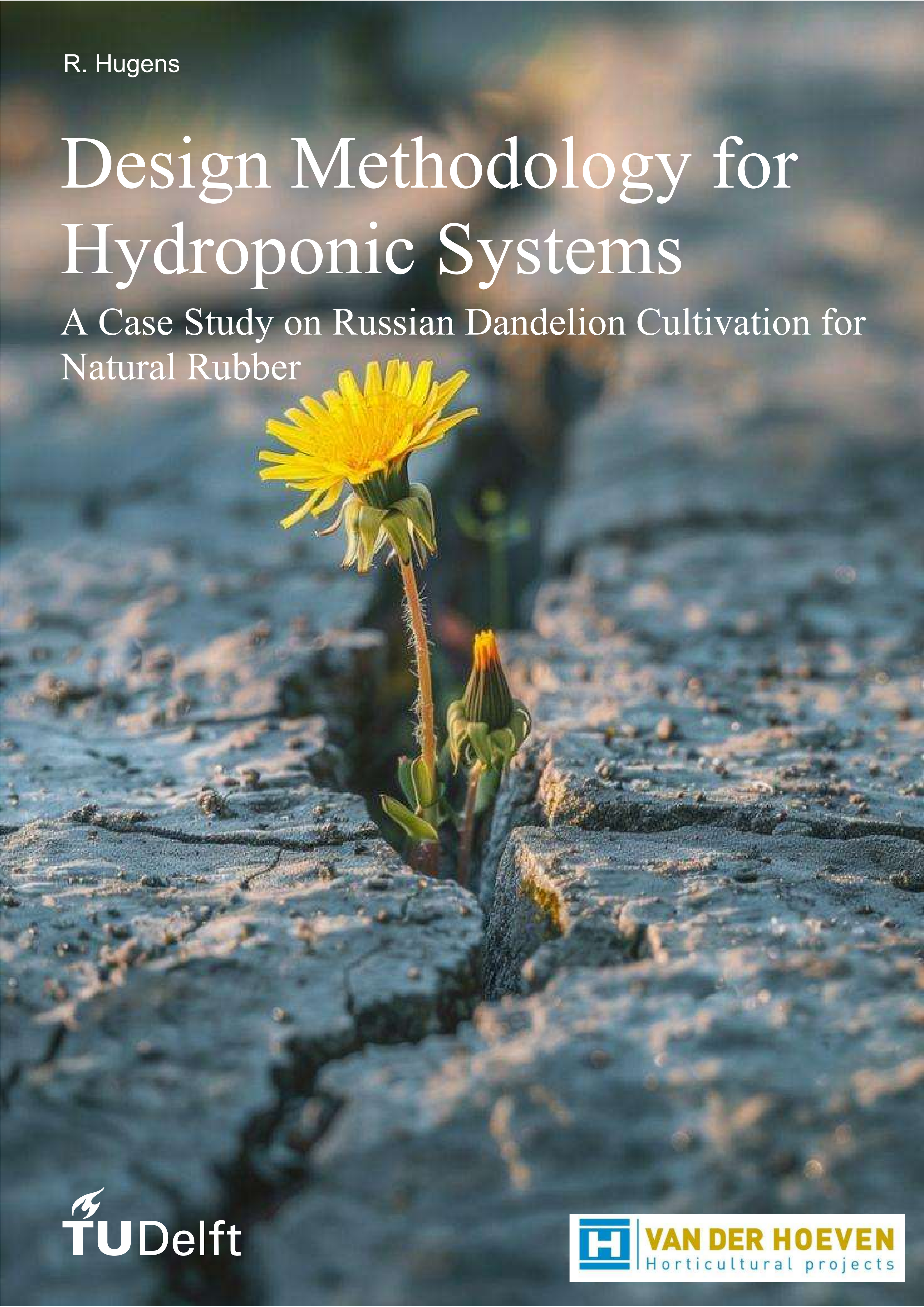
R. Hugens

Design Methodology for Hydroponic Systems

A Case Study on Russian Dandelion Cultivation for Natural Rubber



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Design Methodology for Hydroponic Systems

A Case Study on Russian Dandelion Cultivation for Natural Rubber

By

R. Hugens

Master Thesis

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Supervisor:		
Thesis committee:	Dr. J. Jovanova,	Supervisor, TU Delft
	Ir. A. Napoleone,	Chair and Supervisor, TU Delft
	Ir. W. van den Bos,	Committee Member, TU Delft
	Ir. L. Baart de la Faille,	Supervisor, Van der Hoeven
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Acknowledgments

This thesis marks the completion of my Master’s degree in Mechanical Engineering at Delft University of Technology, with a specialization in Multi-Machine Engineering.

My story in Delft started at De Haagse Hogeschool, where I obtained my bachelor’s degree in Mechanical Engineering. My curiosity and eagerness to learn brought me to study at TU Delft. After completing the Bridging Program, I began my Master’s, a period in which I continued to learn and develop both as an engineer and as a person. During this last phase of my studies, I had a great team of supervisors to guide me.

First of all, I would like to thank my supervisors at Van Der Hoeven, Leonard Baart de la Faille and Marc Middeldorp. Thank you for the opportunity I was given, and for your time and energy in guiding me. I would also like to thank the colleagues at the R&D team for their enthusiasm and support.

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As this chapter closes, I feel the weight and beauty of an era ending, grateful for everything it has given me. To quote Taylor Swift:

”It was the end of a decade. But the start of an age.”

Thank you for taking the time to read my thesis. Enjoy!

