.

3.5 Data Analysis

3.5.1 Visualisations

The most used method to analyse the data was to categorize and make visualisations for the following subjects.

- External factors influencing the decision-making process of the grower.
- The grower as a sensor.
- The grower versus technology.
- Cultivation methods/strategies by the grower.
- Systems/tools used to control the crop.

3.5.2 Frequency Analysis

The walk-along was analysed by looking back at the video recordings and note down all the terms the grower used in describing plant health and growth. The same was done for the plant health indicators they look at. These results were enhanced with the data of the interviews from other growers to come to a good overview (see Appendix D).

3.6 Limitations

One of the main limitations of the research is that the walk-along was conducted with n=2 growers, and that the results were combined with interview data to get an overview of all the terms mentioned by the grower to describe the plant. Ideally, these terms would only be collected with the walk-along, meaning that the plants and the grower's perceptions would both be filmed. Analysing solely these movies would give a more accurate representation. Unfortunately, a walk-along was not possible for some grower, due to the risks of spreading the ToBRFV virus.

Moreover, sometimes the insights from bell pepper growers will be woven into the text, however, I have tried to minimize this, plus cultivating the bell pepper is very similar to that of the tomato. The only difference is that the bell pepper plant does not give a purple colour as plant health indication.

Table 1: Participant table

Participant	***Description***	***Method***	***Crop type***	***Materials***	***Contact moment***	***App.***
CM-1	*Is manager of many acres of greenhouse*	*Interview*	*Tomato*	*Notes*	*10/06/2024*	*I*
CM-2	*Is manager many acres of greenhouse*	*Interview*	*Tomato*	*Notes*	*09/07/2024*	*J*
CM-3	*Is manager many acres of greenhouse*	*Interview*	*Tomato, cucumber*	*Notes*	*22/04/2024*	*K*
N-1	*Young grower*	*Interview, walk-along*	*Bell pepper*	*Notes, video recordings*	*14/05/2024*	*L*
N-2	*Is manager of many acres of greenhouse*	*Interview, observational research*	*Bell pepper*	*Notes*	*15/04/2024*	*M*
E-1	*Tests breeds at seed company Rijk Zwaan*	*Interview, walk-along*	*Tomato*	*Notes, video recordings, photos*	*16/05/2024*	*N*
E-2	*Tests greenhouse technologies at Tomato World*	*Interview, observational research*	*Tomato*	*Notes*	*12/03/2024*	*O*
TG-1	*Traditional grower*	*Interview*	*Tomato*	*Notes*	*09/04/2024*	*P*
RD-1	*Researcher at Delphy*	*Expert interview Delphy*	*N/A*	*Notes, photos*	*25/03/2024*	*Q*
MP-1	*Research team from Priva*	*Expert meeting Priva*	*N/A*	*Notes*	*27/06/2024*	*R*

4 Empirical Research

4 Empirical Research

4.1 The Decision-Making Process of the Grower

This Paragraph will explore the following sub-research question:

What factors influence how the grower cultivates its crops (besides the status crops status)?

The context diagram in Figure 13 shows the complexity of the decision-making process of the grower. The circle represents this process. The rectangles surrounding the circle are the external entities, with whom the grower may interact to come to the best cultivation decision. The arrows between the circle and rectangles represent the data streams. Each interaction will be discussed into more detail, including the trade-offs growers need to make, but first the grower's primary goal in cultivation will be discussed.

4.1.1 The grower's primary cultivation goal

Growers are real entrepreneurs. Their main goal in cultivation is therefore not to keep their plants in the best condition and achieve the highest yield, but to make most efficient use of their investments. This idea is reflected by participant TG-1:

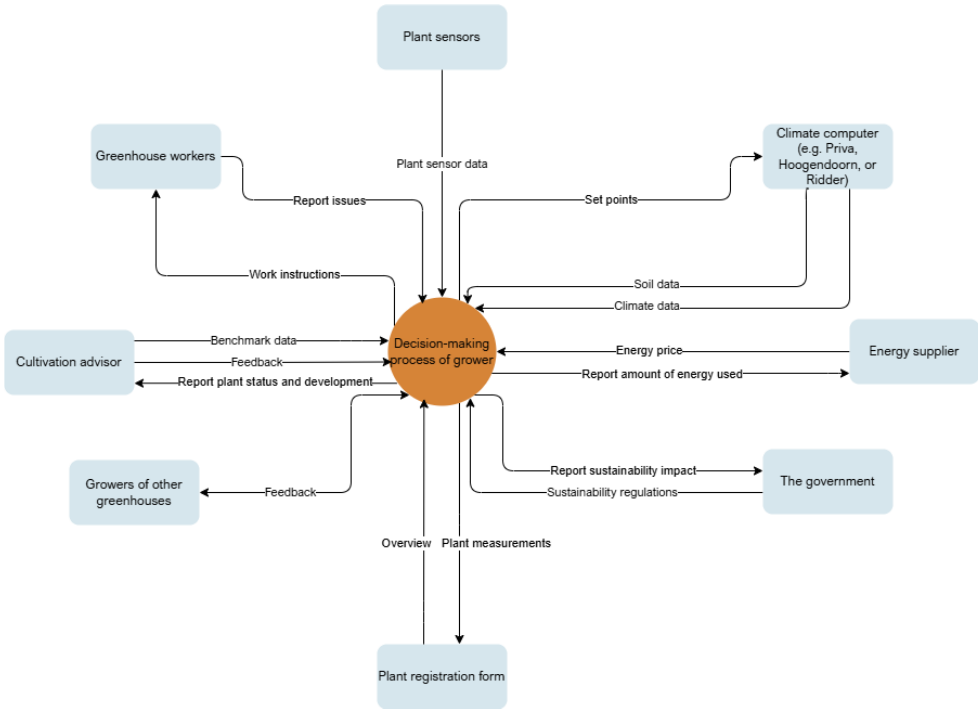


Figure 13: Factors influencing the grower's decision

"Higher yield is not the goal, but making most efficient use of your investments is."
~TG-1

Examples of the investments include: The costs for labor, investments to become more sustainable, and energy costs. Often, increasing investments will benefit the quantity and quality of the yield. However, growers must weigh these potential benefits against the costs to determine if they align with their broader business goals.

4.1.2 Cultivation advisor & plant registration measurements

All the growers spoken to, mentioned to get the support of a cultivation advisor every once a week or bi-weekly. Often the cultivation advisor has been a grower himself before, so he possesses a good knowledge base. He takes plant registration measurements, just as the grower himself, such as stem diameter and more. An overview of such plant registration measurements used in practise can be found in Appendix B. These measurements are used to compare to measurements of the past and to those of other growers cultivating similar breeds. It helps to understand whether the issues a grower faces are a common problem or not. Moreover, the ways to tackle them are also discussed with the cultivation advisor, then the cultivation advisor again can compare the strategy with the other strategies used by other growers and see what has worked. Being able to compare data is what participant N-1 calls the power of the cultivation advisor:

“This is the power of the cultivation advisor.”
~N-1

The grower takes the advice of the cultivation advisor into account, but the grower will always be in control of the final decision. This stubbornness is reflected by the statement of E-1.

“Growers are stubborn, they will not easily take advice from someone.”
~E-1

The grower will mostly rely on his own experience and knowledge, as he thinks with this mindset the last percentages extra yield can be achieved:

“The little changes, that make the crop perform a little better, must come from the feeling of the grower”
~E-1

4.1.3 Greenhouse workers

Reporting

Large greenhouses have a lot of workers, and because the grower cannot monitor every path of his crops every day, workers often take over these tasks. Participant CM-3 tells that workers can give feedback on crops via the labour registration system. The device enables the greenhouse workers to report the plants with abnormalities. This informs the grower where in the greenhouse he must check the plant.

Participant CM-3 tells often, reports are made whilst there is nothing wrong. He thinks this is sometimes annoying, but that teaching workers how to look at the plant is hard.

"It is hard to learn workers how to read the plant."
~CM-3

Labour hours
Not only is the grower informed by the greenhouse workers on the plant's conditions, but he also considers their labour hours needed to perform certain tasks. He does this via the labour registration system. Labour hours are expensive and there is a labour shortage, so the hours that the growers hire workers must be effective and efficient. If this is not the case the grower might consider investing in long-term investments to decrease the labour hours (e.g. a picking arm).

4.1.4 Climate computer

Climate & soil data
The grower bases how he steers the greenhouse partly on data. Nowadays, this is often done solely based on climate and soil data (see Chapter 2). Participant E-1 mentions to look back at the development of the climate data to see how the conditions could have affected the crop negatively. This informs the grower on how to react in the future when a similar situation occurs.

Set points
According to N-1, the overall strategy for managing plant health and growth is broadly determined on an annual basis, using historical climate data (specifically weather data) from previous years. Fine-tuning of this strategy occurs daily, as accurate weather forecasting is only possible for the current day. Once the grower has finalized the climate and soil strategy, they input the necessary set points into the climate computer for control.

"The yearly strategy is determined at the beginning of the year. Finetuning is done daily. For every grower this is the same."
~N-1

4.1.5 Plant Sensors

Plant sensor data
Not yet are plant sensors implemented in practise by growers, because of the challenges growers see in their physical implementation and the data (see Paragraph 4.3).

4.1.6 The Energy Supplier

The price of energy is very determining for growers. Often inside the offices of growers, besides the climate computer, there is also a screen with the current energy price. Whenever energy prices get too high, growers will most probably decrease the amount of gas they use, if they see they will not get enough yield out of it. For the plants, using less gas, thereby heating the greenhouse less, will result in a slower cultivation cycle. Participant TG-1 mentions that this slower growing does not influence the quality of the crop. In times of the energy crises, as a last-resort option to give the plant an extra boost of energy, TG-1 mentions to have picked the leaf at the top. This is however not desired, is what both participant TG-1 and CM-3 say.

“During the energy crisis I decided to pick a leaf at the top of the plant, instead of increasing the temperature.”
~TG-1

“I would rather steer the climate conditions than apply pruning techniques.”
~CM-3

4.1.7 The Government

Growers are largely affected by sustainability regulations set by the government. They are affected most of all by the changing of these policies, which decreases their will to invest in for example renewable energy sources.

To reduce emissions and take the above regulations into account, some growers have chosen to invest in geothermal energy, which is a renewable energy source. Other growers have their own ‘WKK’, a Combined Heat and Power. This is a way in which energy is generated, often with natural gas. Politically this is still seen as a problem, because the source of energy is not renewable, however the WKK is very efficient. The warmth that is produced during the generation of energy is used to warm the greenhouse, and the carbon dioxide is also used in the greenhouse for photosynthesis. Although the amount of carbon dioxide that is used for the latter is only a small part of all the carbon dioxide that is produced.

4.1.8 The Grower Community

Participant E-1 tells tomato growers share a lot of knowledge with each other, because they are not in direct competition with each other. They all receive the same price for their sales, depending on the type of crop and breed. In contrast, the flower industry operates differently, where growers often compete against each other, leading to less sharing of knowledge.

In the past, tomato growers shared knowledge via bi-weekly study sessions. At these sessions growers of similar breeds met each other at one of the greenhouses to exchange knowledge, however, participant TG-1 tells that due to the

ToBRFV-virus these sessions are not possible nowadays anymore. Participant E-1 mentions nowadays this knowledge exchange is often done via sharing photos, video, and phone calls. The same is done for businesses who have greenhouses abroad. It is noteworthy how involved growers are in each other's greenhouses and how they also use each other's expertise in their own decision-making process.

4.2 The grower as primary sensor

This section explores the following sub-research question:

How does the grower sense the crop's plant health and growth status?

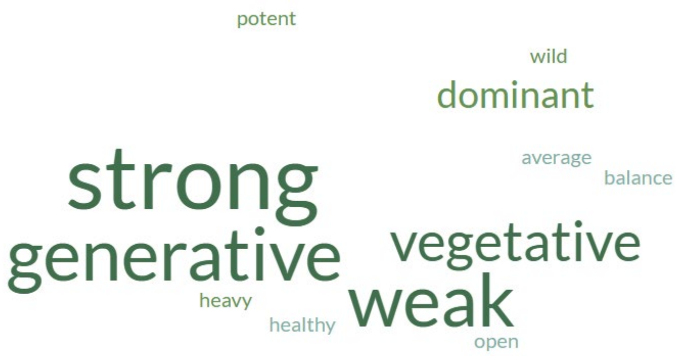


Figure 14: Word-cloud terms growers use to describe plant health and growth

4.2.1 Describing plant health and growth

The results of the walk-along can be found in the word cloud in Figure 14. The word cloud shows that plant health and growth is expressed by growers in terms of vegetative, generative, weak, and strong.

Generative growth means that the plant is putting its energy, or sending assimilates, into the development of flowers and fruits, rather than in the development of the green parts of the plant. Vegetative growth is used in practice as the opposite of generative growth. This means that the plant is putting its energy, or sending assimilates, into the development of the stem and leaves, rather than in the development of flowers and fruits. TG-1 says these terms say something on where the assimilates are sent within the plant. By Geelen, Voogt & Van Weel (2021) these two terms are also referred to as sinks. Then there is also 'strong' and 'weak' in describing plant growth. TG-1 says these terms say something about the amount of assimilates produced. By Geelen, Voogt & Van Weel (2021) these terms are referred to as the source, as this gives an indication on how many assimilates are produced. The terms strong and weak, are alway combined with the terms generative and vegetative by the grower to describe plant health. He visualises the terms on a matrix, with strong and weak, and vegetative and generative against each other. An example of a weak generative plant is a plant that is too weak to carry its fruits.

Note that through the cultivation season there will not be one type of growth desired, regarding the above-mentioned terms. The plant must be in balance is what growers tell. For example, when the plant is in a generative state, it must not be too strong, because then it shows that most energy is put into the production of the vegetative parts of the plant and not in making the fruits.

Plants behave as people

Often the grower describes the behaviour of the crop by comparing its behaviour to that of people. An example is given by E-1 'Plants should be tired at the end of the day, just as people.' E-2 says it is therefore not wrong if the plants get sloppy at the end of the day, as this means the plant is resting.

4.2.2 Indicating plant health and growth

In Figure 15 an overview can be found on all the plant health indicators growers use to come to a plant health and growth assessment. Below some of the indicators will be further explained:

Purple colour of the head

The purple colour of the stem is very important for the tomato plant. This colour is found at the head of the plant, where the most growth can be seen. The colour on the stem

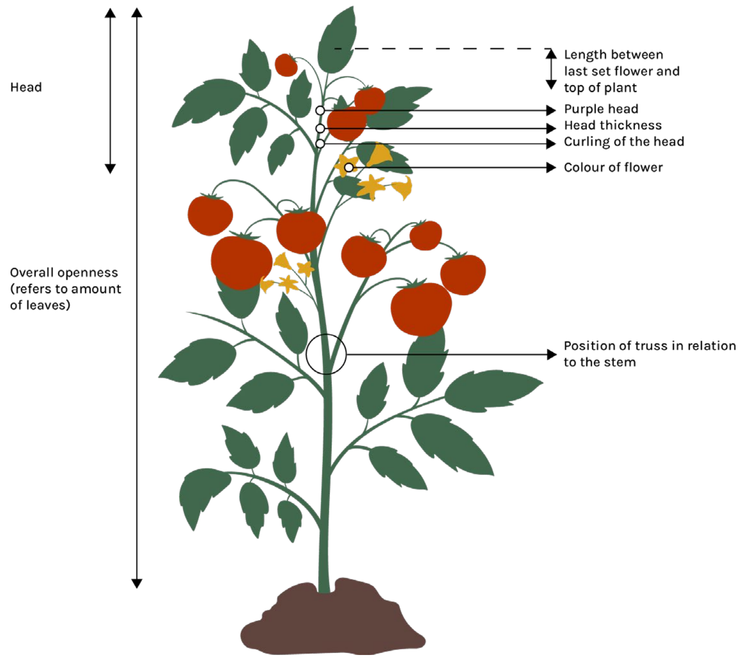


Figure 15: Overview of plant health and growth indicators by the grower

is indicative for strong growth, meaning the plant has a surplus of assimilates. Whenever the grower sees this, he might decide to for example leave one extra flower on the vine. The stems of the bell pepper and the cucumber do not colour, so this is only an indicator to consider for the tomato growers.

Colour of the flower

The colour of the flowers is important. The colour should be bright yellow, however, some plant breeds are paler from itself.

Length between last set flower and top of the plant
The place where the flowers develop is important. If the flowers grow near the top of the plant, this is indicative for generative growth. If the length of the top of the plant to the first flower is too long, this is indicative for vegetative growth. Growers will try to keep this length about approximately 10 centimetres, depending on the breed.

Position of the truss towards the stem
A very upright position and small angle of the leaf regarding the stem is indicative for strong and vegetative growth. If the leaf hangs a little bit, this means the plant is growing weak. Note that the desired position of the leaves also differs during the day. Just as humans the leafs should have an active position during the day, and a resting position at the end of the day. This is why sloppy leaves at the end of the day are not a problem.

Overall openness/amount of leaves
Very leafy plants are considered to grow vegetative. A lot of assimilates are then put in the production of the vegetative parts of the plant. If a plant is too vegetative, it will have a hard time producing fruits, because the focus is diverted away from fruit development. It is also not desired to have a small number of leaves, because then too little photosynthesis will take place to make assimilates and make the plant strong enough to carry more fruits.

Head thickness
A thick head is in general linked to a vegetative strong plant. Also, with this indicator it is key that it should be in balance. It is acceptable if the head thickness is slightly thinner than the main stem, when the plant is in a generative state.

Curling of the head
If the head is curling this is associated with more generative growth. Whenever the head is more upwards, just like the leafs, this is considered as more vegetative growth.

4.2.3 Estimating Plant Development
Growers mention that they are not only able to assess current crop health and growth, but that they are also able to guess this. Participant E-1 says that whenever he has the climate data for over a week, that he can make a good estimation in terms of vegetative/generative, weak/strong growth. In this estimation they take into how the plant will develop and what is desired. He will define a strategy to steer the crop towards what is desired.

4.2.4 Validating the Grower's Observations

The session results of the Priva Meeting are shown in Figure 16. This shows that there is little consensus amongst growers regarding the crop's status, while the desired status was more aligned, generally indicating a preference for a strong, generative crop.

The variability in growers' assessments stems from numerous influencing factors, including mood and personal motives. To improve app design, it is crucial to understand how and why growers arrive at their assessments, not just the outcomes. Incorporating features that allow growers to explain their thought processes could enhance the assessment quality.

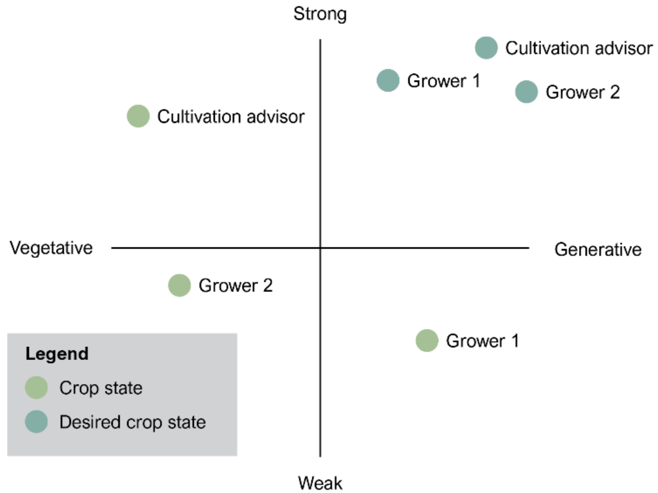


Figure 16: Impression of the results of Priva's research

Discussion

Priva's research did not track crop status over a longer time span, limiting the ability to identify trends. The current project will address this by monitoring crop status and desired states over a longer period.

4.3 Challenges and attitudes on Plant Sensor Data

This section explored the following research questions:

How does the grower see his role changing with arising greenhouse technologies?

Which systems/tools are used to control the health and growth status of the crops?

According to RD-1, in practice plant sensors are not widely used yet. If growers have plant sensors, which is rarely the case, they use either the temperature sensors, sap flow metre, or the stem diameter sensor. It was explored what the challenges are regarding plant sensors, and what the attitudes are of growers towards these technologies, to know why the current adoption rate is that low.

4.3.1 Technical Challenges

High costs

Most sensors require high investments of the grower. Often it is also not known how many sensors the grower should buy to get a comprehensive view of how plant health is spread over the greenhouse. N-2 mentioned having used plant sensors in the past, but he did not think the benefits of the data outweighed the price.

Usability Issues

A lot of sensors have usability challenges. Some sensors (e.g. the photosynthesis efficiency sensor) require specific attachment points on the plant for precise measurements, however, keeping the sensor in place is time-consuming. Plants move continuously due to growth, but also because of cultivation practices (e.g. re-hanging the plant). Moreover, not only the positioning of the sensor is a challenge, but also the invasiveness of some sensors is. Take for example the sap flow sensor, which places needles into the plant stem. This makes that the sensor itself is affecting the health and growth of the plant already, which is not desired and also makes the measurement inaccurate.

RD-1 sees that most companies of plant sensors focus mainly on the software of the measuring devices, instead of the hardware. The measurement itself can be carried out correctly, however, these measurements cannot yet be applied in practice.

"Everything that is placed on the plant is hard and little attention is given to the physical design. There is more focus on the software."
~RD-1

Integration Challenges

CM-3 notes that many companies operate their own software platforms and are hesitant to integrate their data. He does not want to use all these different platforms. This contributes to him not wanting to adopt the plant sensors with their own software platforms.

Data Interpretation Difficulties

Moreover, the data coming out of the sensor is not interpretable yet, not by the grower, as well as by the company itself. This is reflected in the statement of participant CM-2.

"Often only the people of the company itself know what the data means."
~CM-2

RD-1 tells some sensors gather data that has never been measured before. The data is often hard to interpret, and growers do not know how to use the data in practice. Additionally, the extreme values of plant parameters are not yet fully understood and vary throughout the plant cycle. For instance, although we can now measure stomatal aperture, the optimal width of stomata during the day and night, as well as throughout different stages of the plant cycle, remains unknown.

Risks
N-1 says there are also risks in using technology. He mentions that growers need to understand how the technologies work, before implementing them. If one of the technologies is malfunctioning, the grower should be able to detect it. If this is not the case the grower might measure incorrect data via the sensors and steer the greenhouse according to incorrect data.

4.3.2 Attitudes

Supportive but Cautious
Several emerging technologies can take over specific tasks from growers, but growers do not expect these technologies to fully replace them or make autonomous cultivation possible short term. This thought is reflected in the statement of N-1.

"It's an illusion that AI can take over the grower in the coming 10-20 years."~N-1

The data gathered by these technologies is useful, but mainly in a supportive way. Growers mention that they will always need to make decisions regarding plant growth. While they might incorporate data into their decision-making process, they will always retain the final say.

As technologies take over monitoring tasks of the grower, this does not necessarily mean the grower has more time. They will just do other things instead. CM-3 mentions if he had more time, he would expand the business.

"I want to grow."
~CM-3

The Grower as Indispensable
Technologies like plant sensors provide valuable data, yet growers emphasise the necessity of physically going into the greenhouse to see and feel the plants. They believe that this tactile and visual assessment cannot yet be replicated by sensors. Growers see themselves as the biggest sensor in the greenhouse. Technologies are helpful, but the assessment of the grower is needed for the finetuning of the crop. CM-1 says that when cultivation practices will be taken over by only technologies, you will see that the yield will diminish, because of the lack of fine-tuning by the grower.

4.4 Seasonal Methods & Strategies

This section explores the following research question:

Which methods/strategies does the grower use to control the crops or steer them towards the desired direction?

The actions and cultivation strategies of the grower differ through the season. This Paragraph gives an overview on which strategies and methods are important at specific moments of the cultivation season, but first the role of the breeder will be discussed, and then the tools that the growers can use to steer the conditions within the greenhouse

4.4.1 The Role of the Breeder

Grower E-1 tests breeds at the seed company RijkZwaan. This is one of the nine seed companies world-wide. Five of the operate from the Netherlands, contributing to the fact that the Netherlands possesses a lot of agricultural knowledge. Besides RijkZwaan there are: Enza Zaden, Bejo Zaden, De Ruiter Seeds, and Nunhems that come from the Netherlands.

These companies are very important in developing the best breeds. The quality of the seed is most determining in the performance of the plant, however, the better the quality of the seeds, the more they cost. A high-quality seed, that is for example resistant to the ToBRFV virus, can cost approximately 1 euro per plant for the grower. Growers may have thousands of plants in their greenhouse, which makes it very expensive to buy high-quality plants. Grower E-1 says that if you have the right seeds, cultivating becomes easy.

"If you have the right seeds, cultivating becomes fairly easy."
~E-1

Participant E-1 tells the best breeds are made through a process called grafting. Then the best roots of the plant and the best leafy part of the plant are put together with a clip. TG-1 says that these plants are then put under a plastic sheet under 100% humidity, for the roots and leaf parts to grow together. Once they are grown together the plants are tested like in the greenhouse of E-1. Here they have to pass two stadia, to get into production for the commercial market.

4.4.2 Toolbox

During interviews some growers mentioned having a 'toolbox' for steering the greenhouse. This toolbox refers to all that can be deployed to steer plant health and growth. An overview of this can be seen in Figure 17.

E-1 mentions that when one of the tools is adjusted, the effects can be seen and felt quickly in the greenhouse. The larger the change, the faster these effects become noticeable. The speed at which the crop reacts to the changes also differs per crop. Cucumbers and bell peppers will react faster to changes than the tomato, with the

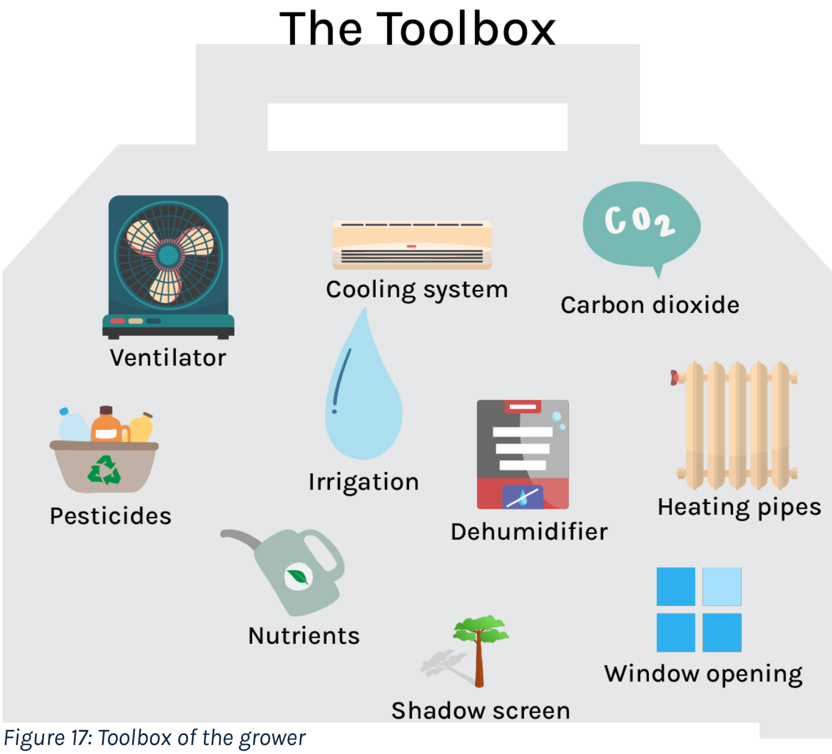


Figure 17: Toolbox of the grower

cucumber being the fastest of the three.

4.4.3 Preparing for the season

According to grower TG-1 typically the breeder seeds the plants in December. Growers then buy the plant from the breeder when they are approximately 30-40 centimetres in height. Grower TG-1 says that when the plants come into the greenhouse, firstly they are placed on substrate matts (the growing medium of the plant), with drippers next to it, so the plant can soak itself up with water entirely.

After this, the suckers are taken off the plants. These are the small leaves that grow within the armpits of the main plant stem and leaves. This is done to direct the energy that the plant has into strengthening the green parts of the plant, giving a strong base for eventually fruit formation.

Then, the plants are wrapped in rope (see Figure 18). This is done to support the plant, because they can become very long. The average tomato plant grows around 30 centimetres per week and the height of the greenhouse is limited. As the plant soon outgrows the height of the greenhouse, the ropes are rehung sideways every 1-2 weeks by workers in the greenhouse. They do this often by working from an aerial working platform.

4.4.4 Vegetative Growth

In the vegetative growth stage it is important for the grower that the vegetative parts of the plant become strong enough to later carry the fruits. Also, it is important that the most yield is taken from the plant, because as mentioned seeds are expensive, and with more stems there is also more production. Of course, there is a limit to the number of stems, which is approximately around 4-5 stems.

Multiplying is done by topping. This is the practice of removing the head/top of the plant, which enables lateral growth. The number of stems per plant that should be reached, depends on the breed. Smaller breeds are topped to more stems than larger tomatoes, because they have smaller leaves (E-2). Therefore, they require more stems and leaves to achieve a certain Leaf Area Index (LAI).

Strategies for the grower to steer more vegetatively, which is most of all done at the beginning of cultivation, but can also be done in the generative growth stage, include the following:

- Higher the amount of light in comparison to temperature (radiation/temperature ratio).
- Decrease carbon dioxide and temperature (CM-3).
- Increase the humidity rate in the greenhouse (TG-1). The plant will not be able to get rid of its moisture, which is why the moisture is pumped into the leaf. The leaf will develop the green parts of the plant more, thus the plant becomes more vegetative. Also, CM-1 explains increasing humidity rate will make the plant

Figure 18: Binding the plants

think it has more competition, thus it will feel the urge to grow more vegetative.

4.4.5 Generative Growth

Generative Influences

Once the plant begins to produce flowers it comes into the generative growth stage. Growers say that the plant must be bullied to get into the flowering stage. With bullying the plant, they mean for instance exposing the plants to more extreme climate conditions or pruning the plant. It is known that the climate in the Netherlands tends to be very vegetative, which is why the emphasis of the strategy of Dutch growers will be on the generative steering methods. Here are the most common strategies to steer the crop generatively:

- Higher the temperature in comparison to light (radiation/temperature ratio).
- Dry substrate gives a more generative influence (E-1). Limiting the use of water is mainly done in the beginning of cultivation to get them in the generative state. Once the plant is generative in general other things are done to make the plant more generative than limiting the water usage. This strategy is used mainly to promote the production of small roots, which take up the nutrients faster (E-2). This is in line with what Medyouni et al. (2022) say on the water deficit strategy. Additionally, they say that this strategy has low influence on the tomato quality.
- Increase the temperature variation between day and night (Raaphorst, n.d.). This is also what TG-1 and E-1 say from experience.
- Sometimes the leaf is picked at the head next to the truss. This means more light is received, which gives a generative influence (TG-1).
- Increase light received by the plant (CM-3).
- To make the plant generative the plant must be bullied (CM-1).
- When the plant is generative, the fruits should be kept warm (N-2). If the fruit is warm, more energy will go to the development of it. He mentions this does not necessarily mean the plant should be kept cold when it is vegetative.

"The crop must be bullied to steer it in the right direction." *~CM-1*

Pruning Flowers

Flowers are pruned once the stem of the truss is straighter and more lengthened (TG-1) (see Figure 19).

Figure 19: Moment to prune flowers

The amount to which flowers are pruned differs for the type of tomato (e.g. cherry tomato or flesh tomato), and is largely driven by the consumer's demand. Some tomatoes are marketed while still attached to the vine. Many consumers perceive vine-ripened tomatoes as fresher, and indeed, they tend to stay fresh longer when sold in this manner (TG-1). As the tomatoes are sold on the vine and there has to be uniformity to meet market standards, the amount of flowers is picked to a vast amount. TG-1 says he sells the vines at 12 tomatoes, but he picks the flowers between 11-13, otherwise the counting will take too much time for the workers.

Most tomatoes that are sold on the vine are small tomatoes. Larger tomatoes are often sold loose, therefore the number at which the flowers should be pruned matters less. Bigger tomatoes are often pruned to around three flowers on each truss. These tomatoes are also heavier, so less fruits can stay on one vine.

Maintain Tomato Quality

Once the flowers turn into fruits, it's essential to maintain their quality. At this stage, the focus is on ensuring the tomatoes ripen evenly and that, in the case of vine tomatoes, the first one to colour doesn't become overripe. While most of the tomato's quality depends on the breed and cannot be altered by changing climate conditions, careful monitoring is still important.

"The process of overripening is fastened in the summer, because there is more sunlight." *~TG-1*

4.4.6 Harvesting the tomatoes

Once the (vine) tomatoes have developed enough colour, they are ready for harvest. The grower primarily checks the colour of the last ripe tomato. If it shows sufficient colour, then it's time to harvest (E-1). They can be harvested until the end of September or October.

4.4.7 Wrapping Up

Before the new cultivation cycle begins, with new plants bought from the breeder, the whole greenhouse is emptied and cleaned to be prepared for the next cultivation season. Until then, growers often take a holiday or cultivate other types of crops that can be cultivated year-round (e.g. Chrysanthemums).

4.5 Take-aways

- The grower's decision-making process is multifaceted, influenced by various factors. Streamlining this process by providing actionable insights can significantly enhance their efficiency.

- In their discussions with fellow growers and cultivation advisors, growers frequently use terms such as "vegetative," "generative," "weak," and "strong." These terms not only reflect the status of the plants but also convey the desired growth direction and expected developments for the upcoming week. Providing actionable insights using this familiar language has value for the grower, as it aligns with the terms they already use in their communications. By integrating this language, we can enhance the ultrasound sensor data and make it more interpretable for the grower.

- Growers assess plant health based on multiple indicators. Understanding these indicators will deepen our insight into how growers arrive at specific plant assessments.

- Key challenges in adopting plant monitoring sensors include practical implementation issues and difficulties with data interpretation. Delivering actionable insights in the growers' terminology can help overcome these barriers.

- Growers possess a strong understanding of what actions to take to improve crop growth, based on their assessments. Integrating this knowledge with sensor data can optimize cultivation practices.

- Finding a common understanding of the plant assessments made by growers using the terms "vegetative," "generative," "weak," and "strong" will be challenging, as noted in the research conducted by Priva. However, their study did have some limitations that I can address.

5 Define

5 Define

5.1 Defining the Design Direction

For the project, I want to collect the expertise of the grower, however, this is still a broad domain. This Paragraph presents three design directions that were considered and explains my choice.

5.1.1 Direction 1: Gather data on how growers monitor their crops

The first design direction focuses on creating a system that collects data on how the grower monitors the crop. They monitor the crop by looking at how vegetative/generative, strong/weak the plant is. Mainly these observations can be collected of the grower, to later on be correlated to the ultrasound sensor and make actionable insights out of it in their own language. This means first the data of the grower should be collected, validated on whether there is a truth on the data, and afterwards the data can be correlated to the ultrasound sensors to give the grower actionable insights in their own language.

5.1.2 Direction 2: Gather data on grower's steering methods and strategies

This design direction aims to gather knowledge on the methods and strategies that the grower uses in cultivation. As these methods and strategies are dependent on so many factors, collecting and combining all this data to unravel the grower's strategy is expected to be very complex.

Moreover, part of the steering methods and strategies may already be gathered by existing technologies. Climate computers can track soil and climate strategies, and software like Source.ag is able to track their pruning strategies.

5.1.3 Direction 3: Gather data through knowledge exchange

Knowledge exchange is very common amongst growers, however, due to the risk of spreading the ToBRFV virus, this is done most of all digitally. This design direction aims to make this digital knowledge exchange more accessible and efficient for growers, simultaneously, collecting data on their knowledge.

5.1.4 Choosing the Design Direction

Direction 1 was chosen, as this can be seen as one of the first steps in enhancing the data of plant sensors, such as the ultrasound sensors. After the plant sensor data has been made actionable for the grower, there could be bigger focus on how growers steer the crops (Direction 2), which can serve as input in giving the grower eventually advice in cultivation.

Direction 3 was not chosen as a primary focus, because gathering this data would give an overload on probably textual data, making it hard to process the data and give the grower actionable insights short-term.

5.2 Vision statement

This thesis explores the following main research question:

How can ultrasound plant sensor data provide actionable insights for the grower?

The research question can be combined with the chosen design direction, to come to a vision statement. This vision statement describes how the research question will be addressed:

"I aim to make ultrasound plant sensor data actionable, by integrating it with the grower's observations."

5.3 Design Parameters

To design a system that collects data on how the grower monitors the plant it must be considered that there is a tension between the amount of data collected and the usability of the system. If more data is collected, this means there is more information for Plense to validate the ultrasound data. However, this also means the grower must take more steps and time to fill in the data, which decreases the usability. Additionally, if there is too much data, it will take Plense a lot of time to process the data, which is also not desired.

The following guidelines on the data volume should be used for designing the system:

- Collect enough data to have valuable insights on the grower's subjective plant assessments.
- Collect a volume of data per plant assessment that is manageable for the grower and does not take too much effort and time to fill in the data. This must be manageable for the grower to fill in once a week, because this is also how often plant registration takes place.
- Do not collect so much data that it becomes hard for Plense to process.

Moreover, not only the volume of the data should be considered, but the grower should also be able to experience value from collecting the data. Of course, later when the data is able to be correlated to that of the ultrasound sensor and this can be done automatically, they will perceive value. However, first data should be collected, and it is desired to already give the grower value. So, the additional guideline for the design is:

- Give the grower value during the collection of data.

6 Ideation

6 Ideation

The ideation phase in the design process focuses on generating ideas for a broad variety of problems. To facilitate this generation of ideas, I used the How-To method from the Dutch Design Guide (Boeijen et al., 2013). This method formulates problem statements in the form of questions, guiding and facilitating the ideation process. These were the main questions used:

- How To collect data efficiently? (Appendix E)
- How To deliver value for the grower? (Appendix E)
- How To interact with data? (Appendix E)

These questions formed the basis for generating ideas to create a simple and intuitive experience for the grower.

6.1 How To Collect Data Efficiently?

Various methods are available for collecting subjective plant assessments, such as questionnaires, diaries, calendars, annotated photos, and voice memos. However, the data collection system must support long-term engagement since data is needed throughout the entire cultivation season. For this reason, an app was selected as the primary touchpoint within the data collection system. An app not only enhances user engagement but also allows for the incorporation of features, such as updated overviews of the entered data.

To further improve the efficiency of data collection in the future, it may be beneficial to integrate the data collection system with an existing software platform. This approach aligns with growers' preferences for a singular software solution. An example of such a platform could be Source.ag, which already has an established client base. By leveraging another platform, we can also tap into their existing user community.

6.2 How To Give Value?

To ensure the grower continues using the app, they must perceive value in it. This section explores ways to create value for the grower.

6.2.1 Knowledge sharing

Although design direction 3 was not chosen as a primary focus, some elements can still be incorporated into the system to enable and facilitate knowledge sharing. Ideas include allowing the system to generate reports based on subjective plant assessments, which growers can use in communication with cultivation advisors or other growers. Another idea is to enable growers to request feedback on their assessments from peers. This idea would not only deliver value for the grower, but also for the cultivation advisor.

6.2.2 Learning platform

The subjective plant assessments made by growers can serve as learning data for greenhouse workers, helping them become more adept at monitoring plants. One way to facilitate this is by including an informative section in the app on expert monitoring practices. This idea is expected to be valuable for primarily cultivation managers.

Additionally, the app can serve as a self-assessment tool for growers, allowing them to match their actions with subjective plant assessments to evaluate the effectiveness of their interventions. By comparing weekly prognosed values with real-time plant assessments, growers can also gain insights into their estimation skills regarding plant development.

6.2.3 Data overview

Growers currently receive data overviews based primarily on objective and measurable data through platforms such as LetsGrow, Source.ag, and BlueRadix. However, the subjective data, which has not been tracked before, can also provide valuable insights for growers. With this data, they can, for example, interpret climate data in a more contextualized manner. Recognizing that growers may find direct value in visualizing this information, the decision was made to further develop this concept in the app

6.3 How To Interact with Data?

This ideation phase focused which data types to collect, regarding the subjective plant assessments of growers, while also generating ideas for the app interface to ensure data is collected in the simplest and most intuitive way.