Rhea Hugens
Delft, October 2025

Abstract

This thesis develops a conceptual design methodology for hydroponic systems tailored to specialty crops where biological requirements are often incomplete or uncertain. The proposed methodology adapts established mechanical engineering design principles (Pahl & Beitz, Roozenburg & Eekels, TRIZ) by introducing iterative feedback loops, explicit decision points, and the parallel integration of biological, technical, and economic analyses. A critical innovation is the inclusion of a dedicated Testing phase between the Conceptual and Provisional design phases. The methodology was applied to a case study on Russian dandelions, a potential alternative source of natural rubber that grows in its roots. The case study successfully structured the complex design problem, generated multiple cultivation concepts, and systematically exposed critical knowledge gaps regarding root rubber content, single- or multiple harvesting techniques, and cultivation strategies. Experimental trials confirmed the feasibility of hydroponic cultivation but revealed significant biological challenges, such as plant stress from root trimming. Economic modeling, based on current assumptions, indicated a lack of viability, highlighting a dependency on future agronomic research. The thesis contributes to both literature and practice by bridging engineering methodologies with controlled-environment agriculture, expanding the scope of hydroponics beyond food crops, and offering a design-support guideline for future innovation in non-traditional crop systems.

Summary

This thesis investigated the systematic design of hydroponic systems for specialty crops by developing and testing a novel conceptual design methodology. The research addressed a clear gap in the literature: the lack of a structured approach that integrates the biological, technical, and economic uncertainties inherent in cultivating new crops like the Russian dandelion. Through a comparative analysis, existing mechanical engineering methodologies (Pahl & Beitz, Roozenburg & Eekels, TRIZ) were synthesized and adapted to create a more flexible, iterative framework. The proposed methodology progresses through defined stages of Task clarification, Analysis, Conceptual Design, Testing, Provisional Design, and Decision. It is supported by continuous feedback loops across the phases and includes go and no-go decision points.

The Russian dandelion was chosen as a case study to validate the methodology, due to its potential as a new source of natural rubber. The latex is harvested from the roots, making this a special crop to grow. Hydroponic cultivation concepts with the option of multiple harvests were compared against field cultivation. The methodology revealed key trade-offs, such as single or multiple harvests and design choices. Small-scale experiments, a core component of the Testing phase, provided practical insights but also contradicted some literature, revealing plant stress from root trimming and management challenges like unpredictable flowering. These findings were fed back into the design process, demonstrating the importance of the methodology's iterative nature. Remaining uncertainties within the root morphology, rubber-improving content and quality, and cultivation strategies were analyzed, and appropriate tradeoffs or assumptions were made to continue the design. The remaining research questions are made, and a future research approach is created.

Ultimately, the provisional design and economic analysis concluded that, based on current data, large-scale hydroponic production of Russian dandelion rubber is not yet feasible. The sensitivity analysis showed that financial viability is most dependent on operational parameters and cost structure, rather than minor improvements in growth or rubber price. The contributions of this work focus on two things: (1) the creation of a conceptual design methodology that bridges biological and technical aspects, and (2) a guideline of the specific factors required to determine the future feasibility of hydroponic Russian dandelion cultivation. The study confirms that the methodology is a powerful tool for structuring complex design problems and guiding research and development decisions under conditions of significant uncertainty.

Samenvatting

Deze thesis onderzocht het systematisch ontwerpen van hydrocultuursystemen voor speciale gewassen door het ontwikkelen en testen van een nieuwe conceptuele ontwerpmethodologie. Het onderzoek richtte zich op een duidelijk gat in de literatuur: het ontbreken van een gestructureerde benadering die de biologische, technische en economische onzekerheden bij het telen van nieuwe gewassen, zoals de Russische paardenbloem, integreert. Door een vergelijkende analyse werden bestaande werktuigbouwkundige methodologieën (Pahl & Beitz, Roozenburg & Eekels, TRIZ) gesynthetiseerd en aangepast om een flexibelere, iteratieve methode te creëren. De voorgestelde methodologie verloopt door de gedefinieerde fasen: Taakverduidelijking, Analyse, Conceptueel Ontwerp, Testen, Voorlopig Ontwerp en Beslissing. Deze wordt ondersteund door continue terugkoppeling over de verschillende disciplines heen en bevat go/no-go-beslispunten gedurende de fasen.

De Russische paardenbloem werd gekozen als casestudy om de methodologie te valideren, vanwege het potentieel als nieuwe bron van natuurlijk rubber. De rubber wordt uit de wortels geoogst, waardoor het een speciaal te telen gewas is. Concepten voor hydrocultuur met de optie voor meerdere oogsten werden vergeleken met veldteelt. De methodologie onthulde belangrijke afwegingen, zoals enkelvoudige of meervoudige oogsten en ontwerpkeuzes. Kleinschalige experimenten, een kernonderdeel van de Testfase, leverden praktische inzichten op, maar weerlegden ook enkele bevindingen uit de literatuur, zoals plantstress door wortelknippen en problemen met onvoorspelbare bloei. Deze bevindingen werden teruggekoppeld in het ontwerpproces, wat het belang van de iteratieve aard van de methodologie aantoont. De resterende onzekerheden rond wortelmorfologie, de verbetering van rubberinhoud en -kwaliteit, en teeltstrategieën werden geanalyseerd, en passende afwegingen of aannames werden gemaakt. De resterende onderzoeksvragen zijn geformuleerd en een toekomstige onderzoeksaanpak is opgesteld.

Uiteindelijk concludeerden het voorlopige ontwerp en de economische analyse dat, op basis van de huidige gegevens, grootschalige hydrocultuurproductie van rubber nog niet haalbaar is. De analyse toonde aan dat economische haalbaarheid het meest afhankelijk is van operationele parameters en kosten, in plaats van kleine verbeteringen in groei of rubberprijs. De bijdragen van dit werk richten zich op twee zaken: (1) het creëren van een conceptuele ontwerpmethodologie die biologische en technische aspecten overbrugt, en (2) het opstellen van een richtlijn van de specifieke factoren die nodig zijn om de toekomstige haalbaarheid van hydrocultuur van Russische paardenbloem te bepalen. De studie bevestigt dat de methodologie een krachtige methode is om complexe ontwerpproblemen te structureren en onderzoeks- en ontwikkelingsbeslissingen te sturen onder omstandigheden van onzekerheid.