Guided by the How-To questions, inspiration was drawn from various applications and tools that facilitate data interactions. By incorporating familiar interactions, we anticipate that the overall user experience will be more intuitive.

The interactions are categorized in three categories: Onboarding, Data Entry, and Data Overview.

6.3.1 Onboarding Ideas

In Table 2 the ideas for the onboarding can be found.

Table 2: Onboarding Ideas

User Action	App Interaction
Fill in settings (in general)	Show progress bar
Indicate years of experience in cultivation	Show reflective statement
Indicate attitude towards technology	Show reflective statement
Select crop type	Visual components
Breed selection	List + search bar
Fill in optimal temperature and humidity	Give default and let grower adjust the values with arrows
Indicate the breeds natural behaviour	Drag-and-drop system on a matrix with generative/vegetative, strong/weak on it
Select user profile	Select between traditional, modern, experimenter, and cultivation manager
Seeding date	Calendar
Location of the greenhouse	Drag-and-drop dot on a map
Selecting crop location	Drag-and-drop a dot on layout of a greenhouse
Fill in notification preferences	Click on shift
Updating settings	Provide settings page/button
Make first tour through app	Give suggestion to already start first plant measurement after completing the settings, to lower the barrier the next time.

6.3.2 Data Entry Ideas

In Table 3 the ideas for the data entry can be found.

Table 3: Data Entry Ideas

User Action	App Interaction
Fill in general satisfaction score	Fill in with a smiley, colour, percentage, or grade
Fill in real-time growth status, desired, weekly prognosed status	Drag-and-drop all three dots onto a matrix with generative/vegetative, strong/weak on it
Review how other growers have made a plant assessment	Info button to give information to help making the plant assessment
Capture photo	Get real-time feedback via the app on how to aim the camera
Consult climate data	Provide climate data/more data on the context of the grower to make a good plant assessment
Submit data	Receive notification when data is submitted but not yet complete
Entering the same value of data frequently	Auto-fill functionality that fills in certain fields if it recognizes frequently used values
Fill in indicators used to make real-time growth assessment	Annotate photos with text or simply by placing a dot
Fill in a relative/absolute plant assessment, meaning at the relative assessment a data point is added in relation to older data. The absolute data assessment does not have this.	Grower can choose himself what is preferred, by clicking on different tabs for them.

6.3.3 Data Overview Ideas

In Table 4 the ideas for the data overview can be found.

Table 4: Data Overview Ideas

User Action	***App Interaction***
View data over a period	*Select the period/ select desired view (e.g. reports, graphs, visualisations, and more)/ select the specific plant*
View individual plant data	
Export data in desired format	*Provide options for PDF, WhatsApp, and more*
Look back at whether weekly prognosed growth status was correct	*Give celebrations when the estimation is close to the assessment*
See the amount of plants measured	*View this in a circle with progress bar*
Compare data of plants amongst each other	*See graphs of two plants in relation to each other*
Correct data when needed	*Show an edit icon to edit data*
View combined score of growth status and satisfaction score	*Show matrix for the growth status and represent each dot as a smiley*

6.3.4 Notifications and Reporting

For the notifications and reporting there were two ideas:

- Users are encouraged to collect data through notifications generated at the designated time for plant registration. This integration aims to seamlessly fit into the grower's workflow.
- Bi-Weekly Reports: Users receive bi-weekly reports that serve as conversation starters during study sessions with fellow growers or cultivation experts.

7 Conceptualisation

7 Conceptualisation

In the conceptualisation phase, typically the best ideas are selected from the ideation phase and combined to form a concept.

7.1 Notifications and Reporting System

In the conceptualization phase, we began by taking a broader view of the system, focusing on its notifications and reporting features. Key questions emerged: When should the user be notified to collect subjective plant assessments? And, when should the user receive a report with an overview of the data? Most importantly, these system features needed to be seamlessly integrated into the workflow of the grower.

To achieve this, we first created a broad timeline of the grower's main activities within the system. Next, we overlaid notifications onto this timeline, followed by the reporting schedule, making it easy to see how these elements could be integrated effectively. In Figure 20, you can see the resulting concept, which outlines when notifications and reports should be delivered within the grower's workflow. Further explanations on the notifications and reports will be given.

Weekly Motivational Notification
Growers will receive a weekly reminder to take their plant registration measurements and begin with collecting the subjective plant assessments. These measurements are entered alongside existing plant registration data, making the data entry process seamlessly integrated into the grower's routine.

Celebrative Notification
In the ideation phase, the idea arose that the grower could make a weekly estimation of the plant growth type. This gave me the idea to send the user a celebratory notification when they have guessed correctly, based on the new assessment for that week. This adds a fun and engaging element to the concept, but it is also educational, as the user will get feedback on how well they can make a weekly prognosis of the plant growth type.

Reporting
Users will also receive notifications when reports are ready. This helps motivate the grower to stay informed on plant growth development before discussing it with, for example, a cultivation advisor or other growers. Reports will be generated on a bi-weekly basis, ideally one day before the grower has study sessions with other growers. This way, the data from the app can also be used as a communication tool to facilitate these conversations. Additionally, reports can be generated at the end of each key growth stage, such

as during the vegetative and flowering phases, providing actionable insights specific to those stages of plant development.

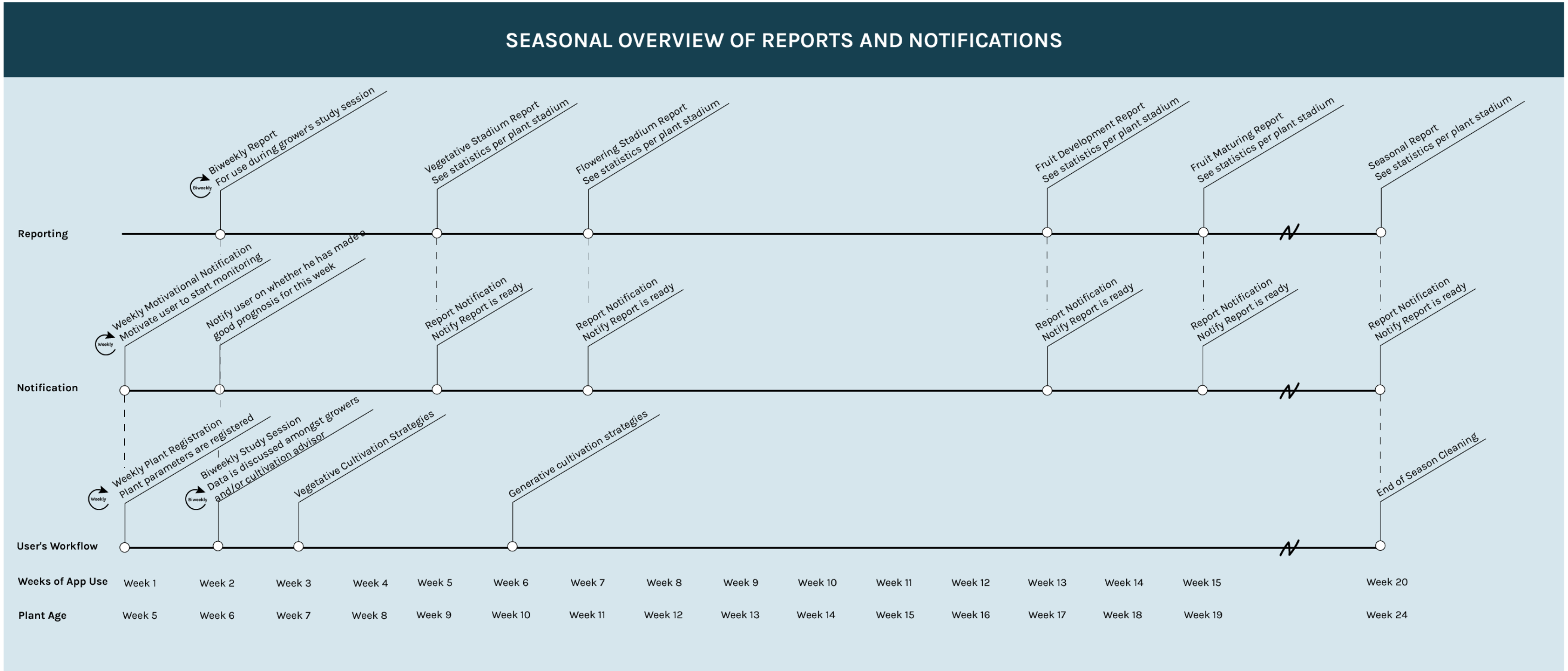


Figure 20: Notifications and reporting timeline

7.2 Onboarding Flow

Onboarding refers to the process where users fill in settings to get started with the app and use it effectively (e.g. setting preferences for notifications). These settings include information that only needs to be provided once but adds significant value to Plense. For instance, collecting data on the type of crop, breed, and seeding date is essential, as without this information, the subjective plant assessments cannot be accurately interpreted. Different breeds may behave very differently under the same conditions, and the age of the plant plays a crucial role in how it will respond to environmental factors.

In addition, other information, such as the grower's experience level and their attitude toward technology, is less critical for now but could become valuable later. This data might help Plense develop different user profiles in future versions of the app, enhancing the experience by offering tailored insights or suggestions based on the user's experience level or technological preferences.

To conceptualize the user flow of the onboarding process, a timeline of user actions was created (see Figure 21). In some cases, steps were removed because the data collected would not add enough value and would only increase the time it takes for the user to complete the process. In other cases, steps were added when it became clear that gathering certain information would improve the quality of the subjective plant assessments over time.

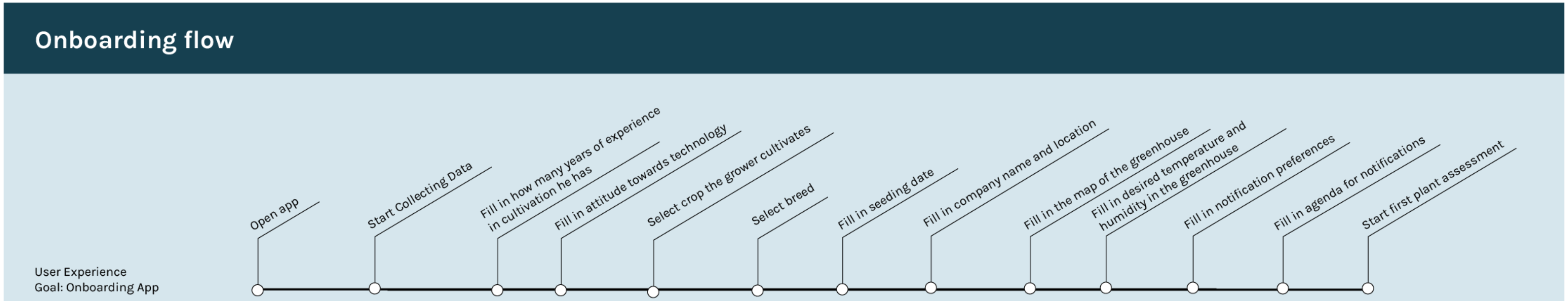


Figure 21: Onboarding timeline

7.3 Service Blueprint

A service blueprint is a valuable method for visualizing the entire system, particularly in how the grower collects subjective plant assessments. It serves to clarify the service process, enhance user experience, and guide development decisions. This blueprint focuses solely on the scenario of the grower filling in plant assessments, not on reviewing or analyzing data. This focus is intentional, as the primary goal of this project is to gather measurements from the grower.

The blueprint consists of five rows: physical evidence, customer actions, front-end interactions, back-end interactions, and support processes, arranged in chronological order. This structure helps identify potential pain points and streamline the assessment process. In Figure 22, you can see a visual representation of the service blueprint, which illustrates these components and their relationships.

7.3.1 Physical Evidence

The physical evidence in the service blueprint includes all the touchpoints the user encounters. In this case, the grower's main touchpoints for collecting measurements are the app, the plants, and the greenhouse.

7.3.2 Customer Actions

Customer actions involve the steps the user takes to collect data. The user must first install the app and complete the onboarding process (see Figure 21). Once the app is ready, the user can make an initial plant assessment with guidance, helping lower the barrier for subsequent assessments.

When the user is ready to collect measurements for their plant registration, they receive a notification prompting them to also start measuring the more subjective plant assessments via the app. They open the notification, select the current crop (which matches the plant registration), take a photo of the crop, and begin filling in the data. After submitting the data, they can continue with the next plant by choosing it from the list. The user sees a list of monitored plants and can select the next one to assess.

7.3.3 Front-End Interactions

The front-end interactions include in this case all the interactions with the interfaces of the app.

7.3.4 Back-End Interactions

Back-end interactions refer to processes that occur behind the scenes and are not visible to the user. These include in this case retrieving information from servers, such as notification preferences and lists of measured and unmeasured plants, as well as onboarding processes that verify whether the user is indeed a grower.

7.3.5 Support Processes

Support processes include all necessary actions to carry out the system. This encompasses hiring a UX designer to visualize the interfaces and requires personnel to validate and process submitted data.

Service blueprint- Assessing the plant

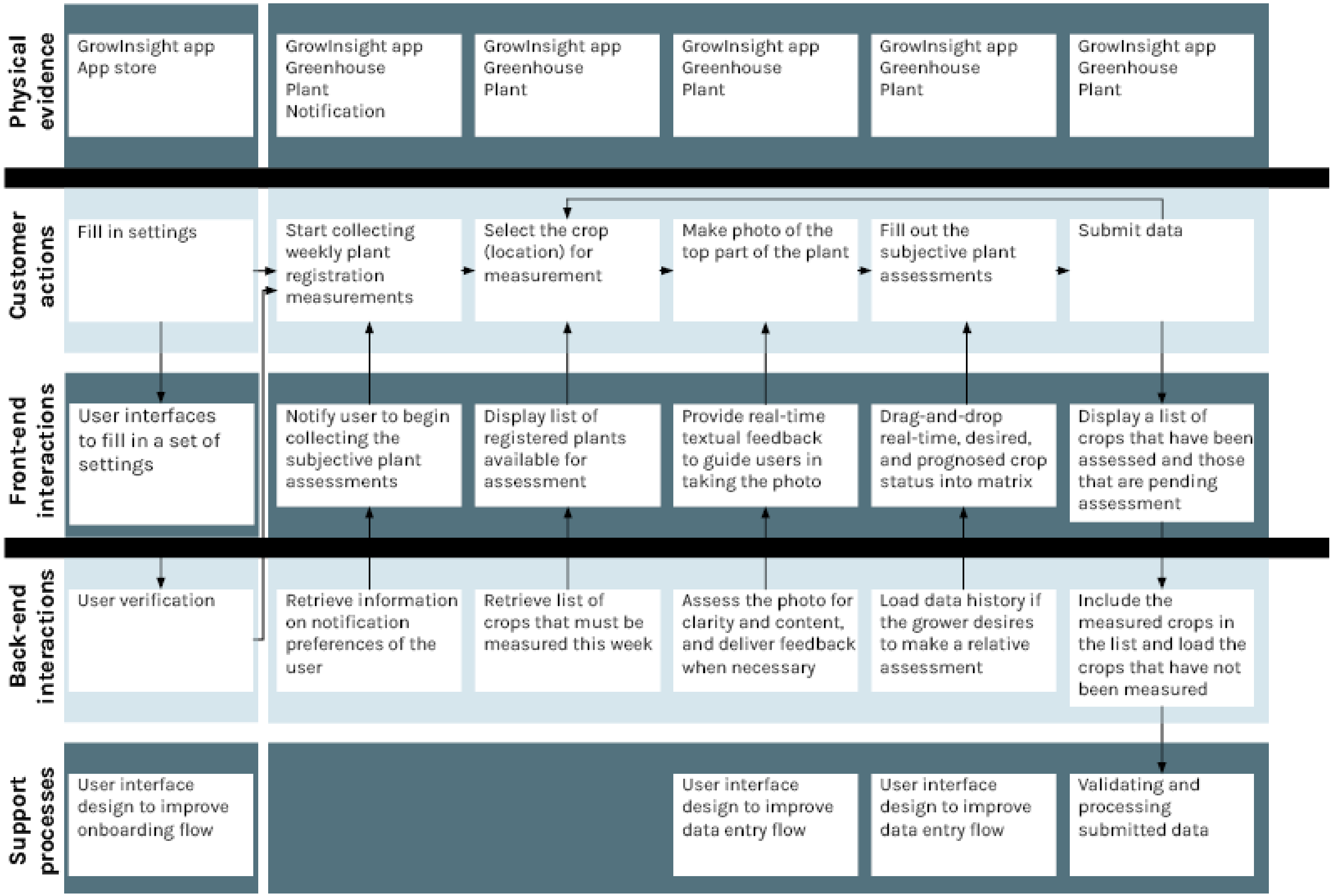


Figure 22: Service blueprint

7.3 Prototyping

Interaction Prototyping and Evaluation is a method by the Dutch Design Guide that is often used in the early conceptualisation phase (Boeijen et al., 2013). This method uses low-fidelity prototypes to test whether the interactions found were desired or not in discussion with the participant. For this project, this was done in three iterations, with three different participants.

7.3.1 Iteration 1

Setup

The first iteration of the app was tested with the target group: the grower (see Figure 23). This was an extensive session of approximately an hour, in which a test was carried out with a low-fidelity paper prototype. The session was video recorded.

Figure 23: Setup Iteration 1

Goal

The goal of the first iteration was to evaluate preferences on the following topics:

- A/B-Test on the design of the data entry. Prototype A included a data entry interface on which the grower could fill in the absolute data, so without being biased by earlier collected data. Prototype B included a prototype in which the grower could fill in the data in a relative way, meaning that the grower could add data in relation to older data.
- Interpretability and desirability of the way the data types are visualised in the overview of the data overview interface. This is important to already test, to know how actionable data for the grower in the future can look like.
- Desirability on the timing of the notifications and reporting of the system.

Results

In analysing the results all the insights on top of my head were included in the annotated prototype. At some parts in the research where I still had some gaps, I used the video to look up the information needed.

The results of the session were visualised in an annotated prototype for the two data entry prototypes and the data overview prototype. The constructive feedback of the grower is visualised in orange, the positive feedback in green, and the observations in blue. The feedback on the notifications and reporting was visualised on the timeline. See Appendix F for the prototypes.

Discussion

It should be considered that the prototype was made in English and that the grower had difficulties with this, which is why sometimes he did not understand the prototype, but this could be largely influenced by the language barrier. If there would be a next session with a Dutch grower, the prototype must be made in Dutch to prevent this.

Moreover, a small co-creation session was planned with the grower to come to a first schematic version of the report, however, the user was not used at all to get reports from an app and did not know at all what to do. When I mentioned this, I tried to give the user some ideas, but this also did not help, which is why I decided to keep this part out. More research will be done on how to assemble a report, taking inspiration from other apps.

Another limitation of the study includes that the test was carried out with only one person, however, for such an early stage user test and the fact that it was a highly qualitative session this is alright. The small sample size also has to do with the timing within the cultivation season. Growers are very busy these days and it has been a challenge to find growers who were able to participate in the user test. This is why the next iteration of the prototype will be tested on solely usability, with other participants than growers.

Take-aways:

<u>Data Entry A versus Data Entry B</u>

- The user preferred filling in absolute data rather than relative data because they wanted to make the plant assessment straightforward, without being influenced by other data. They had no issue providing assessments without reference data. This does not necessarily imply that the app should only offer the absolute version of data entry. It was chosen to give the app only at the part of the matrix the option to fill in absolute or relative data. For the other collected data types only, the absolute data was collected. In Figure 24 the two different data entry tabs can be found.

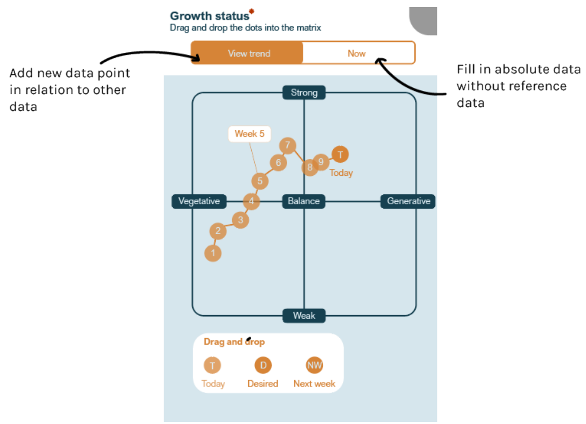


Figure 24: Two data entry tabs

Data Overview

- The grower expressed a preference for concrete numbers over visual representations (e.g., using smileys to present the general crop status). It is likely that other growers share this perspective, as they typically work with concrete numbers rather than visuals. Thus, the app design will prioritize presenting data in percentages, numbers, and graphs instead of relying heavily on visual formats.
- The grower did recognize the value of tracking their feelings towards the plants over time, suggesting it could serve as a useful self-assessment tool. To enhance this self-assessment aspect, the app could send notifications every two weeks to inform users whether their prognosed plant status was accurate. Additionally, a section in the data entry part could allow growers to select the steering strategy used, enabling them to review and evaluate how well their strategy performed.
- The user also expressed interest in individual crop data. If a plant is failing, they indicated it would be useful to access indoor climate data at that moment to understand the reasons behind the decline.
- The data overview page has been arranged in the same chronological order as the data collected during data entry. However, since not all data holds equal importance, a reorganization is needed to prioritize the most relevant information at the top of the page.

Notifications and Reporting Timeline

- The grower appreciates the integration of notifications into their current workflow regarding plant registration. However, he lacked experience with app reporting and was uncertain about what to expect in a report. Further research is needed to determine how the report itself should be structured, potentially by analyzing reports from other apps.

Other

- For the grower, it is important to see the development of the average plant rather than just focusing on the plants at the edge of the greenhouse. During plant registration, the average plants are always the same. For the design, it may be beneficial for the grower to specify the locations of the departments and rows for plant registration in the settings, allowing them to consistently monitor the same plants. This has implications for the data overview as well; rather than providing an overview of the average plant, the app should offer an overview of data for each individual plant.

- The grower is willing to measure the same 16 plants each week as part of the plant registration, although the time required for data entry will influence their decision.

7.3.2 Iteration 2

Setup

A new prototype was developed, incorporating insights from the first iteration. This session was tested with an IDE (Industrial Design Engineering) student, who has a strong sense of intuitive app flows and offers valuable feedback for improvements. The testing session was conducted via Zoom, utilizing a digital prototype developed with iteration 1 insights in mind. The session lasted approximately half an hour, during which we navigated through the whole app while I took notes (see Appendix).

The primary goal of this session was to identify any major flaws in the app and evaluate its intuitiveness. To achieve this, no context was provided to the student regarding the project, allowing us to focus purely on the user experience.

Take-aways

As this session was less extensive than iteration 1, only the most important take-aways will be discussed.

- After completing a plant assessment, the user expected feedback indicating which plant had been measured and a list of plants yet to be assessed. I plan to implement this feedback mechanism in the next prototype by providing a clear list of the measured plant and the unmeasured plants. Additionally, this causes the order of interactions to be adjusted: users will first select the plant during the data entry process before taking a photo of the crop. This change will also remove the need to select the plant again on the plant assessment interface, streamlining the user experience (see Figure 25).

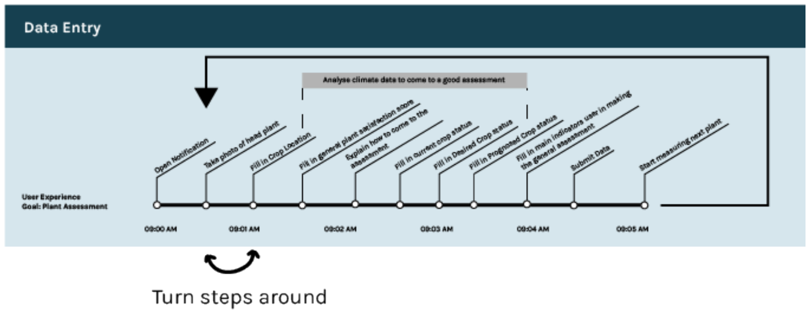


Figure 25: Streamlining the user experience by turning two interactions around

- The subjective plant assessment matrix lacked distinct colours for different data types, making it difficult to read (see Figure 26). This oversight will be corrected in the next iteration.

- The interactions, such as the drag-and-drop feature in the data entry matrix and clicking on dots to select indicators, were easily understood by the user. These features will remain unchanged.

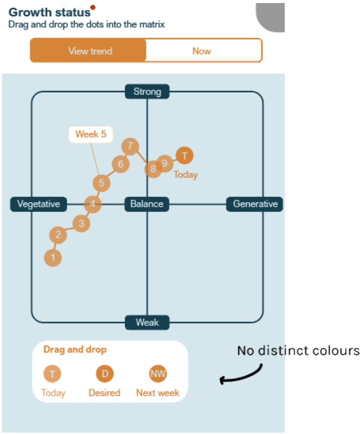


Figure 26: Matrix lacks distinct colours

7.3.3 Iteration 3

Setup

Also, for this session a new prototype was developed, incorporating insights from the second iteration. This session was done with an idea student in a session of half an hour. During the session we went through the app, and I made notes on the comments of the user (see Appendix F).

The goal of this test was like that of iteration 2.

Take-aways

- The grower may not be able to fill in the data on optimal settings at that moment. To address this, the data entry field will be made optional. Additionally, I might implement a notification message stating, “You haven’t filled in the data. Whenever you can, you can update it in the app settings.”
- The feedback button for user input was perceived as too prominent. In response, I have resized the feedback button to a smaller dimension and positioned it logically within each interface to enhance usability without being intrusive.
- The two tabs for absolute and relative assessments were understood by the participant. While she believed the relative assessment might be more accurate, she noted that the choice should ultimately depend on the grower’s preferences. I plan to maintain this flexibility in the next version.
- She noticed some differences in intonation during the session, prompting me to pay closer attention to alignment in future interactions to ensure consistency and clarity.
- The “plus” button in the menu was not clearly associated with collecting measurements. To improve clarity, I will resize this button to align with the other

menu buttons, ensuring it conveys a consistent meaning throughout the app.

7.4 Brand Identity

Plense Technologies is a start-up and has not yet delved into how they visually want to present themselves in terms of brand identity.

7.4.1 Values

However, the company does have three core values it wishes to convey to its stakeholders: reliability, excitement, and ambition. These values were identified by Paul, an intern at Plense Technologies who is pursuing an MSc in Strategic Product Design. He conducted research to determine how the company should present itself, what values to emphasize, and how these can be effectively communicated both visually and through messaging.

7.4.2 Visual identity

Colours

The colours used to present the brand identity include three main colours: light blue, dark blue, and orange. Light blue serves as the base color for the app, as dark blue was found to be too harsh and serious, which doesn't fit with the youthful vibe of a start-up. The blue tones convey a sense of

Figure 27: Brand identity of Plense

reliability. In contrast, orange is the colour representing ambition and excitement, chosen as an accent colour within the app.

Forms

For the forms, sleek and sharp shapes were chosen, as they look robust, which helps enhance the perception of reliability among growers.

See Figure 27 for a general impression of the look and feel of the brand identity for Plense. This is also going to be the basis for the design of the app.

7.4.3 Tone of voice

The tone of voice used in written communication reflects the message Plense Technologies wants to share with its stakeholders. This tone has been shaped by personal experience, input from colleagues, and social media analysis on LinkedIn. The aim is to convey professionalism while also expressing the excitement and enthusiasm typical of a start-up eager to make its mark; therefore, the overall tone will be more formal. This approach is expected to resonate with growers, who are practical and professional and may not respond well to an overly casual or humorous tone.

Moreover, there is room to incorporate metaphors and analogies in the written content. From personal experience, I've observed that growers often use such expressions in their verbal communication, which could enrich our messaging.

8 Final Concept

8 Final Concept: GrowInsight

In this chapter, the main touchpoint of the data collection system will be presented: the GrowInsight app (see Figure 28). First, the app's interfaces will be introduced, followed by a table detailing the data it collects.

8.1 Application

Figure 29 provides an overview of the app's main functionalities, which include Home, Overview, Messages, Plant Assessment, and Settings. The arrows indicate how these different features are connected to the Home screen. Each function will be discussed in more detail below.

8.1.1 Home

When the grower opens the app, they are welcomed by the Home page, which provides an overview of the most important information. During an interview with a cultivation manager, he emphasized that an app should offer a quick overview of the most critical data. Specifically, he mentioned it was essential to know which plants were struggling and needed attention. Based on this insight, I decided to include an overview of registered plants with a simple color-coded system: red indicates plants that need attention, orange shows those that have room for

Figure 28: Final concept: GrowInsight app

improvement, and blue represents plants that are doing well.

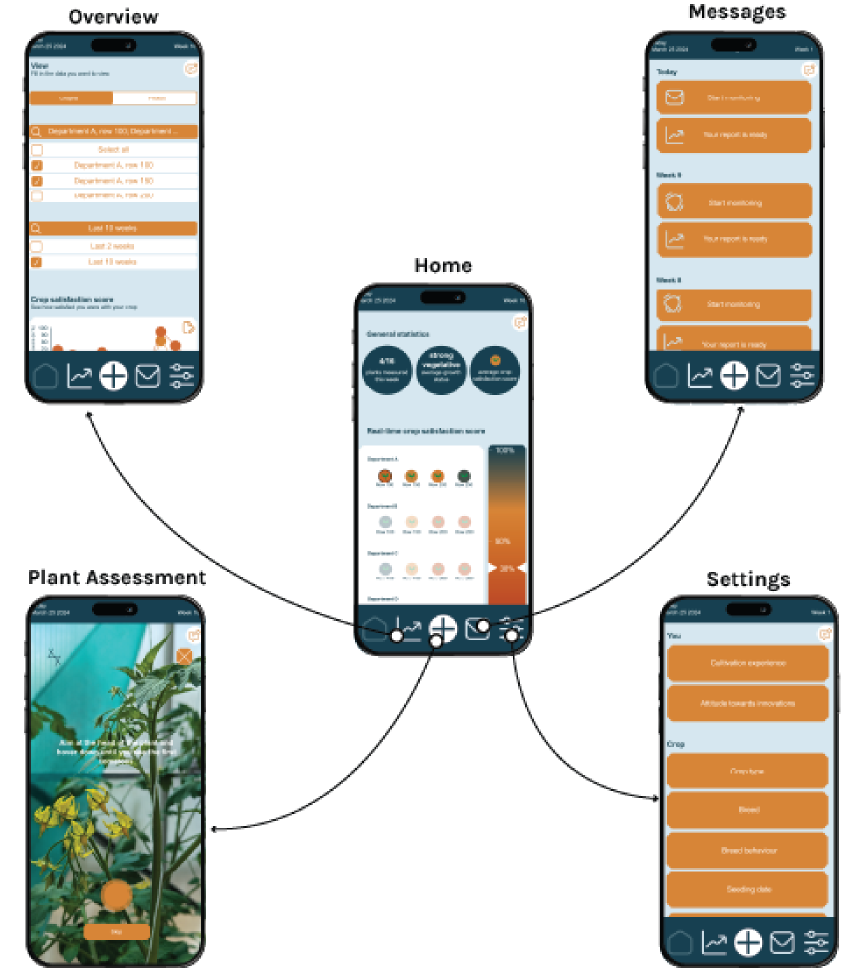


Figure 29: Overview main functionalities of the app

8.1.2 Settings

In the first interaction, the user fills in their settings during the onboarding process (see Figure 30). As onboarding can sometimes take time, a progress bar at the top provides the user with a sense of control. Required information is marked with a red star. If this information is not completed, the grower's subjective plant assessments will not be valid.

Settings may need to be updated after one cultivation season, for instance, the breed of plants may change from year to year due to ongoing improvements. This essential information can be updated via the Settings page (see Figure 29).

8.1.3 Messages

The Messages section serves as the central point for weekly notifications and bi-weekly reports. Notifications are sent weekly after the grower registers plants, allowing the new data to be seamlessly integrated into the app's existing flow.

This section also houses reports, which the grower can select and use during communication with, for example, their cultivation advisor or other growers. These meetings are typically bi-weekly. To better integrate the plant data collection system into the grower's workflow, the app asks the grower in the Settings to specify their notification preferences, including the timing of plant registrations and study sessions.

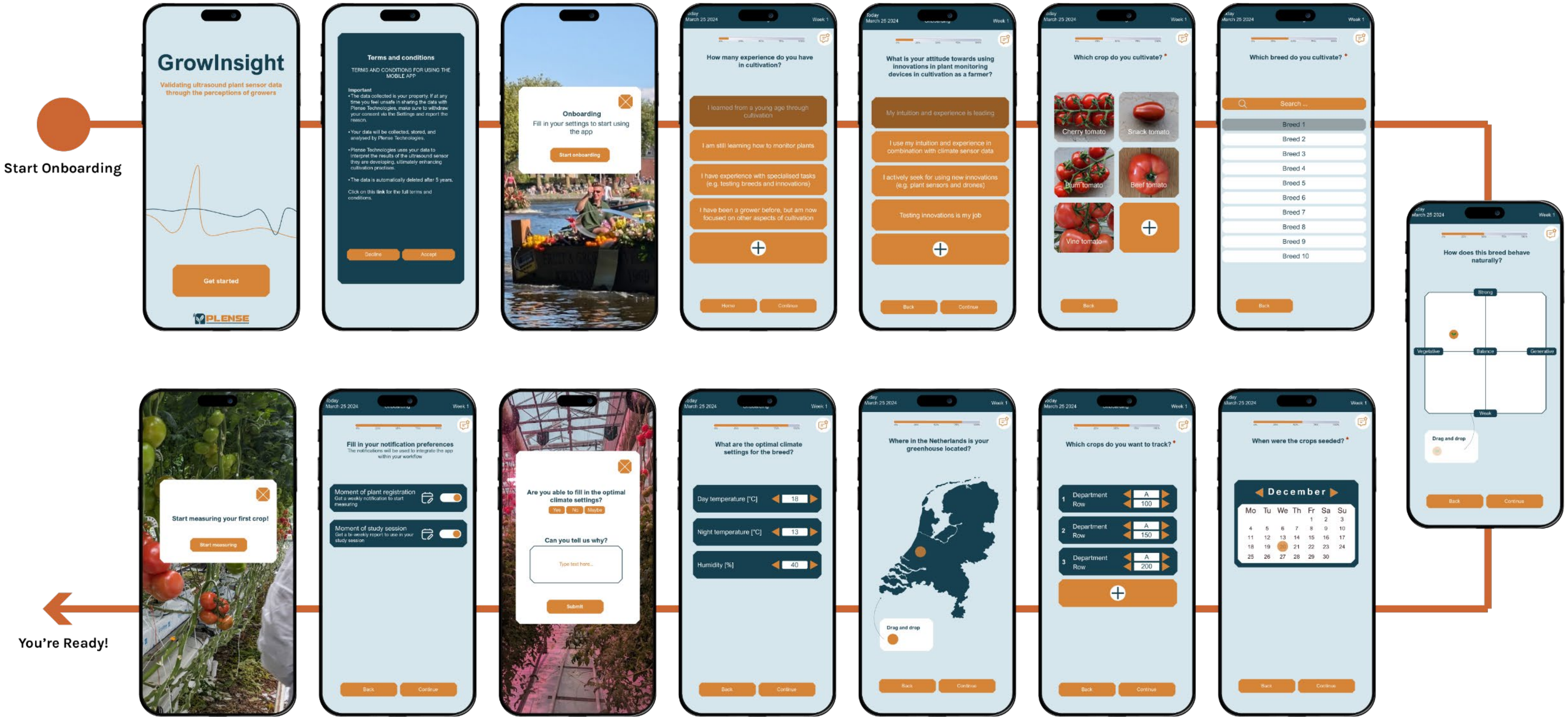


Figure 30: Onboarding process

8.1.4 Data Entry

Data entry is the most crucial section of the app, where the data collection takes place (see Figure 31).

Choose Crop

First, the grower selects the crop to be measured, allowing the measurement to be tied to a specific plant. The crop's location is identified by two parameters: the department (typically referred to by a letter) and the row number. This information ensures accurate tracking of the specific crop.

Photo

Next, the grower takes a photo of the crop. This image should include both the top of the plant and the latest set of flowers, trusses, or tomatoes. These parts of the plant are critical because they exhibit the most growth changes and provide key indicators of plant health.

Crop Satisfaction Score

The crop satisfaction score reflects how pleased the grower is with the plant's overall growth, expressed as a percentage. This format aligns with the user's preference for working with concrete numbers. The score is input using a simple slider.

Areas of Attention

In this section, a textbox allows the grower to note areas they want to improve, providing insights into their cultivation strategy. Labels in the text box enable the grower to quickly identify these focus areas.

Growth Types

The grower can plot growth types on a matrix using a drag-and-drop system. The horizontal axis represents a score for how vegetative or generative the plant is, while the vertical axis scores the crop's strength.

The grower can input both the current and desired growth types. According to research from Priva plants are typically expected to be generative and strong. However, a grower from the test in the first iteration of the iterative prototyping session disagreed, believing this isn't always ideal. If a grower consistently inputs the same values, the app will automatically set the dot in its place for future assessments, a feature called progressive default, enhancing the user experience.

Besides real-time and desired growth types, the grower can make weekly forecasts. For this, the weather forecast is crucial, so a future app version could potentially include it. There are two tabs for filling in growth types: "Today" and "View Trend." The "Today" tab presents an empty matrix for unbiased assessments, while "View Trend" displays previous trends and assessments, allowing for more accurate entries. The grower can choose which method to use. Over time, if statistics show one tab is used significantly more, the app could be adjusted to include only that option.

Growth Type Indicators
The top of the plant is where the key indicators for growth assessment are found. To better understand the rationale behind the grower's real-time assessment, the app allows them to click directly on predefined areas of the photo.

Choose Next Crop
After submitting their plant assessment, the grower is presented with a list of the completed assessments and the remaining crops yet to be assessed. It's expected that both plant registrations and subjective assessments will follow a weekly cycle. The next plant in line is automatically displayed at the top of the list.

8.1.4 Data Overview

The Data Overview section of the app offers valuable insights for the grower, whilst he is collecting data over a certain period (see Figure 32). This section is organized into three different levels, which are explained in more detail below.

Photos
The Data Overview section contains two main tabs: *Graphs* and *Photos*. In the *Photos* tab, the user can easily select a specific plant and compare its photos over time. By selecting the crop, the grower can use arrow keys to scroll through the weeks, allowing for a quick and simple comparison of images from different time periods.

Graphs
In the Graphs tab, the grower can find the most important data visualized in a user-friendly way. To maintain simplicity and clarity, this section is limited to displaying three types of data.

First, the grower selects the crops they want to view, followed by the time span they are interested in. Based on feedback from participant TG-1, who mentioned the need to look back approximately 10 weeks, this option is set as the default in the app.

The grower can view the crop satisfaction score in graph form, which is the preferred format. This feature allows them to compare selected crops and provides the option to edit any data point. For example, if the grower feels their original assessment was influenced by a bad mood, they can easily adjust it. Clicking on a data point reveals more detailed information related to that entry.

In addition to the crop satisfaction score, the grower can also view growth type data in a matrix format, identical to how the data was originally entered. The user can choose between real-time plant development values, desired values, and review their prognoses. The numbers in each data point represent the week the plant assessment was made, not the plant's age.

Finally, a combination of growth type and crop satisfaction score is presented in a comprehensive overview. The growth type is displayed based on its position on the axes, while the satisfaction score is indicated through colour coding.