Contents

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List of Abbreviations

AD Axiomatic Design. 20, 21, 115

CAD Computer-aided design. 44
CAPEX Capital Expenditure. 26, 27, 44, 50, 53, 73, 75, 78
CEA Controlled Environment Agriculture. 1, 3, 12–15, 47, 49, 50, 85, 123

DFA Design For Assembly. 20
DFM Design For Manufacturing. 20
DFMA Design For Manufacturing and Assembly. xi, 20, 21, 23, 44, 114, 115
DFT Deep Flow Technique. 13, 58
DO Dissolved Oxygen concentration. 15, 30, 32
DoE Design of Experiments. 43, 66, 81–83
DP Design Parameters. 29, 31, 34
DRW Dry Root Weight. 49, 62, 65, 71, 72, 74
DSR Design Science Research. 6, 25
DWC Deep Water Culture. xi, 13, 16, 17, 19, 58, 68

EC Electrical Conductivity. 8, 14, 30, 32, 129
EF Ebb and Flow (Ebb and Flood). 13, 18
EUI Energy Use Intensity. 33

FMEA Failure Mode and Effects Analysis. 44
FR Functional Requirements. 29, 34, 120

HAZOP Hazard and Operability Study. 44

IFR Ideal Final Result. 41, 117
IPM Integrated Pest Management. 41, 54, 123

KPI Key Performance Indicator. 3, 25, 29, 32, 34, 37, 38, 40–42, 45, 53, 58, 68, 75, 82, 88

LAI Light Area Index. 33, 56, 58
LCA Life Cycle Assessment. 2, 44, 90
LED Light Emitting Diode. 8, 15
LUE Light-Use Efficiency. 33

MCDA Multi-Criteria Decision Analysis. 42–44

MGS Multi-Gulley System. 17, 135
MoSCoW Must, Should, Could, and Won’t Have (requirements prioritization method). 29

NFR Non-Functional Requirements. 29
NFT Nutrient Film Technique. 7, 8, 13, 17, 18, 56, 60, 68, 83, 84
NR Natural Rubber. 46–49, 51, 52, 122

OPEX Operational Expenditure. 27, 33, 44, 53, 73, 78

PAR Photosynthetically Active Radiation. 33
PB Project Boundaries. 29
PESTLE Political Economical Social Technological Legal Environmental. 40
pH Potential of Hydrogen. 8, 14, 16, 30, 32, 129
PV Process Variables. 29, 32, 34

ROI Return on Investment. 26, 34, 53, 54, 58, 75, 83

SR Synthetic Rubber. 46, 50
SWOT Strengths Weaknesses Opportunities Threats. 40

TKS Taraxacum Kok-Saghyz. xiii, 47–51, 54, 69, 72, 73, 80, 83, 122
TRIZ Theory of Inventive Problem Solving. 20, 21, 23, 24, 35, 37, 38, 41, 42, 44, 82, 84, 88, 116, 117

WRW Wet Root Weight. 62, 65, 71, 72
WUE Water Usage Effectiveness. 33

1

Introduction

This chapter introduces the research topic and provides background information that highlights the knowledge gap, leading to the problem definition. Based on this, the research objectives and questions are established. The chapter also outlines the research approach and scope, and concludes with a reading guide to navigate the report.

1.1. Background

Agriculture has always been a rapidly developing sector. Open-field cultivation has been the traditional way of growing food, but with a rising population of 9 billion people in 2050, food security is more crucial than ever (Baulcombe et al., 2009). Waste must be reduced and production must increase while keeping the environmental impact in mind (Beddington, 2010). Protected agriculture has been used to boost production, and new technology has been developed and applied to achieve higher yields (Andreescu & Gurban, 2018; Blanco et al., 2022). These developments also enable the cultivation of food on land that previously seemed unsuitable due to the climate or soil conditions. From the open-field cultivation, there is a shift towards the cultivation in greenhouses, some of which are entirely automated.

(a) Open Field Cultivation (Olrat, 2019)

(b) Indoor Soil Cultivation (Cheiffetz, 2015)

Figure 1.1: Comparison of Two Cultivation Types of Spinach

Greenhouses can be equipped with raised beds, soil, and also with hydroponic systems. Hydroponics has been applied to specific crops in greenhouses for several years. It is a soilless cultivation technique in which plants are grown in a water-based nutrient solution (Kumar, 2024). Other definitions specify that hydroponics refers to growing roots directly in nutrient solutions without media, whereas in some systems the crop grows in an inert substrate (Jones, 2014). Proposed cultivation methods include both horizontal hydroponics and vertical farming (Cornish et al., 2019; Kopicky, 2014; Muhammad Akbar Bin Abdul Ghaffar, 2017), with numerous variations in substrates, system configurations, and nutrient solutions. Additionally, hydroponics can be integrated into a Controlled Environment Agriculture (CEA) systems, enabling automation of environmental factors such as temperature, humidity, and light intensity (Walters et al., 2020). These systems can be implemented in high-tech greenhouses. By eliminating outdoor risks and uncertainties, hydroponic systems improve growing conditions, enhance resource efficiency, and ensure more consistent yields compared to field cultivation (Fuentes-Peñailillo et al., 2024; Shen et al., 2021; Walters et al., 2020). They also enable year-round production by removing seasonal constraints, which provides a major advantage over traditional field cultivation. Furthermore, hydroponics requires less water and arable land than both open-field and conventional soil-based greenhouse cultivation (Fuentes-Peñailillo et al., 2024).

(a) Horizontal Layers (Insider, 2023) **(b)** Vertical Layers (Brandon, 2025)

Figure 1.2: Comparison of Horizontal and Vertical Layering Approaches

Hydroponic systems are applied at a range of scales, from small home-growing setups to large commercial greenhouses. For large-scale cultivation, comparisons can be made between open-field cultivation, soil-based greenhouses, horizontal hydroponics, and vertical hydroponics. These comparisons, highlighted in Table 1.1, are the key challenges and opportunities associated with different cultivation strategies (Fuentes-Peñailillo et al., 2024; Kumar, 2024; Shen et al., 2021). From this comparison, it can be seen that indoor cultivation is more sustainable than field cultivation in terms of water efficiency, space efficiency, and land use. A big disadvantage is the high energy use, and if this is created with fossil fuels, the carbon footprint can spike. Results from Life Cycle Assessment (LCA) studies often show trade-offs between local conditions, climate, availability of renewable energy, and distance to markets (Shen et al., 2021).