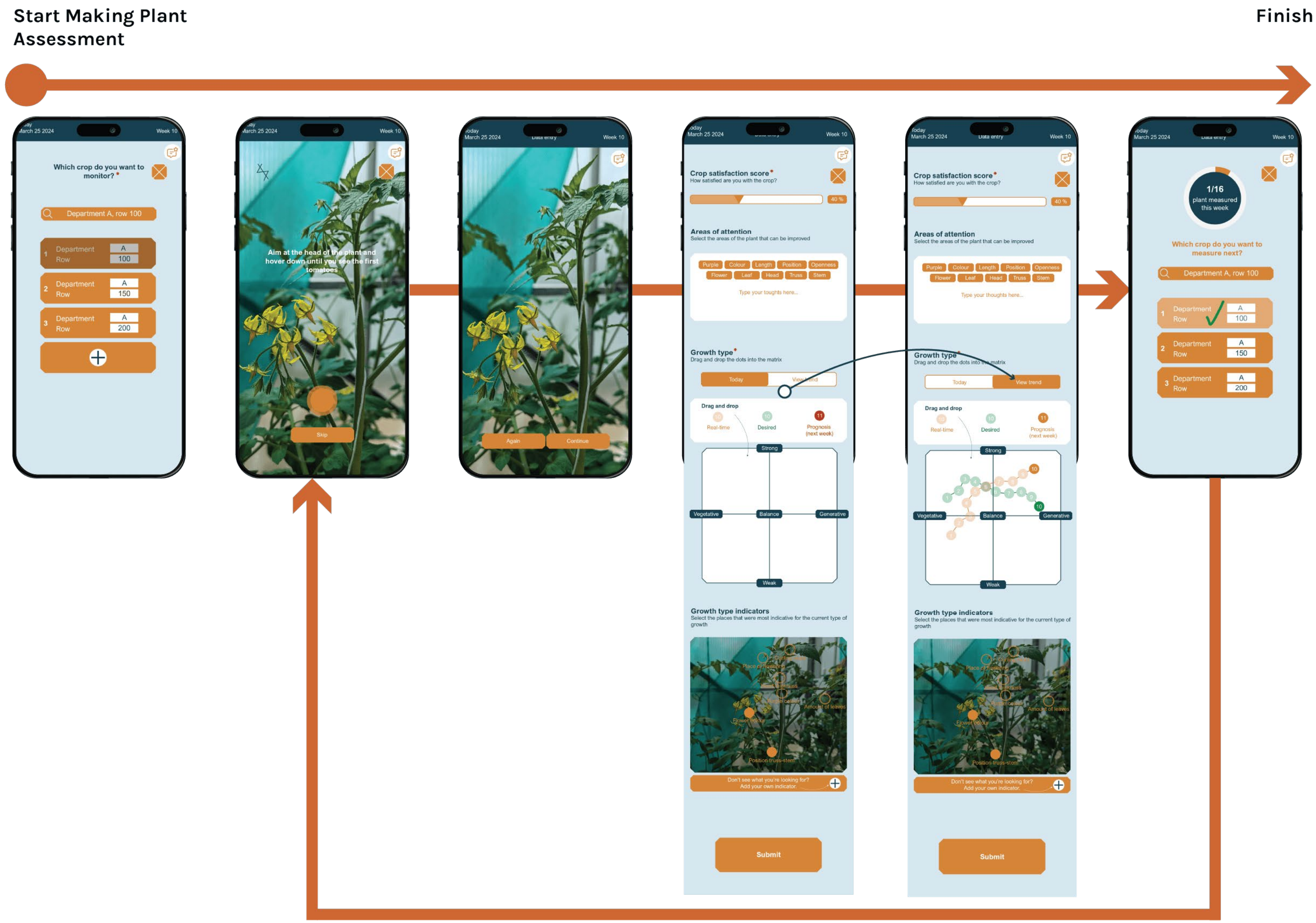


Figure 31: Making the plant assessment

Data Overview

Figure 32: Data overview

8.2 Data collection

This Paragraph contains all the collected data from the app: The grower's subjective plant assessments, the settings, but it also shows how the app can collect user feedback, which can be used to improve the app. Moreover, the ethical constraints will be explored of collecting the data of the GrowInsight app.

8.1.1 The grower's subjective plant assessments

In Appendix G a table can be found of all the data that will be collected via the Data Entry page of the GrowInsight app. It includes the data type with its description, the threshold values, the query frequency, the data volume, criticality to the system, and an exploration on what the value is of the data. From this data table the following is found:

- The photos require the most volume in the system. The other data types ask numbers, which does not have a significant volume.
- It is critical to have the general satisfaction score of the real-time growth type, because otherwise the data will still not be interpretable for Plense.
- For both the grower, as well as Plense, and the cultivation manager, the data collected will have value.

8.1.2 Settings

In Appendix G the data table of the collected settings can be found. The same aspects of the data are discussed as the grower's subjective plant assessments.

The following can be concluded from the table:

- Location, breed, and timestamp are most critical to the system. If this data is not collected and can not be paired to that of the subjective assessments, then the data can not be interpreted.

8.1.3 User Feedback

During the early stages of app development, growers may experience various issues when interacting with the app. This section outlines the feedback mechanisms that will be integrated to collect user feedback efficiently. The following design parameters were used in making the design decisions:

- There should be a balance between collecting a broad range of feedback without overwhelming Plense with too much diverse data, which could complicate analysis.
- Providing feedback should not be time-consuming or frustrating for the growers.

Application analytics software

Using application analytics software, such as Google Analytics, Mixpanel, or Mouseflow, will allow us to track key usage metrics. This software can monitor various aspects, including page views, the number of clicks required to complete a task, or the click rates of specific buttons. These insights help identify usability issues without requiring extra effort from the user.

For example, one important metric is the number of clicks on the "continue" button when a user is asked about their experience in cultivation (see Figure 33). This button is presented for non-mandatory fields, except for crop type and breed, which are essential for interpreting the grower's perceptions. If users frequently skip these fields by clicking "continue," it could indicate several issues:

- The data requested may be perceived as too sensitive.
- The user may be unsure how to complete the required fields.

By analysing the click data, for in this case some of the settings, we can identify potential pain points in the

Figure 33: Continue button

user experience. These insights can then serve as starting points for personal discussions with the growers, ensuring a more user-centric approach to resolving issues.

Other click data that is interesting for Plense that can be tracked with the software include:

- Feedback is wanted on the preferred view of the user to make the crop assessment. The user can make an assessment, based on earlier filled in data points, but the user can also make the assessment without. Having an answer to this question is important to Plense, as eliminating one of the view types will also decrease the amount of time needed for the analysis and most of all gives more focus on the interpretation of the data. In analysing the preference of this view type it is suggested that the default of the view is randomised.
- The time it takes users on average to complete one plant assessment (thus to achieve a certain task). If this takes too long, it should be explored where in the app the user stagnates, and take further steps to improve these pain points.
- In the data overview section, there are two tabs to view the data: data overview and data point. If one tab has significantly lower views than the other, it may be considered to take this view out of the app, to further simplify it.

Central feedback component

A central feedback button will be available as a fixed component on the screen of the app to gather any unforeseen issues at any point in the app. At first, I had ideas to only integrate feedback components on specific pages of the app and about very specific topics, such as asking the user what types of data he desired to make a proper plant assessment, however doing this would limit the app's ability to gather broad feedback (e.g. usability issues or potential ethical concerns). To address this, the support button has been made central and fixed (for at least the first year of deploying the app). In Figure 34 the feedback button can be found, with the page the user gets to see after

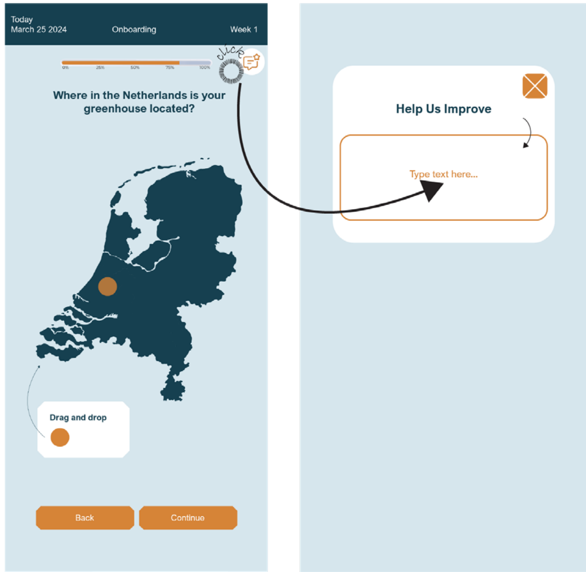


Figure 34: Central feedback component

clicking on the button.

Qualitative feedback messages
To enhance the more quantitative feedback with qualitative feedback, it was chosen to send feedback messages to the user at certain points within the use flow that have important interactions, with a question that refers to the topic relevant at that point in the user flow. This can include for example the moment at which the grower submits his assessment, asking the user how to rate the experience of filling in the data entry and why this is the case.

Other important points in the app to ask for more qualitative feedback include:

- Matrix
- Views

As it is not meant to overwhelm the user with messages, it is chosen to give the user a maximum of three feedback messages per four weeks. The feedback question they eventually get will always differ from before, and also be very random amongst the users. With four messages per month the user will receive three weeks one message and one week nothing. If the user often clicks away the messages after a while, it may be chosen to give the user less feedback messages.

Feedback conversations
Gathering solely feedback on the use of the app, via the app, would feel very impersonal. This is why Plense Technologies should keep on talking to growers. In these conversations they should get a deeper understanding on why the user uses the app in a certain way, and where there is room for improvement.

8.1.4 Ethical constraints

It is important to recognize the ethical implications of a system before launching it, although not all implications can be foreseen. The concept will be evaluated against the five principles of data ethics outlined by Cote & Harvard Business School (2021). These principles include ownership, transparency, privacy, intention, and outcomes. Additionally, suggestions will be provided to help mitigate potential ethical challenges.

Ownership
The grower is the owner of the data and determines whether the data may be used by Plense Technologies. The grower should always give consent, before any data can be collected. This can be done by sending a message with the terms and conditions of the agreement (see Figure 34) for

an example). Also, whenever the grower feels unsafe of what is done with the data by Plense, he should always be able to withdraw his consent. Changing this can be done in a privacy section within the settings. If the settings are changed the user gets asked to report why he does not want to give consent anymore. Every time when the app is updated, with for example new pieces of data that will be collected, the user should again agree to the new terms and conditions of the system.

Transparency

It should be clear to the grower that the data of the grower will only be used by Plense Technologies, and also the purpose of the data usage should be clear for the grower, so they know what they are agreeing to. For the app this means the data is collected, stored, and analysed by Plense. This has to be clearly communicated in the terms and conditions of the agreement (see example Figure 35). As terms and conditions are often very long and difficult to understand, it is advised to give a short notice of this in bullet points in the app, and the extensive version into a link. This is more transparent than hiding information on what is done with the data in a very long document.

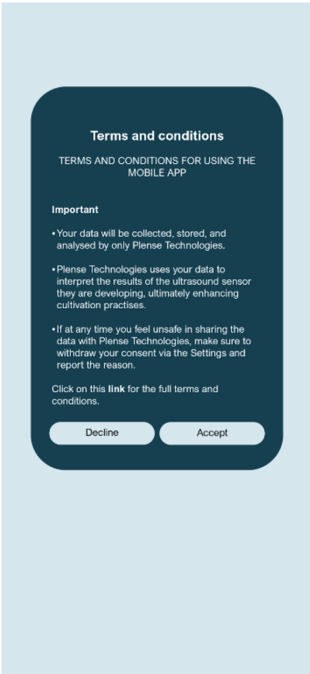


Figure 35: Terms and conditions

Privacy

All the data collected through the app can be related to one individual, if the data from the settings and the perceptions is combined. As this is not desired, the data that is filled in by the user in the settings (such as company location, attitude towards technology, and experience in cultivation), will be stored in a separate secured database, so they can not be linked to each other.

Plense can only be held responsible for securing the data they get from the system, they can not be held responsible for any negative consequences that might occur when growers share their own data with other growers.

Intention

The intention of Plense is to collect the growers' perceptions to eventually improve agricultural practices. This is completely ethical. Not only the overarching intention of the app should have an ethical intention, but also the collected separate data pieces on their own. The data personal data pieces should give a minimum viable amount of data. An example of how this is done in the app is in the settings, where the user is asked to fill in the location of the greenhouse. The minimal viable amount of data is that we have an indication of where in the Netherlands the greenhouse is, so that whenever it is needed Plense can look more specifically at the weather data of that area in the Netherlands. Initially, I asked in the app for the name of the company and the exact location, however I already felt that this was too sensitive information.

Outcome

The following negative outcomes are foreseen:

- In large greenhouses there are often multiple growers. If multiple growers use this same system, they will see between them how they assessed the crops. There are privacy issues with this, as it is reasonable that a grower does not want to be checked by another grower, which would feel for the grower as if the other grower may question his experience.
- If cultivation managers would log into the system, and the system will be used by multiple growers of the company, it would enable him to compare the expertise of the growers amongst each other and more easily pick out the grower who monitors the crop very differently than the others or average perception. The system will then be used for a whole other intention than it was supposed to. If growers experience difficulty with this, they should be able to report how their data is misused by the cultivation managers, after which Plense could search for fitting solutions.

9 The Future of GrowInsight

9 The Future of GrowInsight

The subjective assessments made by growers will introduce a new data stream alongside existing climate, soil, and plant physiological data. While these traditional data sources are objective and measurable, the subjective assessments, combined with grower expertise, represent a novel and valuable input. This new stream can be correlated not only with data from the plant sensors but also with other relevant sensor data, offering deeper insights into plant health and growth.

This Chapter aims to explore how the data of the growers can be integrated into the vision of Plense and with other data types, to eventually be able to give the grower first actionable insights and then advice.

9.1 Roadmap

In the roadmap is shown how the GrowInsight app will contribute to achieving Plense's Vision, but most importantly the steps that must be taken to achieve this will be added. This is done by using the method of Simonse (2024).

A design roadmap can be fully adjusted to the needs of a company, in this case Plense Technologies. It is therefore also meant mostly for Plense to use this roadmap in the communication with for example colleagues to talk about where the company is going and which phases they should go through to achieve what they are aiming for. One common thing about roadmaps are the horizons at the top. There are three, and they can be seen as essential phases to achieve the vision. These horizons will be explained in more detail below.

9.1.1 Horizon 1: Data Collection

The first horizon is where we currently stand. With the ongoing labour shortage and the declining number of skilled growers, there is a significant risk of not having enough food in the future. Plant sensors can play a crucial role in addressing this challenge. By taking over some of the monitoring tasks traditionally performed by growers, sensors can help reduce the demand for labor and free up growers' time to focus on scaling up food production.

Although plant monitoring techniques are still relatively new, they hold the potential to provide growers with actionable insights. However, before that can happen, the data from these sensors must be made interpretable for the grower. One way to achieve this is by translating the sensor data into familiar terms such as vegetative, generative, weak, or strong growth. These are concepts that growers understand and can act upon. To reach this point, where the signal from an ultrasound sensor can be linked to terms or to the data collected through the GrowInsight app, a significant amount of subjective data must first be gathered from the growers, who will assess plants in their own language. This is the primary focus of the first horizon.

The GrowInsight app is being developed to collect this data, aiming to capture the expertise of growers, which is becoming increasingly scarce. This data must be gathered and validated to identify common patterns or truths in the growers' assessments. For example, feedback from growers can be cross-checked with sensor data to ensure consistency and reliability in their subjective assessments.

Meanwhile, the app will provide growers with an overview of their own subjective assessments, functioning as a sort of logbook. This adds value for the grower while collecting the data, as it can facilitate discussions with other growers or cultivation advisors. The app also serves as a self-assessment tool or a way for cultivation managers to identify areas where additional training might be beneficial.

To make data collection more efficient, collaboration with an existing software platform, like LetsGrow, is suggested. This would not only help reach a larger client base but also make it easier for growers, allowing them to collect and view the data through a platform they are already familiar with.

9.1.2 Horizon 2: Actionable Insights

In the second horizon, the data from the ultrasound sensor has been validated and correlated with the data provided by the growers. At this stage, the grower will receive actionable insights from the ultrasound sensor in terms they understand, such as vegetative, generative, weak, or strong growth. For example, a grower might receive a message like:

“Your plant is too vegetatively strong for this time of the year.”

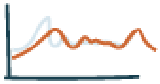
9.1.3 Horizon 3: Advice

In the third and final horizon, data from the ultrasound sensor will be integrated with various data types, such as climate, soil, labour, and energy data, to provide more precise advice to growers. By combining these diverse data streams, the app can offer tailored recommendations. For instance, a grower might receive advice such as:

“Your temperature during the day can be lowered to 20 degrees Celsius.”

PLENSE

TACTICAL ROADMAP

		HORIZON 1 2024-2025	HORIZON 2 2025-2026	HORIZON 3 2026-2027
MARKET	Trends	Emerging plant sensors Diminishing amount of growers and expertise Labour shortage		
MARKET	Customer insights	Growers cannot use plant data yet, as the outcomes are not easily interpretable Growers describe plant health and growth in terms of vegetative, generative, weak, and strong growth	Growers want sensors that classify plant growth as vegetative, generative, weak, or strong growth to guide cultivation decisions Growers want one software platform, instead of multiple that all present different data	Autonomous plant monitoring and greenhouse technologies would reduce labor costs, give growers more spare time, and enable business scaling, all while maintaining high yields
ULTRASOUND TECHNOLOGY	Plense's goal	Ultrasound data validation&early interpretation	Generate actionable insights	Give growers cultivation advise
ULTRASOUND TECHNOLOGY	Main touchpoints grower	Plensor GrowInsight app Other plant monitoring technologies Climate sensors	Plensor GrowInsight is integrated into one central software platform to collect and present actionable data Climate sensors	Plensor Give growers advice via central software platform Climate sensors
ULTRASOUND TECHNOLOGY	Data development	Data collection Data validation Early Plensor interpretation	Data analysis Data visualisation	Combine and interpret plant data with e.g. labour, irrigation, and energy data to formulate advice
ULTRASOUND TECHNOLOGY	Data output example		*"Your plant is too vegetatively strong for this time of the year."*	*"Your temperature during the day can be lowered to 20 degrees, this will save you X joule energy."*
GROWINSIGHT APP	Data development	Collect the grower's subjective assessments Correlate data with Plensor data Collect user feedback	Give actionable insights in the language of the grower Improve user experience accordingly	Give advice based on interpreted data Personalized user experience
GROWINSIGHT APP	Value tensions	Knowledge vs privacy	Expectations vs feasability	Advice vs expertise
GROWINSIGHT APP	Value grower	Assess own plant assessments over time Facilitate communication with other growers and/ or the cultivation advisor	Receive actionable insights while maintaining the freedom to cultivate according to grower's own strategy	Increased efficiency in decision-making, gives growers more time for other tasks Precision farming: increase yield, decrease resources
GROWINSIGHT APP	Value cultivation manager	Gain insights in personal performance of growers and use this to see who needs education	Ability to educate workers and young growers how to monitor the plant	Ability to scale up business due to more expertised workers
RESOURCES	Possible partners	Companies of other plant monitoring technologies to collect ground-truth data Collaborate with existing software platform company to collect data for GrowInsight app		Collaborate with software platform company to integrate all the data and give advice
RESOURCES	Team development	Data scientist	UX Designer Plant physiologist	Consultant

Empower the grower to get his plants in top form

Laura Drost

ultrasound sensor.

9.2 Context diagram

In this section, the future scenario of how Plense can ultimately give advice to the grower will be explored. For this, they will hypothetically need to work together with a software platform like that of LetsGrow, and integrate the GrowInsight app within the system of LetsGrow. A collaboration would provide Plense with the other necessary data types, such as soil, climate, and other plant sensor data, to be able to formulate advice based on their

9.2.1 Process

The process is the inner circle in the model, which stands for the data collection system, that should collect data and give back data to the growers, but also Plense in this case. In this case the GrowInsight app will be integrated within the platform of LetsGrow.