Table 1.1: Comparison of Cultivation Methods

Criteria	Field	Indoor Soil	Horizontal Hydro	Vertical Hydro
Production rate	Low	Medium	High	Highest
Space efficiency	Low	Medium	High	Highest
Fit-for-use land needed	Yes	No	No	No
Water efficiency	Low	Medium	High	High
Environmental factors	Yes	No	No	No
Production all year	No	Yes	Yes	Yes
Weeds, pests	Yes	Yes	No	No
Possibility for automation	Yes	Yes	Yes	Yes
Cost	Low	Medium	High	Highest

Note. Adapted from (Fuentes-Peñailillo et al., 2024; Kumar, 2024; Lubna et al., 2022; Mir et al., 2022; Sardare & Admane, 2013; Shen et al., 2021).

1.2. Problem Definition

Although hydroponic systems are increasingly applied in high-tech greenhouses, a formal design methodology tailored to these systems is currently lacking in the literature. Existing research focuses mainly on control systems, resource circulation, and robotics (Fuentes-Peñailillo et al., 2024; Mahajan et al., 2022; Van Os et al., 2019), and is focused on well-established crops such as lettuce and tomatoes (Jones, 2014). However, a big part of this research is kept in-house by developing companies. In contrast, novel or specialty crops have unique cultivation requirements and are cultivated on a small scale, or not yet at all. Examples of these specialty crops are vanilla [1], saffron[1], and the Russian dandelion (Cornish, 2019). For the Russian dandelion in particular, the value is in the roots, which have specific cultivation requirements that are not addressed by conventional hydroponic systems. Applying conventional hydroponic systems to these crops hinders performance and inefficiencies, or may not be economically feasible (Cornish, 2019; Muhammad Akbar Bin Abdul Ghaffar, 2017).

The lack of a formal design methodology that integrates biological, technical, and economic factors hinders both academic research and practical implementation. There is insufficient guidance on system development, including design decisions, trade-offs, and constraints for cultivating non-standard crops. As a result, industry efforts to expand hydroponic production to new crops often face economic uncertainties and limited knowledge (Kopicky, 2014; Muhammad Akbar Bin Abdul Ghaffar, 2017).

Developing a structured methodology would provide a framework and guidelines to overcome these challenges, enabling efficient, reliable, and scalable hydroponic system designs for specialty crops. In addition, a quicker evaluation of whether the crop is suitable for hydroponic cultivation could be found. The methodology should apply to both academic and industrial perspectives.

[1] Cultivation information gathered through discussions with experts.

1.3. Research Objective

The aim of this research is to develop a systematic methodology for the conceptual design of large-scale hydroponic systems for specialty crops in CEA environments. This methodology seeks to address the current gap in the literature by providing a structured framework that guides design decisions, considers functional requirements, and incorporates Key Performance Indicators (KPIs) and trade-offs.

The objectives of this study are to:

- Define a structured approach for conceptually designing hydroponic systems for specialty crops.
- Ensure the methodology supports both academic research and practical industry implementation.
- Demonstrate the applicability of the methodology through a case study on Russian dandelions, including an evaluation of cultivation feasibility and economic considerations.

1.4. Research Questions

The main research question of this study is:
How can a conceptual design methodology be developed for hydroponic system design and validated through a case study on Russian dandelions?

To answer the main research question, four Sub-Questions have been defined to guide the research:

SQ1 Which existing design methodologies in mechanical engineering are relevant to adapt for the development of hydroponic systems?

SQ2 What functional requirements, constraints, design parameters, process variables, and KPIs define and guide the conceptual design of hydroponic systems?

SQ3 What structure and core components define a design methodology tailored to hydroponic systems?

SQ4 Case study: How does the proposed design methodology perform when applied to the system design for the Russian dandelion?

1.5. Approach

This research follows a research-based design method to develop a systematic methodology for the conceptual design of large-scale hydroponic systems for specialty crops. The approach is iterative, combining literature studies, theoretical adaptation, and practical validation, with feedback loops allowing the methodology to evolve as new insights are gained.

The first step is an extensive literature review to collect information on greenhouses, hydroponic systems, and existing design methodologies in mechanical engineering. Principles from these methodologies will be examined, compared, and adapted to provide a theoretical foundation for the methodology. This review helps identify best practices, limitations, and gaps. Building on the literature and Sub-Question findings, the methodology will be iteratively refined to address system-level aspects

The practical aspect of this research involves a case study on Russian dandelions. The crop is illustrated in Figure 1.3. This crop was selected because it is a specialty plant with high economic potential, unique cultivation requirements, and limited prior hydroponic research (Cornish, 2019). Its roots contain natural rubber in the form of latex, making root-focused hydroponic cultivation both innovative and challenging. Hydroponic systems have traditionally been used to harvest the above-ground parts of crops, so designing a system for root harvesting represents an untested application. By using a test setup in a climate chamber, experiments provide data on this crop's specific cultivation requirements, which are incorporated into the methodology. The developed methodology is then applied to a conceptual design for a hydroponic system for Russian dandelions, including an economic evaluation of different growing options.

Figure 1.3: Russian Dandelion (Zibek & Hahn, 2025)

1.6. Scope

The scope of this research focuses on hydroponic systems within greenhouse environments. While general knowledge of greenhouses is required to understand the context (see section 3.1), the design of greenhouses itself is not included. The methodology focuses on the conceptual design of hydroponic systems for specialty crops. Hereby, the methodology takes the biological, technical, and economic considerations into account. The methodology emphasizes macro-level mechanical design, covering system-level choices. Detailed machine design, fluid dynamics modeling, structural calculations, and system control are beyond the scope of this project. However, the basics are taken into account while creating the methodology. Performance is taken into account for the methodology, but optimization is too crop-specific and outside the scope.

Crops considered in this research are limited to those feasible for hydroponic cultivation under the defined system constraints. Crops that are impractical due to growth requirements or system limitations are excluded. These include trees, cereals, and heavy fruiting plants, as their root systems are too large, their life cycles are too long, or they require specific machinery for harvesting. Both in- and excluded crops are given in subsection 3.2.4.