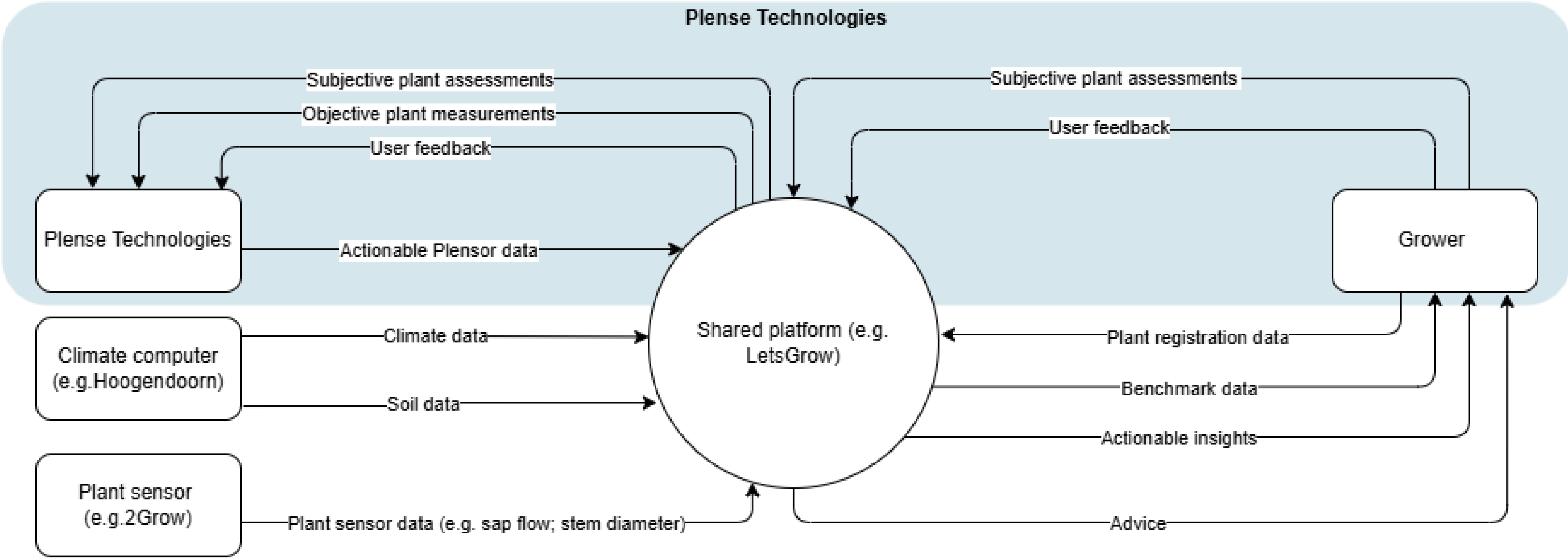


Figure 36: Context diagram

9.2.2 External entities

The external entities surround the process are the rounded rectangles. The ones shown are Plense Technologies, the climate computer, plant sensors, and the grower. The external entities are the ones in the diagram that can collect or send data. The arrows in the diagram show the data flows. The external entities will be discussed further below.

Plense Technologies
Through the platform, Plense will receive the subjective plant assessments collected from growers. These assessments are crucial for correlating the ultrasound data. To provide actionable insights, Plense will also require objective measurements, including climate data, soil data, and plant physiological data. By processing this comprehensive data set, along with user feedback from the LetsGrow data collection system, Plense can deliver meaningful plant sensor data back to the growers.

Grower
The grower is responsible for collecting subjective plant assessments and providing feedback on the data collection system. Additionally, they supply plant registration data, which is often done manually. Through the platform, growers will access actionable data, benchmark data (allowing comparisons with other greenhouses), and tailored advice.

Climate Computer
The climate computer contributes climate and soil data to the process, which includes information on irrigation and nutrient levels.

Plant Sensor
In addition to the ultrasound sensor, various plant sensors will provide data to the process. Like Plense, these plant sensor companies can also benefit from receiving climate, soil, and plant physiological data from the shared platform, allowing them to make their data actionable and contribute insights back to the system.

9.2.3 Associated Challenges

While it is generally acknowledged that a shared platform and database for plant sensor data hold significant potential, implementing such a system is more challenging than it may seem. Insights from a Senior Business Developer in the AgriTech sector (see Appendix S for details) highlight the following key points:

Business Case Complexity
Finding a viable business case that satisfies all

stakeholders is a significant challenge. Different stakeholders bring various values and priorities to the table, complicating profit-sharing agreements. Additionally, when a new business seeks to join the partnership, it must negotiate terms and conditions with all existing partners, further complicating the process.

Uncertainty in the Purpose
There is uncertainty regarding how to effectively use the various types of data within the integration hub. Determining the most valuable applications for diverse data streams remains an open question.

Lack of Standardization
For different types of data to correlate with each other and identify additional applications, it is crucial to establish a standard. Each data point must include a timestamp and location. The timestamp is essential for tracking how data changes throughout the season, while the location of the plant within the greenhouse is vital since plants behave differently at the edges compared to the center due to varying climate conditions. By incorporating these two values, it becomes easier to draw meaningful conclusions about plant data, climate data, and plant registration data.

9.3 Data Flow Diagram (level 1)

The diagram in Figure 37 focuses on illustrating how Plense Technologies processes all incoming data to generate actionable Plensor data for the grower, via the shared platform. Plense's processes can be found within the light blue rectangle.

9.3.1 Incoming Data

Incoming data
The incoming data for Plense include the following:

- The subjective plant assessments of the grower come via the shared platform.
- The objective plant assessments, including for example soil and climate data, also comes via the shared platform.
- The user feedback on the data collection system of Plense also comes via the shared platform.
- Data from the Plensor.
- Data from other sensors that Plense is testing, such as the thermographic camera, and the stem diameter sensor.

Data processing and Output

The incoming data will go to the datastore of Plense and from there further processed. The processes can be found in the circles.

First, Plense will validate all the incoming data, then they will try to combine and interpret the different data types (data analysis), report the data, and visualize it. After it has been visualised it will be ready to go back again to the shared platform, where the grower can find the data and use it in his cultivation practises.

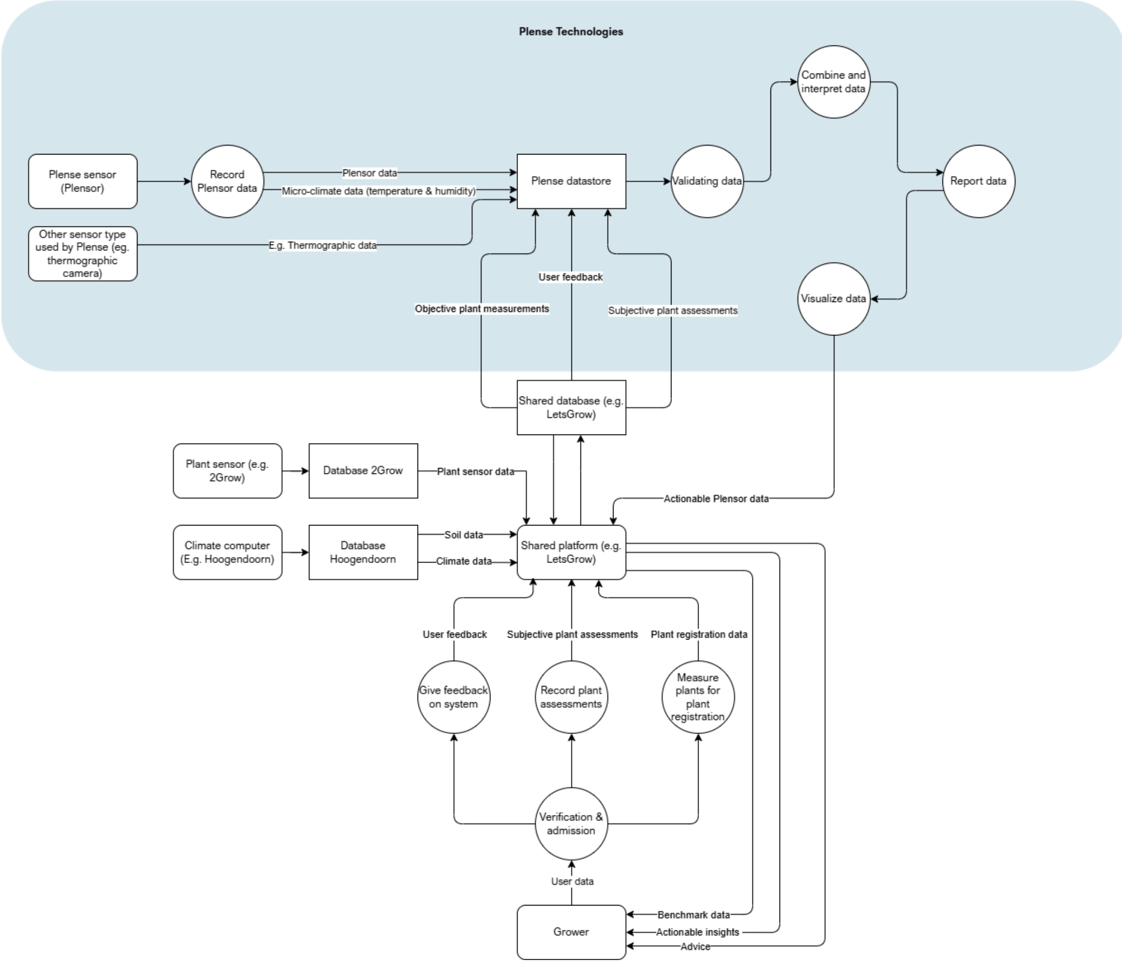


Figure 37: Data flow diagram (level 1)

9.4 Criteria for Data Correlation

To be able to eventually correlate the subjective plant assessments of the grower with the Plensor data, there are several criteria to take into consideration.

9.4.1 Frequency

Ultrasound sensor

Data is collected every 5 minutes, generating about 500 KB per measurement. Over a cultivation season of 20 weeks with 10 sensors, this gives roughly 192 GB of data. Plant processes can vary hourly, justifying the need for such frequent measurements.

Grower's assessment

The plant changes that the grower observes are much slower and given the fact that it is impractical to ask the grower every 5 minutes for an assessment, a weekly assessment per plant is sufficient.

9.4.2 Volume

- To reduce bias multiple growers should make the plant assessment, although the exact amount of grower to do this is uncertain.
- Fewer ultrasound sensors are needed to come to a reliable signal compared to the grower's assessments.
- The number of plants to be assessed is the same as the amount of sensors.

9.4.3 Accuracy

- Accurate timestamps are required for both the ultrasound sensor data and the grower's assessments. Grower assessments should be conducted weekly, ideally at a consistent time.
- Moreover, it is best if the ultrasound sensor and the plant assessments are made in a commercial greenhouse, and not in a testing environment, because the plants in the testing environment perform less than the plants in the commercial greenhouse due to the extra movements. These movements are for example caused by more frequent riding through the plant paths with an aerial working platform.
- Data collected from both the ultrasound sensor and grower assessments should be linked to specific plants, including their location within the

greenhouse. This linkage ensures that analyses and insights are relevant to individual plant behaviour, enhancing the validity of the correlations drawn between subjective assessments and sensor data.

- Different growers may cultivate various breeds of plants, which can react very differently under the same environmental conditions. Therefore, it is crucial to record the breed of each plant. Without this information, the plant data becomes difficult to interpret, potentially leading to inaccurate conclusions.

10 Conclusion

10 Conclusion

To conclude this thesis, I will first answer the main research question, followed by an evaluation of the concept's desirability for the user, the viability of the data collection system, and the feasibility of the system. I will also provide recommendations for further improvements to the concept.

10.1 Answer

The main research question of this thesis is:

How can ultrasound plant sensor data provide actionable insights for the grower?

My answer is that ultrasound plant sensor data can be correlated with the insights from growers to provide actionable and interpretable information in terms like vegetative, generative, strong, or weak growth. However, before this is possible, the insights from growers need to be systematically collected, which can be done through the GrowInsight app.

Once enough data is collected and there is a common truth seen in the growers' insights, these insights can then be linked to the ultrasound sensor data. Ultimately, the sensor should be able to determine automatically whether the plant is growing vegetative, generative, strong, or weak, providing clear and useful feedback to the grower.

10.2 Desirability

The GrowInsight app is designed to collect data and transform it into first actionable plant insights, aligning with the growers' needs and preferences.

10.2.1 GrowInsight App

The growers I've spoken with find the idea of combining their expertise with plant data very appealing. By doing this, the data gets a more human touch, ensuring that the grower's knowledge isn't lost in the shift toward more data-driven cultivation.

When it comes to collecting the data, growers don't mind doing it themselves. Essentially, they see it as creating a logbook of their own subjective plant assessments, which they can easily access later through the app. However, they expect the app to collect data quickly and efficiently to avoid spending too much time on it.

For growers, the ability to collect subjective data and compare it with the strategies they implement allows for self-assessment. This feature would make the app particularly useful for younger growers, who are still learning the nuances of greenhouse management, turning GrowInsight into a valuable learning tool as well as a practical resource.

10.2.2 Actionable Data

Once the subjective data can be linked to sensor data, like from an ultrasound sensor, and offers insights such as whether growth is generative, vegetative, strong, or weak, growers find this very useful. These are terms they already use daily to describe plant health. When they see this kind of data, they know exactly how to adjust the conditions in the greenhouse to get plants back into top shape.

In this way, the GrowInsight app can help automate some of the plant monitoring tasks, freeing up time for growers to handle other aspects of their business, take time off, or focus on expansion. This makes the app desirable as it helps them be more efficient.

10.2.3 Advice

The next step would be to transform this actionable data into practical advice. While this may be a long-term goal, achieving it could significantly reduce the burden of decision-making for growers. The advice generated could streamline complex choices around sustainability regulations, energy costs, and labor hours, ultimately making it easier for growers to concentrate on broader strategies and business growth.

10.2 Viability

The GrowInsight app isn't intended to be a long-term solution. Ideally, growers won't need to collect subjective plant assessments forever. I hope that, soon, as more growers share their data, we can establish a common understanding. This would allow us to effectively correlate that data with ultrasound sensor readings. Ultimately, the goal is to automate the process so that manual data collection becomes unnecessary. When that happens, the sensors will be able to give growers real-time updates on plant health, freeing them up to focus on other important areas in cultivation.

10.3 Feasibility

10.3.1 GrowInsight App

Regarding the feasibility of the concept, it is feasible to make an app that collects the subjective plant assessments of growers. The only unknown is whether there would be a common truth in the assessments made by the grower, but that it something that we can not tell yet, until there has already been data collected.

10.3.2 Actionable Insights & advice

The feasibility of using the collected data to correlate with the ultrasound sensor and provide growers with actionable insights remains uncertain. It's still unclear whether the ultrasound sensor will effectively measure relevant aspects of plant health, which makes this entire approach experimental.

Additionally, we don't yet know how to combine all the data within the greenhouse context to ultimately offer growers practical advice, such as whether they should start their irrigation an hour earlier than the day before. This uncertainty raises concerns throughout the market about the true purpose and utility of the data collected and whether it can lead to actionable advice that growers can rely on.

10.4 Recommendations

- This project focuses on gathering the subjective plant assessments of tomato growers, but there are also opportunities to apply the same system for bell pepper and cucumber growers. I recommend expanding the data collection system to the bell pepper and cucumber, at the moment that the tomato grower's insights themselves have been validated.
- Once the system has been running for a while, it may be possible to personalize the app based on the user's behaviour. There will likely be differences in user behaviour among the profiles established in Appendix C.
- Use the feedback loop within the system to continuously improve the app and provide updates aimed at enhancing usability and efficiency.
- Research the optimal amount of data that is needed to be able to say something on whether there is a common truth in the insights of the grower or not.

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11 References

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Appendices

Appendix A Plant Monitoring Methods

Plant parameter	n	Description	Relations to Plant Balances	Measuring method(s)	Possible challenges	References
Leaf Area Index (LAI)		*The number of leaves per unit area*	*A high LAI means the plant is leafy, low LAI means the plant does not have a lot of leaves*	*Counting and making the calculation manually, AccuPAR measures amount of light that passes though the leaves*	*Manual method is time-intensive, more advanced options are expensive*	*(METER Group, n.d.)*
Length between top of the plant and first flower/fruit		*-*	*Long distance means the plant is putting energy into green parts of the plant, short distance means the plant is putting energy into the fruits and flowers*	*Caliper, by sight*	*Measuring procedure is not standardized*	
Head thickness		*The thickness of the stem approximately 10 cm under the top of the plant*	*Thick head means the assimilate production was more than the consumption, thin head means that the assimilate production was less than the consumption*	*Ultrasound sensor, by sight, camera, caliper, dendrometer, laser*	*The position of the measurement is not standardized*	
Number of flowers and fruits		*-*	*More flowers and fruits indicate a high yield, low amount indicates low yield*	*Manually filling in measurements on software platform of Source.ag, plant registration forms*	*Time-intensive to fill in data for the grower*	*(Source, n.d.)*
Evaporation rate		*Rate at which the plant evaporates water*	*High evaporation rate means the plant is growing well, low evaporation rate might indicate stress*	*Calculating difference between weight of substrate and plant (see Aqua Balance) at the beginning and end of the day*	*?*	*(Hoogendoorn Growth Management, 2021)*
Reactive Oxygen Species		*Species produced as part of a plant's defense mechanism due to e.g. a plague*	*The presence of ROS means the plant is not doing well*	*Luminol-based chemiluminescence method*	*Highly complex method*	*(Jantean et al., 2022)*
Stem thickness/diameter/water content		*-*	*An increasing stem thickness means the crop is putting energy in the development of the green parts of the plant, stagnating growth in stem thickness might indicate that the energy is put into the development of fruits and flowers*	*Stem diameter sensor, caliper, ultrasound sensor*	*Manually measuring is time-intensive*	*(Aranet, n.d.)*
Plant weight		*Weight of plant excluding substrate mat*	*Increasing weight means an increase in assimilates (and water content), stagnating growth means more assimilates are consumed by e.g. fruits and flowers*	*Load cell*	*Load cell is plant-specific and in re-hanging the plant there is a lot of room for error*	*(Aranet, 2024)*
Dry weight plant		*Weight of plant excluding substrate mat and water content*	*Increasing weight means an increase in assimilates*	*Put plant into oven for a few hours*	*Destructive method, time-intensive*	

Plant parameter	**n**	**Description**	**Relations to Plant Balances**	**Measuring method(s)**	**Possible challenges**	**References**
Slab weight		*Weight of plant and substrate mat*	-	Aqua Balance	?	(Hoogendoorn Growth Management, 2021)
Sap flow		*The flow of water, nutrients and assimilates through the stem*	*Correlates with evaporation rate (see Evaporation rate)*	*Sap flow meter*	*Needles are intrusive*	*(HydroTerra, 2022)*
Calcium levels in leaves		-	*Sufficient calcium is needed to maintain the green parts of the plant*	*Fluorescence microscopy*	?	*(Dixit et al., 2021)*
Stomata (aperture, conductance, density)		*The degree to which stomata exchange gas can be measured through looking at the aperture, conductance, and density*	*Open stomata mean the plant evaporates well, too open means the plant is at risks infiltration of pathogens, closed stomata is not good for growth as then the plant is not able to evaporate anymore*	Camera	*No threshold values known*	*(Sigrow, n.d.)*
Photosynthesis efficiency		*The efficiency at which the plant turns carbon dioxide, water, and sunlight into oxygen and sugars*	*High efficiency means a well-growing plant, low efficiency means a badly growing plant*	*CropObserver, Sendot*	?	*(CropObserver. n.d), (Sendot, n.d)*
Leaf temperature		-	*High leaf temperature means the plant has more energy and potential to evaporate, too high temperature may indicate heat stress, cool leaf means the plant is actively cooling and evaporating which is good*	*Infrared camera, leaf temperature sensor*	*For camera the difference between air temperature and leaf is small, for sensor it is intrusive in leaf*	*(Yu et al., 2016)*
Leaf (length, thickness, weight)		-		*Leaf area scanner*	?	*(Selectech, n.d.)*