The case study is intended to test and validate the methodology itself, not to produce detailed designs of machines, systems, or components, as it is still at an early conceptual stage. That is also why not every single part of the methodology is applied. To create an inclusive case study, missing values will be filled with assumptions. These are based on the data of hydroponically grown lettuce and model crops. These crops have been well studied and contain the necessary data. The geographical scope of the case study is set in the Netherlands due to available information. However, this is not a project-specific requirement. Additional scope limitations are also provided in chapter 7. Due to limited plant material and the absence of agronomic data or control groups, the experiments serve to guide the development of the methodology rather than producing results. The experiment functions as a proof of concept.

1.7. Structure of the Report

This chapter introduces the problem and outlines the research approach. A thorough explanation of the research design and data collection is provided in chapter 2. Chapter 3 then reviews the relevant literature on greenhouses, crop growth, hydroponic systems, and design methodologies, establishing the knowledge for this work. The findings of the literature are compared for hydroponics, and are presented in chapter 4. The deeper analysis for the hydroponic system is provided in chapter 5. The results are then combined into a conceptual design methodology in chapter 6. The case study and the results are given in chapter 7. Finally, chapter 8 discusses the broader implications and limitations of the findings, while chapter 9 presents the overall conclusions and recommendations for future work. Additional information can be found in the appendices.

2

Research Design and Data Collection

This chapter presents the research methodology used to develop a design methodology for hydroponic systems. It outlines the research approach, data collection methods, and experimental set-up.

2.1. Research Approach

The objective of this study is to develop a methodology for conceptual hydroponic system design. To achieve this, the research follows a Design Science Research (DSR) approach. This method focuses on developing solutions to practical problems (Gledson et al., 2024). It fits the design-oriented nature of this project. An adaptation of the traditional DSR model is applied to better fit the objectives of this research. This can be seen in Figure 2.1.

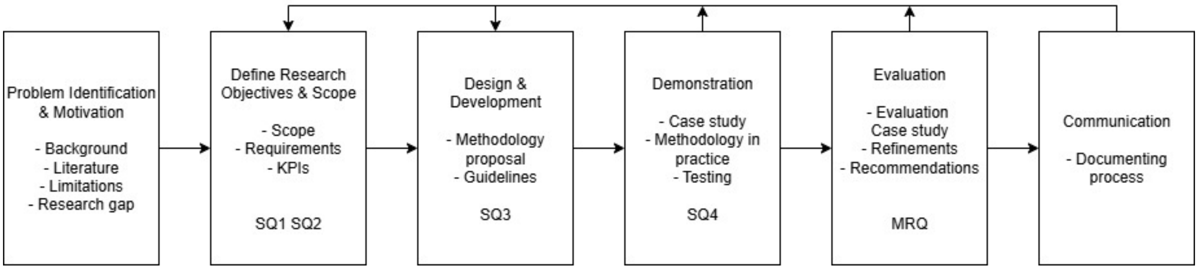


Figure 2.1: DSR Adaptation of Methodology

The research process follows a structured sequence: defining the problem and system boundaries, specifying requirements, designing and developing solutions, demonstrating outcomes, and evaluating results. Iterative feedback loops ensure connection with research objectives and practical feasibility. Additionally, tools from axiomatic design and systems engineering are integrated to support structured decision-making and trade-off analysis.

The study consists of two main parts. The first part, methodology development, is qualitative and focuses on literature synthesis and system analysis. This phase aims to create a flexible and modular methodology that can be applied to different specialty crops. The second part, case study application, is quantitative and practical, involving the conceptual design and experimental observation of a hydroponic system for Russian dandelion. This phase tests the applicability of the developed methodology in a real-world context and ensures its validation. The Russian dandelion was selected as it represents a challenging specialty crop with specific growth requirements, providing a test for the methodology. The insights gained from applying the methodology to this specific case will demonstrate its general applicability.

2.2. Data collection

Data for this research were collected using three approaches. Different types of data were needed at various stages of the study to support both the development of the methodology and the case study.

2.2.1. Literature review

The literature review was focused on four topics:

- Greenhouse engineering: General systems, design factors, and advantages and limitations.
- Hydroponic systems: Large-scale cultivation options, including system layout, machinery, and operational strategies.
- Design methodology in engineering: Existing approaches and methodologies relevant to system design and development.
- Crop-specific research: Focused on crops in general, the impact on growing, and the crops often grown in hydroponics. During the case study, an additional literature review was conducted on the Russian dandelion, including cultivation practices and rubber synthesis in the roots.

2.2.2. Expert and industry knowledge

Not all the necessary data were available from the le alone. To complement the literature review, field visits and semi-structured interviews were conducted to gather practical insights from the industry. Three key site visits were carried out:

- World Horti Center: A hub for innovation, education, and research in horticulture (Info World Horti Center, n.d.). A test set-up for tomatoes demonstrated hydroponic cultivation, including growing choices for media choices and pest management strategies.
- Rijk Zwaan Dinteloord: This breeding and seed development facility provided hands-on insight into greenhouse operations and automation. Greenhouse engineers and cultivators highlighted practical aspects of system design (Info Rijk Zwaan, n.d.).
- Wageningen University & Research, Bleiswijk: Multiple experimental greenhouses were visited (Info WUR, 2012). Professor Filip van Noort demonstrated set-ups for small-scale and specialty crops. The discussion included Russian dandelions and potential methodology limitations.

These visits provided opportunities for direct engagement with experts, allowing concepts identified in the literature and results to be tested against real-world practices. Discussions with horticultural engineers, system designers, and crop specialists contributed to refining system boundaries, confirming design constraints, and ensuring the methodology remained practically relevant.

2.2.3. Experiments and testing

To investigate the specific growth requirements of Russian dandelion, a series of cultivation experiments was conducted within a small-scale climate-controlled chamber at Van der Hoeven Horticultural Projects. Testing was initiated during the literature review phase to ensure plant availability for the time working on the case study. Appendix F contains the pictures of the climate chamber and contains additional cultivation procedures. The dandelion seeds used were kept in a cool place for eight years. The seeds were potted in various potting sizes and mixtures to observe their development.

The experiments were conducted in a 9 m^2 (Nutrient Film Technique (NFT)) room. Standard (shortened) NFT trays, with spacing sufficient to prevent crop overlap, were placed on the growing table. A pump and recirculation system periodically delivered a nutrient solution. Climate control was achieved through a small pad wall for humidity regulation and two fans, ensuring a uniform air environment. Heating and cooling were regulated as well. Fast-growing companion crops (spinach, lettuce, basil) were cultivated alongside the dandelions to increase local humidity and to provide practice with the system's operation.

Germination was initiated in plugs containing either coco coir or rockwool mats. These were irrigated and maintained under a humidity dome for a minimum of five days. The dome was placed in the entrance of the climate chamber, so it had the same conditions but no lighting.

Plant nutrition was supplied via a standard A/B nutrient solution mixture. The pH was adjusted using demineralized water, and tap water was used for system top-ups due to evaporation or leakage. The complete technical set-up consisted of the following components:

- 9 m^2 NFT hydroponic table

- Mechanical valves to control air exchange
- Standard NFT trays with variable hole sizes and spacing. The depth of the trays is not variable. The spacing was big enough that the crops did not overlap
- Flexible tubing for nutrient delivery
- Two fans for air circulation
- Pad wall for humidity control and cooling
- Light Emitting Diode (LED) grow lights
- Nutrient solution (Brand Plagron)
- Reservoir (50x50x70 cm, filled 10 cm)
- Hoogendoorn measurement systems
- iSii climate computer for environmental monitoring and control
- Pot sizes: 4 cm, 6 cm. Made of carton

The chamber's environmental conditions, detailed in Table 2.1, were maintained by a dedicated climate computer. The climate chamber was monitored at least twice a week. During these times, the equipment and resources were adjusted if necessary. The crops were monitored for root growth, flowering, and signs of stress. The results were not intended to guide agronomic practices but rather to inform the design of the case study system. While the rubber content could not be measured due to equipment limitations, the experiment still gave practical insights. Due to the limited availability of fresh seeds, the germination and cultivation were less effective.

Table 2.1: Standard Environmental Conditions Maintained within the Climate Chamber

Parameter	**Value**
Photoperiod (hh:mm)	07:00–19:00
Light source	LED. Full spectrum
Photosynthetic photon flux density (μmol m^{-2} s^{-1})	700
Relative humidity (%)	70–85
Temperature ($^\circ$C)	20–24
Airflow	Continuous (2 fans)
Irrigation, photoperiod (h)	Every 2 hours
Irrigation, dark period (h)	Once
Electrical Conductivity (EC) (mS/cm)	1.2–2
Potential of Hydrogen (pH)	5.5–6.6
CO_2 concentration (ppm)	600-700

3

Literature Review

This chapter reviews the literature on greenhouse and hydroponic systems. Key aspects are discussed while also highlighting the advantages and limitations of hydroponic systems and greenhouses. The chapter concludes with an overview of mechanical engineering design methodologies.

3.1. The Greenhouse

Greenhouses are used worldwide to increase food production by providing a controlled environment in which crops can be cultivated more efficiently (Andreescu & Gurban, 2018; Stanghellini et al., 2019). They shield plants from weather, pests, and diseases, while allowing conditions like temperature, humidity, and irrigation to be adjusted (Blanco et al., 2022; Critten & Bailey, 2002). Due to the predictable environment, irrigation can be done more consistently and efficiently (Critten & Bailey, 2002). This results in higher yields and higher quality crops. Another advancement is the ability to grow a wider variety of crops in a region (Blanco et al., 2022).

Despite these benefits, greenhouse cultivation faces challenges. Climate control is complex, as it must account for both physical and biological processes inside and outside the structure (Andreescu & Gurban, 2018). Although greenhouses create a protected environment, diseases and fungi can still cause problems, so protection measures are needed (Andreescu & Gurban, 2018). Greenhouses can have high energy demands, and there are environmental concerns regarding plastic waste, soil pollution, and biodiversity loss (Blanco et al., 2022). The type of greenhouse affects these issues, but compared to field cultivation, resources can often be reused more sustainably (Fuentes-Peñailillo et al., 2024). Automation can be implemented more easily, reducing the need for manual labor.

3.1.1. Greenhouse Design

As explained by Andreescu and Gurban (2018): ”The greenhouse engineering covers a multidisciplinary approach of the sciences, engineering, and economics, and for final success and sustainability, the social and political support must also be achieved. The most effective innovations in greenhouse engineering design, operations, and management will incorporate inputs from partnerships with the academic, private, and public sectors of society.”

An important factor for the greenhouse system is the location and climate in which it should function (Stanghellini et al., 2019). This determines the level of technology and is also correlated to the costs (Blanco et al., 2022). The structure and system must be matched to local conditions: in mild climates, lightweight constructions with passive climate strategies may be sufficient, while colder or more variable regions require more advanced and expensive designs that minimize losses. These regional variations influence both material choices and the degree of technical integration.

In studying greenhouse optimization, the ultimate concerns are the capital cost of the greenhouse and the cost-benefit for new greenhouse designs or design changes to the grower (Critten & Bailey, 2002). The biggest operational costs for greenhouses are the energy consumption and manpower needed (Breukers et al., 2008). The optimization of a greenhouse is highly dependent on the crop (Critten & Bailey, 2002). For tomatoes, it can be the maximum crop production on a continuous time schedule, while for cut-flowers, the aim is shelf-life and maturity at specific dates.

In general, there are six main technologies applied in the climate control of the greenhouse that need additional explanation. This summary is based on the publication of Stanghellini et al. (2019). Figure 3.1 shows a simplified greenhouse climate overview.