Appendix B Plant Registration Form

Teeltregistratie 2023
Kas 4
Ras:Provine
Pad:423

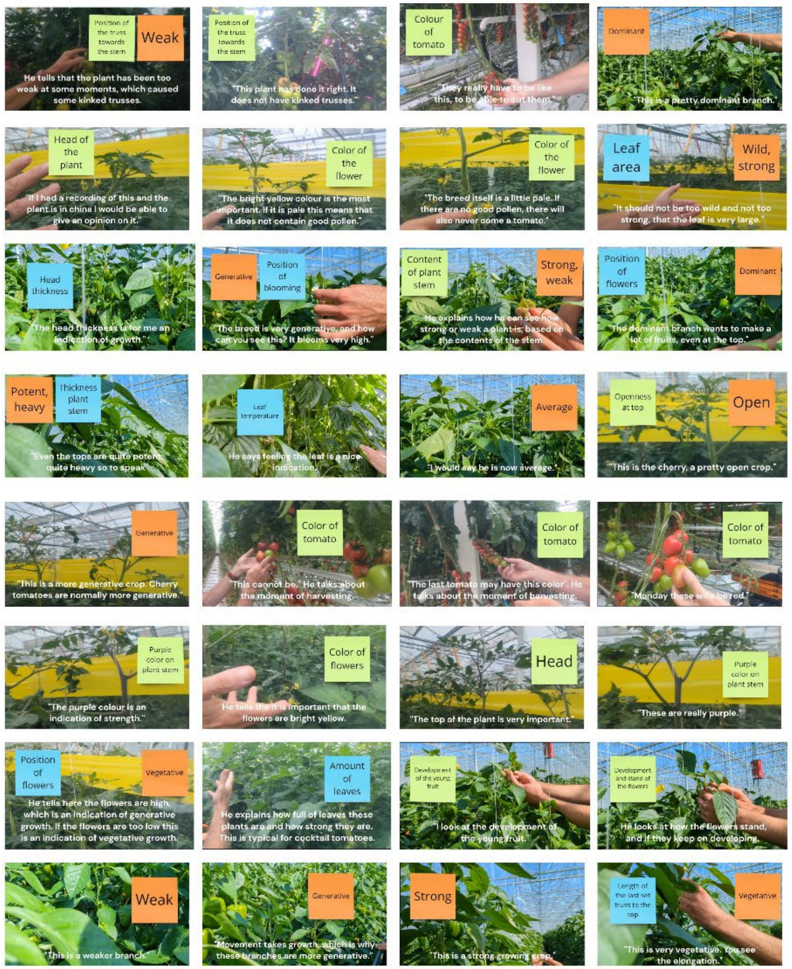
Plant (Rood)	1	2	3	4	5	6	7	8	9	10	Gem.
Lengte groei											#DELING.DOOR.0!
Kopdikte											#DELING.DOOR.0!
Bloeihoogte in cm											#DELING.DOOR.0!
Nr. bloeiende tros											#DELING.DOOR.0!
Nr. gezette tros											#DELING.DOOR.0!
Nr. oogst tros	29	28	27	28		25	27	27	27	27	27,22
Plantbelasting	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6,00
Bladlengte											#DELING.DOOR.0!
Plantgewicht											#DELING.DOOR.0!
Aantal bladeren											#DELING.DOOR.0!
											#DELING.DOOR.0!
Gezette tomaten											#DELING.DOOR.0!
Geoogste tomaten	6	6	6	6	6	6	6	6	6	6	6,00

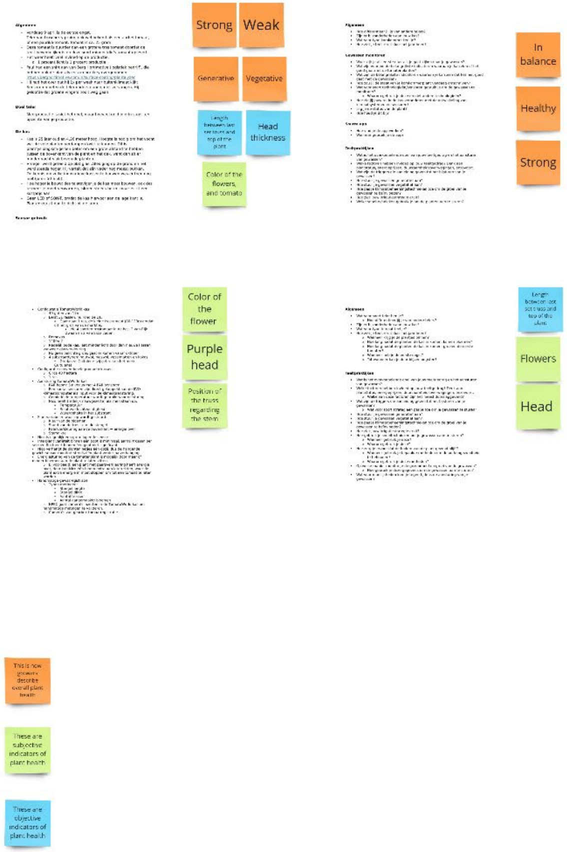
Dief (Geel)	1	2	3	4	5						Gem.
Nr. bloeiende tros											#DELING.DOOR.0!
Nr. gezette tros											#DELING.DOOR.0!
Nr. oogst tros	24	25	27	28	24	24	23	24			24,88
Plantbelasting	-6	-6	-6	-6	-6						-6,00
Gezette tomaten											#DELING.DOOR.0!
Geoogste tomaten	6	6	6	6	6	6	6	6			6,00

Appendix C Types of Growers

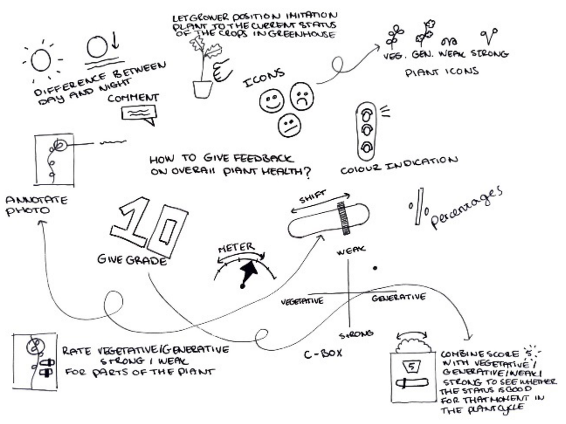
	Traditional grower	Newcomer	Experimenter	Cultivation manager
General differences				
Size of the greenhouse.	Approximately 5 acres	Approximately 5 acres	Small greenhouse less than 1 acre	Often larger than 15 acres
Mindset	Entrepreneurial, taking risks to achieve maximum yield	Entrepreneurial, but cautious	Innovator, focused on testing	Focused on efficiency
Expertise	High level of expertisel , has learned cultivating since he was young	Youngster, still learning how to 'read' the plant	High level of expertise, as cultivating tens of breeds is far more complex than one breed	Knows how to cultivate, but has lost his touch with the greenhouse
Workflow				
Plant inspection	Multiple times each day of the week	Goes daily though the greenhouse, but has to push himself and would rather rely on data	Multiple times per day, at least one time in the morning and in the evening	Has lost his touch with the greenhouse
Sensors and data				
Approach towards data	Rather relies on own experience and intuition than on data, will only use data if others have experienced it to improve cultivation practises	Wants to use more data to save time, but struggles with data interpretation	Actively uses data in daily work	Uses data to improve efficiency, compares data across different companies
Data exchange	Data is exchanged with cultivation advisor and other growers of similar breeds	Data is exchanged with cultivation advisor and other growers of similar breeds	Focus on helping others, because of high level of expertise	Focus on educating workers how to cultivate
Data visualisation preference	Conservative, ideally data is presented in concrete numbers and graphs	More open-attitude, experimental approach	Has to be open for new ways of data visualisation, as this goes hand-in-hand with complex plant data	More open-attitude, experimental approach

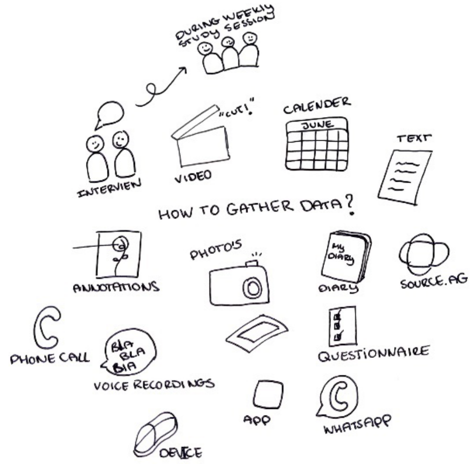
Appendix D Data Analysis

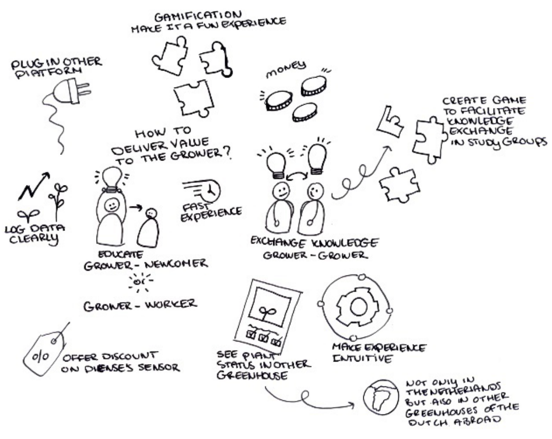




Appendix E How-Tos



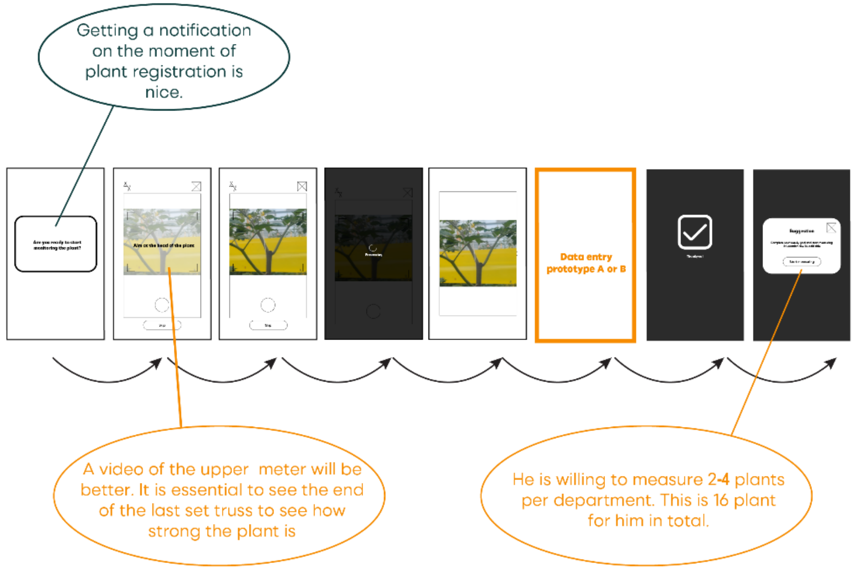


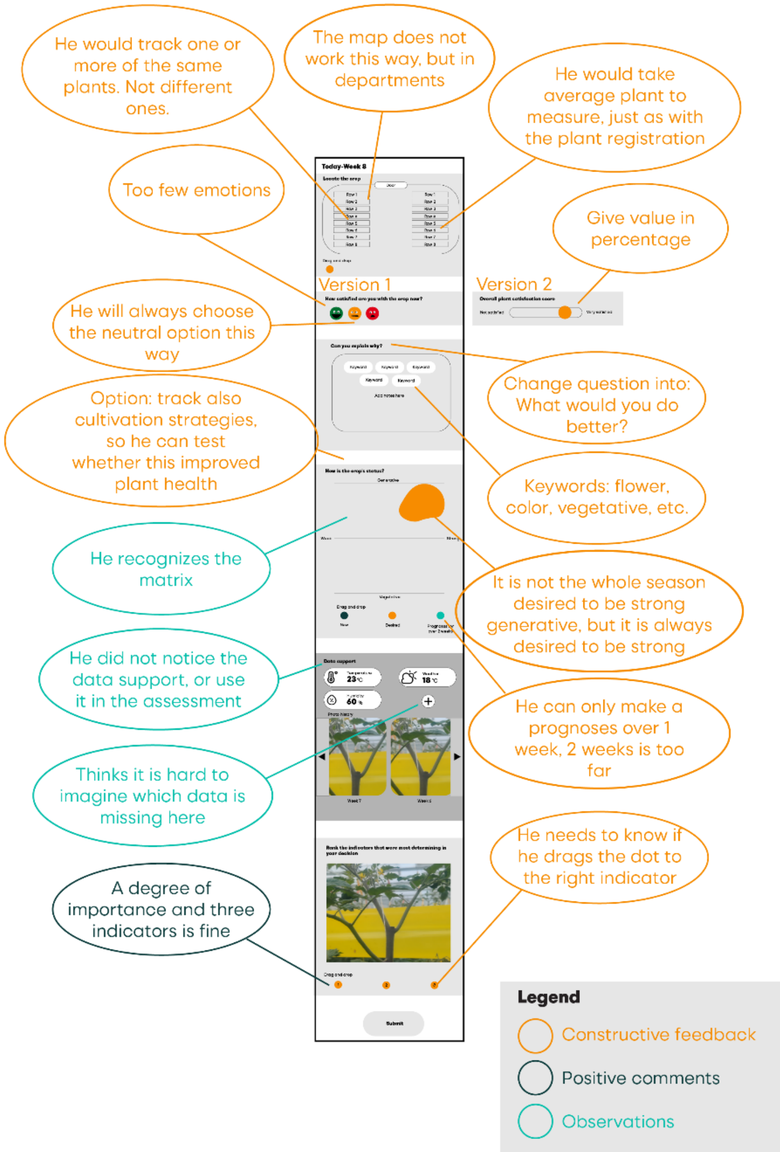


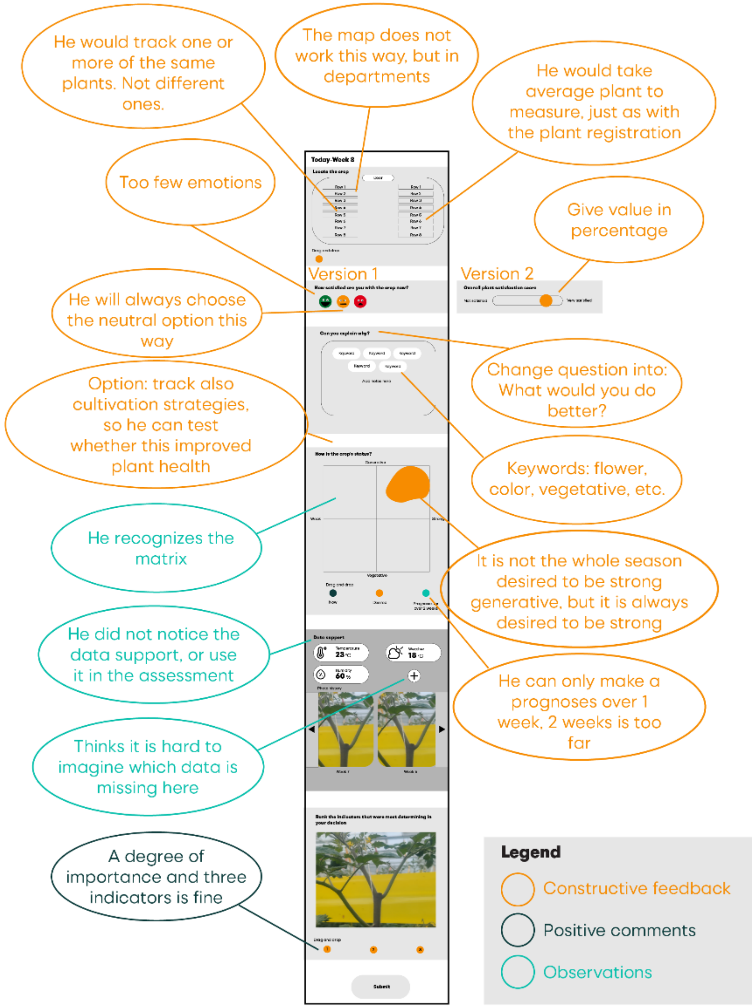
Appendix F Materials Iterative Prototyping

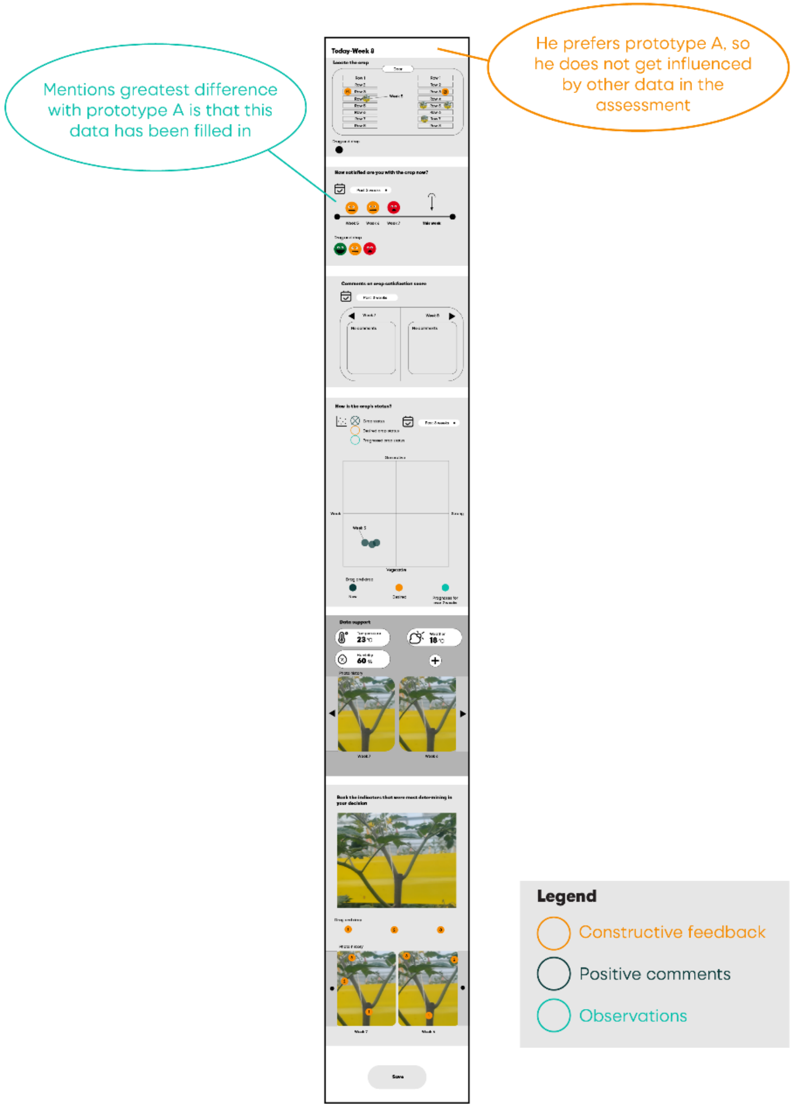
Paper prototype

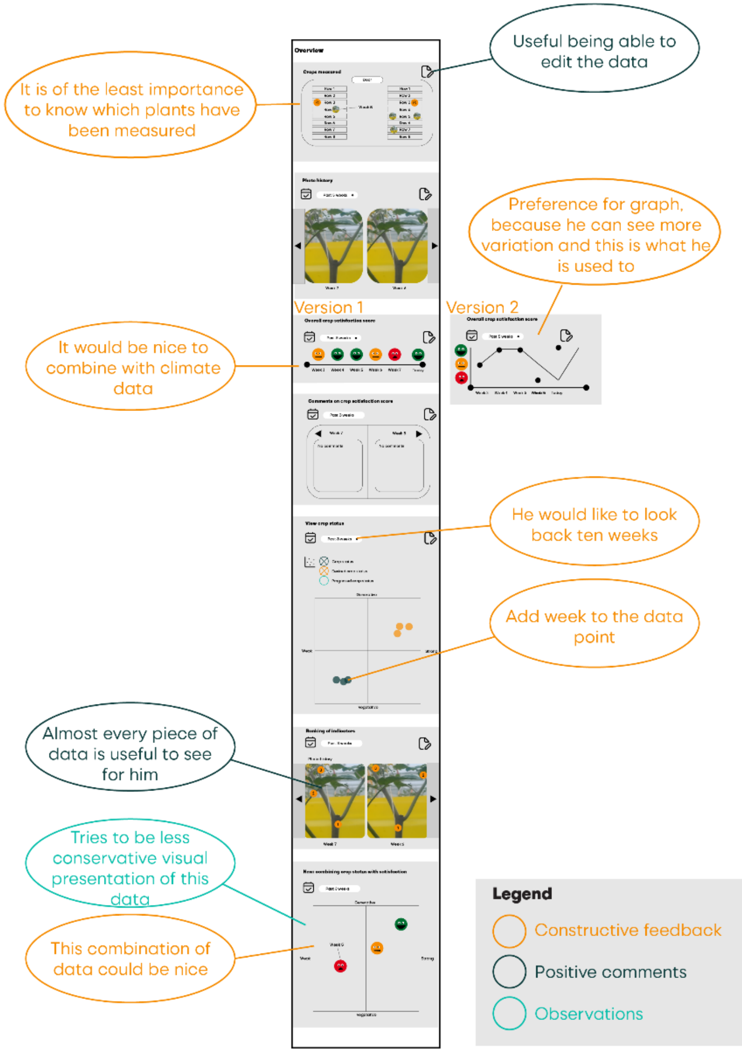
Results Iteration 1




He would track one or more of the same plants. Not different ones.
The map does not work this way, but in departments
He would take average plant to measure, just as with the plant registration
Too few emotions
Give value in percentage
Version 1
Version 2
He will always choose the neutral option this way
Change question into: What would you do better?
Option: track also cultivation strategies, so he can test whether this improved plant health
Keywords: flower, color, vegetative, etc.
He recognizes the matrix
It is not the whole season desired to be strong generative, but it is always desired to be strong
He did not notice the data support, or use it in the assessment
He can only make a prognoses over 1 week, 2 weeks is too far
Thinks it is hard to imagine which data is missing here
He needs to know if he drags the dot to the right indicator
A degree of importance and three indicators is fine
Legend
Constructive feedback
Positive comments
Observations