- Heating: By solar radiation, the greenhouse warms up. Additional heating might still be necessary. This can be achieved by forced and free convection. This can be a fan or piping system to distribute the heat. The energy sources for the heating range from flue gas condensers, geothermal wells, residual industry energy, to wind energy.
- Ventilation: The hot and humid air inside the greenhouse is exchanged for cold and drier air. Ventilation decreases the vapor as well. Ventilation can be done by fans, a method known as forced or mechanical ventilation. It can also be done passively, using wind pressure and buoyancy, by creating chimneys. If ventilation is used, new integrated pest management measures should be implemented. An example of this is insect netting to limit pest access.
- Cooling: If ventilation cannot provide sufficient cooling, active cooling systems are required. Fogging systems can evaporate water to decrease the temperature, and padded walls can also be used. Evaporative cooling methods include fogging systems and pad walls, which lower the temperature by water evaporation. Mechanical cooling using heat pumps or roof sprinklers can be used when evaporation is not desirable. These systems are particularly important in warm climates or during summer months.
- Dehumidification: When high humidity risks plant disease or reduces transpiration, specific dehumidification is needed. This is often required when cooling systems would lower the temperature too much. Methods include condensation on cooling coils (using heat pumps) or chemical dehumidification. Dehumidification needs are strongly dependent on crop transpiration rates and external climate conditions.
- Lighting: To decrease the heating inside the greenhouse, different shading techniques are used. These actions might require the addition of lighting inside the greenhouse to still allow enough light for the crops to grow. These supplementary lights can also be used to extend the growing seasons. The lighting can also be used to adjust the light spectrum to increase yield and consistency by adding blue and red wavelengths into the spectrum. The lighting can also create a difference when working with crops that need a very specific quality.
- Carbon dioxide: Addition of carbon dioxide will greatly influence the photosynthesis and thus the crop. CO_2 can be used from the combustion of fossil fuels, but it is important that it does not contain noxious gases. The gas can be taken from the machines inside the system, or from CO_2 tanks. It is important to have a control system to create an even distribution within the greenhouse.
- Irrigation: To limit the water and fertilizer loss, there are two options to be applied. The first one is precise irrigation, where, with drippers or sprinklers, the irrigation can be controlled. The second option of limiting losses is the re-collection and re-use of the drainage water, which is an option in hydroponic systems. It is important to measure the collected water for accumulating salts or decreases in nutrients. Then the irrigation water needs to be treated or discarded.

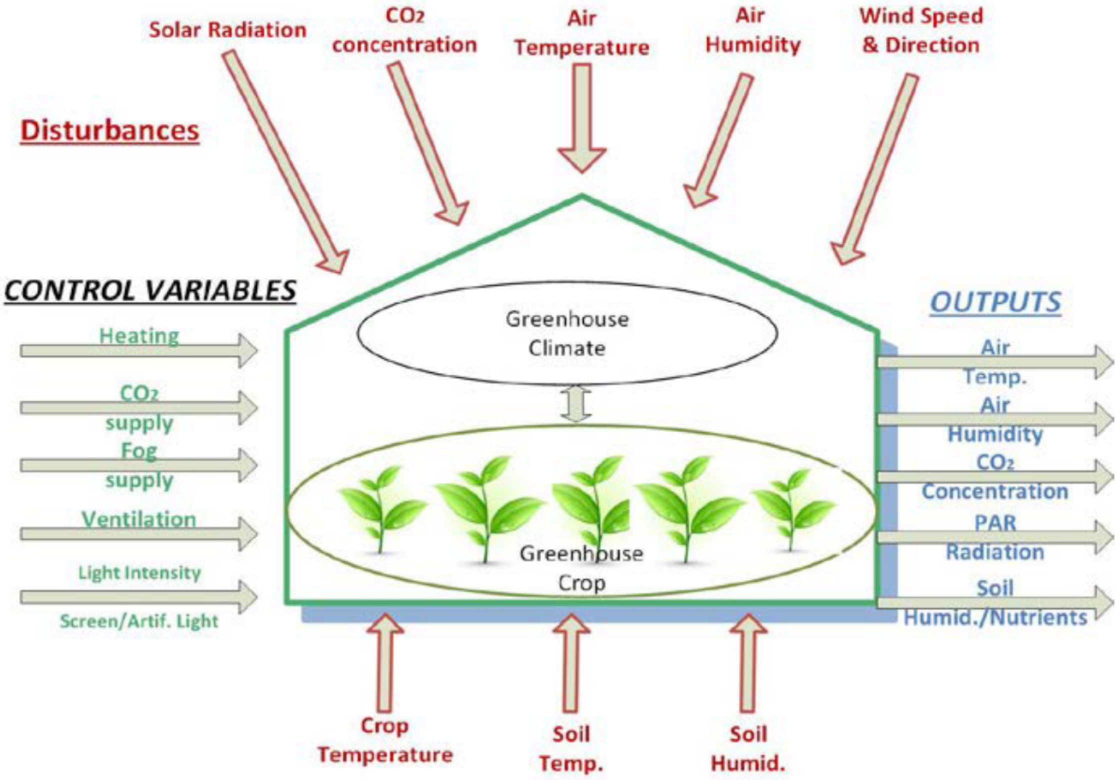


Figure 3.1: Simplified Greenhouse Climate Model (Andreescu & Gurban, 2018)

Greenhouses vary in their level of technological integration, ranging from open and standard designs to semi-closed and fully closed systems. Open and standard greenhouses rely mostly on passive strategies, making them cheaper to build but generally less productive than semi-closed or closed systems. In these simpler structures, soil cultivation, raised beds, or growing mats are commonly used, while hydroponics can be applied, but with limited efficiency. In contrast, closed and semi-closed greenhouses more often use hydroponic systems to take advantage of the controlled environment. Figure 3.3 illustrates an open passive greenhouse, with plastic coverage and raised beds. Figure 3.4 illustrates a high-tech greenhouse, with an automated hydroponic system growing lettuce.

The structural framework of a greenhouse is typically made from galvanized iron, mild steel, or aluminum, with glazing materials such as glass, polyethylene, or polycarbonate (Ashok & Sujitha, 2021). Roof structures can take on various forms, as illustrated in Figure 3.2. The shapes on a commercial level are often the even-span roofs. This is a gable roof (a). A variation on this type is the Dutch Venlo structure, which allows natural ventilation. Roof structure (b) can be seen in Figure 3.3 and roof structure (a) is illustrated in Figure 3.4.