He would track one or more of the same plants. Not different ones.
The map does not work this way, but in departments
He would take average plant to measure, just as with the plant registration
Too few emotions
Give value in percentage
Version 1
Version 2
He will always choose the neutral option this way
Change question into: What would you do better?
Option: track also cultivation strategies, so he can test whether this improved plant health
Keywords: flower, color, vegetative, etc.
He recognizes the matrix
It is not the whole season desired to be strong generative, but it is always desired to be strong
He did not notice the data support, or use it in the assessment
He can only make a prognoses over 1 week, 2 weeks is too far
Thinks it is hard to imagine which data is missing here
A degree of importance and three indicators is fine
Legend
Constructive feedback
Positive comments
Observations


Mentions greatest difference with prototype A is that this data has been filled in
He prefers prototype A, so he does not get influenced by other data in the assessment
Legend
Constructive feedback
Positive comments
Observations


Useful being able to edit the data
It is of the least importance to know which plants have been measured
Preference for graph, because he can see more variation and this is what he is used to
Version 1
Version 2
It would be nice to combine with climate data
He would like to look back ten weeks
Add week to the data point
Almost every piece of data is useful to see for him
Tries to be less conservative visual presentation of this data
This combination of data could be nice
Legend
Constructive feedback
Positive comments
Observations

IDE student 1

- **About filling in the settings:**
    - "I am missing the point that this should only have to be filled in once."
    - "Can you also give the department a name?"
    - About the greenhouse location:
        - "Is the white spot where I am now?
    - About notifications:
        - "How often do I get the notifications? Or, does the grower know how often the plant registration for example is?"

- **About making the assessment:**
    - "Do I need to film until the first truss with flowers or first truss with tomatoes?"
    - "Is the assessment about the plant I just made a photo of?"
    - Does not mention that the crop location should be filled in. She assumed that this was the first crop in the list of registered plants and would also use this sequence in monitoring the plants."
    - Mentions that it is not necessary to see the plant for all the weeks, maybe only for the last 10 weeks, this prevents the graph from becoming very crowded.
    - Mentions the reference data to be very useful, but does not know what the other tab is. She mentions calling the tab "today" and would expect this to be the left tab and overview the right tab.
    - For the first usage she would provide small icons to explain things.
    - After making the plant assessment she would expect a message that shows which plant she has measured and how many she should still measure today/this week. She mentions seeing a check behind the plant measured or "you have measured 1/10 rows".
    - Disconnect maybe plant location from the data entry page.
    - Drag-and-drop system is understood.

- **About home:**
    - She would expect to keep on measuring if she taps the "4/16 plants are measured this week" button.
    - "Maybe it is nice to add that for example ¾ of the plants is in the flowering state."

- **Menu buttons**
  - About the “Plus” button: “it is not clear what this button means on other pages other than the data entry page.” Integrate this button with the other buttons and put them on one line.

- **About overview:**
  - Is the “overview” tab of all plants together?
  - The matrix and what it means is self-explaining, putting “strong vegetative” in the extra box is not necessary.
  - Give all the data other colours in the matrix overview section.
  - “Maybe make a subsection, to compare the plant with other plants in the matrix?
  - “Settings” heading is too small.
  - Have a menu that stays in place whilst scrolling.

IDE student 2

- **Overall**
    - You can not see that the app is made for a grower, maybe add more photos in the app to give more feeling for this, such as the screen of the camera
        - Do not give a visual of the tomato but a photo!

- **About filling in the settings:**
    - “What should I choose when I am now a grower?”
    - Maybe you could give a statement and let the grower choose the best fitting statement
    - Maybe the grower does not at all know what to choose (about level of experience)
    - Progress bar is nice to see
        - Maybe add a small leaf to enhance the grower feeling
    - The grower may not be able to fill in the optimal settings of the climate at that point in time, so what to do about this?
    - “Department” is put in there twice in the settings of the location of the plant

- **About making the assessment:**
    - The flash is in the app not in the camera itself, this is not right
    - Make the photo fill almost the whole screen, just as on your phone
    - Feedback button is also something that will be removed after a while, this can be put in the roadmap
    - It is understood that seeing the trend makes the assessment more accurate and the pro’s and con’s of this.
        - In the trend tab also show the desired trend, but the prognosis does not have to be included here.
        - Make the data points in the trend smaller and much lighter to give a clear contrast with the data points that will be added.
    - Intonation at “type text here” is different than from “don’t see your indicator?”... add on here”
    - Give legend maybe at the top

- **About home:**
    - “Do the general statistics refer to the 4 plant measurements done?” General statistics should be seen in one glimpse, maybe make more abstract and make 4/16 plant measurements

smaller, because grower already knows how many plants, he has measured

- **Menu buttons**
  - "The plus is not really clear, but I think it is to add the data."

- **About overview:**
  - Focus areas> "areas of attention" sounds more positive
  - Data overview and data point should be switched.
    - When ticking on a data point she mentions seeing an overview of that specific plant with an overlay
    - If the grower wants to compare the different plants, integrate this in the search option. Give this option in a drop-down menu.
    - Crop satisfaction score> make terminology more consistent
    - The number in the data point should only refer to the week. Give a bar next to the graph as a legenda which gives a colour and percentage to the data point.
    - Gs should be both capital letters
    - Remove history

Appendix G Data Tables

Subjective Plant Assessments

n	Data type	Example data notation	Description	Criteria/threshold	Query frequency [per week/per plant]	Volume [per plant/per week]	Criticality to system (red=very critical, orange=medium critical, green=not	Value of the data
1	crop_photo		Photo of the crop	The head must be visable of the crop together with the first trus of flowers/tomatoes from the top in order to be useful	1x per week (*amount of plants)	MB		By combining a photo of the crop with the grower's assessments, Plense receives visual feedback alongside the grower's perceptions, aiding in the interpretation of the plant's condition. When this data is compared with the Plensor's signals, it helps differentiate how the signal varies between plants rated as healthy and those rated poorly. For the grower and the cultivation manager, having a photo provides essential context to objective plant data from the past, making it easier to assess and track changes in the plant's health over time.
2	crop_location	Department A, Row 1	The specific location of the crop within the greenhouse.	It is important that the way the crop is located is aligned with the standard way of notating this, to be able to easily be compared with other data (e.g. climate data), however currently there is not yet a	1x per week (*amount of plants)	Bytes		The specific location of the crop is essential for combining and interpreting various data types. For instance, assessing how a crop developed poorly, requires understanding its microclimate, as this directly impacts the plant's health. The ability to combine such data is valuable to both Plense, the grower, and the cultivation manager.
3	gen_satisfaction_score	81%	The degree to which the grower is satisfied with the crop's real-time appearance.	This is a value from 0-100%	1x per week (*amount of plants)	Bytes		The general satisfaction score, along with the photo, will provide Plense with an overall impression of the plant's health. This score can be held besides the signal of the Plensor to learn how the ultrasound signal differs for varying general satisfaction scores.
4	attention_areas	Purple colour stem	The areas the grower sees, regarding the plant that he wants to improve	Maximum of 50 characters, otherwise there will be too much data for Plense to analyse	1x per week (*amount of plants)	Bytes		The attention areas will give Plense insight into the crop parts the grower wants to improve. This data can be combined with the grower's set points, like irrigation and temperature, to understand how they adjust greenhouse conditions for these focus areas. However, adjustments will be based solely on the average plant. For the grower it might be useful to see these focus areas
5	growth_status_now	[-56,38]	The x-coordinate represents the degree to which the crop is in a vegetative or generative state in real- time, while the y-coordinate indicates the degree of weak or strong growth.	Coördinate [x,y] with boundary values of -100 ≤ x ≤100 V -100 ≤ y ≤ 100	1x per week (*amount of plants)	Bytes		By linking this score to the real-time growth status (n5), Plense can assess the grower's satisfaction with the current growth type.
6	growth_status_desired	[-56,38]	The x-coordinate represents the grower's set point for how vegetative or generative they want the crop to be at that moment, while the y-coordinate indicates the grower's set point for whether they aim for weak or strong	Coördinate [x,y] with boundary values of -100 ≤ x ≤100 V -100 ≤ y ≤ 100	1x per week (independant of the amount of plants)	Bytes		The grower's desired growth type enables Plense to identify which growth stages are preferred throughout the year. These insights might help Plense to develop cultivation strategies that align with the grower's goals for optimal growth status.
7	weekly_growth_prognosis	[-56,38]	The x-coordinate represents the grower's weekly prognosis for vegetative or generative growth, while the y-coordinate reflects the weekly prognosis for weak or strong growth.	Coördinate [x,y] with boundary values of -100 ≤ x ≤100 V -100 ≤ y ≤ 100	1x per week (*amount of plants)	Bytes		The grower, Plense, and the cultivation manager can evaluate how accurately the grower has predicted the development of the growth type. This assessment can serve as a measure of the grower's expertise.
9	growth_type_indicators	Flower colour, position truss-stem	The indicators at which the grower has looked to determine the growth type real-time (N5) of the crop.	The grower can fill in 0-6 indicators	1x per week	Bytes		These growth type indicators provide Plense with insights into the grower's reasoning behind their assessments of plant growth. This process allows Plense to learn and improve its own ability to interpret plant health and development over time.

Settings

n	Data type	Example	Description	Criteria/threshold	Query frequency	Data volume	Criticality to system	Value
12	user_experience		This is a measure for the degree of experience a grower has.	-	1x per tomato cultivation cycle	Bytes		**Plense:** This may provide insight into the reliability of the grower's assessments.
13	user_tech_attitude		This is a measure for the attitude the grower has towards plant	-	1x per tomato cultivation cycle	Bytes		**Plense:** This may offer insights into the market and the overall interest in plant sensors.
14	crop_type		This is the type of crop that the grower cultivates.	The crop type assessed should be the tomato for the first 1-2 years, because Plense focuses on this market initially.	1x per tomato cultivation cycle	Bytes		**Plense:**The behavior of the plant is largely dependent on the crop type. Without this context, the crop's behavior cannot be effectively interpreted.
15	breed		This is the specific breed of the tomato that the grower cultivates.	The breeder offers only a limited selection of commercial breeds for each tomato type. The grower is limited to these.	1x per tomato cultivation cycle	Bytes		**Plense:** The behavior of the plant is heavily influenced by the breed. Without this context, interpreting the crop's behavior accurately is not possible.
16	breed_natural_behaviour		This is the natural behaviour of the breed in terms of vegetative, generative, weak, or strong growth,	This depends on the breed, and it is often knowledge that the breeder possesses. Alternatively, the grower typically learns this through a few months of cultivation, as it pertains to the breed's natural behavior.	1x per tomato cultivation cycle	Bytes		**Plense:** Knowing the breed's tendencies allows Plense to interpret plant behavior more accurately, distinguishing between natural growth patterns and the effects of cultivation techniques.
17	seeding_date		This is the date when the tomato plants were seeded by the breeder.	This varies per breeder, but most plants are typically seeded in December.	1x per tomato cultivation cycle	Bytes		**Plense:** The seeding date is crucial for interpreting the data from plant assessments during the growth stage.
19	greenhouse_location		This is the location of the greenhouse in the Netherlands.	Must be in the Netherlands for the first 1-2 years to gather a substantial amount of data within the same climate.	1x per tomato cultivation cycle	Bytes		**Plense:** The greenhouse location helps Plense gain a better understanding of the climate and, consequently, the conditions within the greenhouse.
20	breed_optimal_temp_day		This is the average daily temperature that the grower wants to achieve for optimal growth.	Depends on the breed	1x per tomato cultivation cycle	Bytes		**Plense:** This helps provide a general understanding of the grower's strategy for managing the conditions in the greenhouse.
21	breed_optimal_temp_night		This is the average night temperature that the grower wants to achieve for optimal	Depends on the breed	1x per tomato cultivation cycle	Bytes		**Plense:** This helps provide a general understanding of the grower's strategy for managing the conditions in the greenhouse.
22	breed_optimal_humidity		This is the average humidity the grower wants to maintain to achieve optimal growth.	Depends on the breed	1x per tomato cultivation cycle	Bytes		**Plense:** This helps provide a general understanding of the grower's strategy for managing the conditions in the greenhouse.
23	plant_registration_moment		This is the moment when physical plant parameters (e.g., leaf length) are manually measured by the grower on a weekly basis.	-	1x per tomato cultivation cycle	Bytes		**Grower:** Capturing this moment and aligning notifications with it enables a more seamless integration of the grower's subjective assessments into their workflow.
24	study_session_moment		This is the moment when growers meet growers of similar breeds/cultivation experts to exchange knowledge, often on a bi-weekly basis.	-	1x per tomato cultivation cycle	Bytes		**Grower:** Capturing this moment and aligning reporting notifications accordingly ensures that the grower receives the report one day before their study session, allowing them to use it as a valuable communication tool during the session.

Data Interpretation of Growth Type

Interpretation of the growth type coördinate [x,y]

x-axis value	Interpretation	y-axis value	Interpretation
-100	Extremely vegetative	-100	Extremely weak
-75	Highly vegetative	-75	Highly weak
-50	Moderately vegetative	-50	Moderately weak
-25	Lightly vegetative	-25	Lightly weak
0	In balance	0	In balance
25	Lightly generative	25	Lightly strong
50	Moderately generative	50	Moderately strong
75	Highly generative	75	Highly strong
100	Extremely generative	100	Extremely strong

Interpretation of crop satisfaction score

General satisfaction score [in %]	Interpretation
0	Very unsatisfied
25	Unsatisfied
50	Moderately satisfied
75	Satisfied
100	Very satisfied

Appendix H Project Brief

Personal Project Brief – IDE Master Graduation Project

DESIGN FOR our future

TU Delft

Name student Laura Drost | Student number

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title: Designing a measurement device to track the growth of the tomato plant

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

With the world's population expected to hit 9.3 billion by 2050 (WUR, n.d.), the pressure to feed everyone grows. To meet this challenge sustainably, we must rethink our food production methods, especially considering climate change and environmental limits. The Netherlands, a major global food exporter (CBS, 2016), is crucial in this effort, aiming for carbon neutrality by 2050 as part of its energy and climate plan (Ministry of Economic Affairs and Climate Policy, 2019).

Among the stakeholders in this project are tomato farmers, struggling to cut emissions to zero to achieve carbon neutrality. They rely on energy to maintain the conditions in the greenhouse for optimal tomato growth (see Figure 1). Ignoring this issue could cost them a lot of money due to the yearly increasing carbon taxes.

This is where the client Plense Technologies comes in. Plense, a startup born out of the Plantenna project at TU Delft, focuses on empowering growers with data-driven insights. Plense is developing ultrasound sensors for application in the greenhouse sector, which can measure internal processes of the plant (e.g. plant growth), but also external factors (e.g. minimum temperature for optimal growth). This is all done by looking within the plant. This technology holds promise for reducing amongst other things energy consumption, by helping growers find the minimum temperature that is needed for their crops to still optimally grow. As half of the world's greenhouses grow tomatoes (Meischke, 2024), it will make most impact testing and developing the ultrasound sensors first for the tomato plant and tomato growers. However, as the technology of the sensors is quite new, there are still challenges, of which one is the validation of the measurements.

Plense consists of two founders with a background in both mechanical engineering and one in also business development. The team is further strengthened with a plant physiologist, data analyst and interns. One intern works on the clamping mechanism of the sensors to the stem of the tomato plant, the other is from the SPD master and will focus on the branding.

→ space available for images / figures on next page

introduction (continued): space for images

image / figure 1 The growth of the tomato plant in the greenhouse

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

Plense Technologies is currently developing ultrasound sensors to measure amongst other things the growth of the tomato plant. However, it is a quite new technology, and the data should still be validated. To address this, I want to design a solution that aims to validate the ultrasound sensor's measurements, for in specific growth. Plense Technologies does this now with a prototype of a weighing module, but the starting point for this project will be broader.

The solution must consider the re-hanging of the tomato plant. As tomato plants grow rapidly, greenhouse workers must reposition the plants sideways approximately every week. As the data obtained for validation is plant-specific, the design solution should also stay plant specific and ideally be re-hung with the plant by the greenhouse workers.

Furthermore, the solution must endure the harsh conditions inside the greenhouse, including prolonged exposure to elevated temperatures and high humidity levels. This necessitates, among other things, ensuring the module is waterproof, but also that the correct material is chosen for the housing. The ideal solution would be that the solution is able to withstand the conditions within all types of greenhouses (very controlled greenhouses and commercial ones).

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Design a measurement device that will track the growth of the tomato plant, in order to generate data that can be used to validate the measurements of the ultrasound sensor.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

Firstly, I plan to conduct field research within the tomato greenhouse. This involves understanding the growth patterns of tomato plants and identifying the optimal conditions for their cultivation. Subsequently, I aim to delve deeper into the functionality of ultrasound sensors, exploring their capabilities and comprehending how the data they collect can be integrated to assess plant growth. Also, in parallel to the field research I will explore alternative methods (other than the weighing module) to measure plant growth, in order to assess whether the weighing module is indeed the best way to measure plant growth. At the end of the research phase I want to decide on whether to continue with the weighing module or not.

To systematically address the sub-problems involved (e.g. the wrong re-hanging of the module), I will create a morphological chart. On the basis of the morphological chart I want to generate concepts. After this I would like to prototype and test these concepts in the greenhouse. Then, I want to combine the most promising aspects of the concepts in one final concept, and make a high-quality prototype of it, which will be my final deliverable.

Project planning and key moments

To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a ***kick-off meeting, mid-term evaluation meeting, green light meeting*** *and* ***graduation ceremony****. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	15 Feb 2024
Mid-term evaluation	26 Apr 2024
Green light meeting	5 Jul 2024
Graduation ceremony	

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	
Number of project days per week	

Comments:

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

I wish to start this project as I have a high interest and network within the agriculture and horticulture sector. Currently, I am working on a start-up that focuses on product solutions for within this sector to become more future-proof, because the sector is facing challenges regarding sustainability regulations and labour shortage.

For my graduation project, I sought to explore a different aspect within this sector, one not entirely aligned with the current activities of my startup. Specifically, I aim to gain a deeper understanding of using data for design, as this is an area I haven't delved into before.