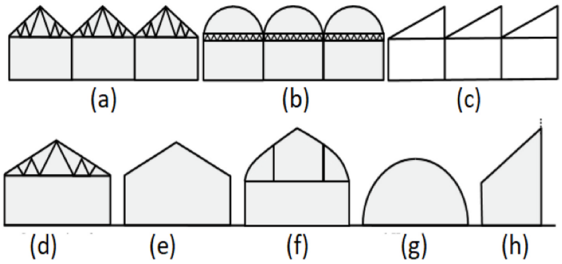


Figure 3.2: Roof Shapes of Greenhouses (Badji et al., 2022)

Figure 3.3: Strawberry in Raised Beds (Stanghellini et al., 2019)

Figure 3.4: Lettuce in Hydroponic High-tech Greenhouse (Van der Hoeven, 2025)

3.1.2. Growing Crops in Greenhouses

A plant carries out several essential processes, but the three core physiological processes are photosynthesis, respiration, and transpiration. Through photosynthesis, plants convert light, water, and CO_2 into sugars. With respiration, the sugars are transformed into energy for growth. With transpiration, the plant loses water through its leaves, but this allows the nutrients and water to enter the root system (Stanghellini et al., 2019). The efficiency of these processes depends strongly on environmental conditions. The main factors influencing the growth of crops are temperature, light, and CO_2 (Stanghellini et al., 2019). That is why a CEA is important to use in a greenhouse. A crop's life cycle begins with germination, followed by vegetative growth, flowering, and reproduction. The growth of crops can be seen as an S-curve. This is illustrated in Figure 3.5, which is the general shape for annual crops.

- Lag Phase: Slow growth after germination.
- Exponential Phase: Very rapid growth.
- Linear Phase: Steady, strong growth (the numbers below approximate this phase).
- Senescence Phase: Growth slows and stops as the plant matures and fruits.

This means the growth rate is not linear throughout the life cycle of the crop. Size, volume, or weight is often needed to create enough photosynthetic capacity to reproduce. However, the growth and development are not directly linked to each other and differ per crop (Stanghellini et al., 2019). This can be seen in lettuce, where the biomass increases without reproductive development. Also, lettuce is often harvested before the flowering stage starts, so it does not go beyond the linear phase. This is different for tomatoes. Tomatoes need specific triggers for flowering. Only then can the pollination happen, and finally, a harvestable product is produced. Also, for strawberries is the graph is different as it has a double sigmoid curve due to the fruits (Miura et al., 1990).

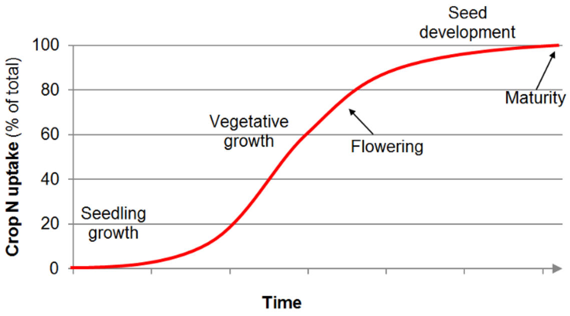


Figure 3.5: S-curve Growth of a Crop (Daniel Geisselle & William R. Horwath, 2025)

3.2. Hydroponics

The term 'hydroponics' originates from two Greek words: *hydro*, meaning water, and *ponos*, meaning labor (Jones, 2014). The two words combined give working water. The definition of hydroponics has different interpretations, but essentially, it involves growing plants in a nutrient solution without soil, using an inert growing medium (Jones, 2014). The term ”soilless” refers to systems where plant roots interact with a substrate rather than natural soil (Fuentes-Peñailillo et al., 2024). Historically, hydroponic techniques date back to ancient civilizations, such as the Hanging Gardens of Babylon (Jones, 2014). The method became widely used during World War II when it was employed to increase the food production in remote military locations (Jones, 2014; Walters et al., 2020).

Moreover, indoor hydroponic farming minimizes external threats from pests, weeds, and pathogens (Viscon Hydroponics, 2025). Additionally, less water is used in comparison to outdoor farming (Fuentes-Peñailillo et al., 2024; Kannan et al., 2022). Also, less space is required for the same yield. Automation techniques can be used to control and predict (Fuentes-Peñailillo et al., 2024), and they can also be applied in handling, growing, harvesting, and shipping, as seen in state-of-the-art farms.

In addition to its advantages, hydroponics systems come with a high initial investment (Fuentes-Peñailillo et al., 2024). These costs include the CEA, the greenhouse, and the need for higher technical knowledge in growing the crops (Fuentes-Peñailillo et al., 2024; Kannan et al., 2022). Fuentes-Peñailillo et al. (2024) also mentions there are higher operational costs and energy usage in comparison to field cultivation. A big limitation of the hydroponic system is the risk of a waterborne disease that can quickly spread all over the system (Jones, 2014; Kannan et al., 2022).

Hydroponic systems are particularly suited for high-value, fast-growing crops such as leafy greens, vegetables, herbs, flowers, medical crops, and fodder crops (Jones, 2014; Sardare & Admane, 2013). These crops require minimal structural support and align well with automation. On the other hand, fruiting plants that require structural support or manual tasks like pruning can be difficult to fully automate. Due to the higher-profit products, fruiting plants in a hydroponic system can still be beneficial.

3.2.1. Hydroponic System Typologies

Hydroponic farming consists of different system designs, primarily based on how nutrients reach the plants (Fuentes-Peñailillo et al., 2024). The choice of system depends on factors such as available space, root depth, and the structural requirements needed to support plant growth (Sardare & Admane, 2013). Each system has its own advantages, making certain designs more suitable for specific crops and growing conditions. An overview of the basic systems:

- NFT: A thin film of nutrient solution continuously flows over the plant roots. The excess solution is collected and recirculated (Fuentes-Peñailillo et al., 2024; Kumar, 2024; Mahajan et al., 2022).

- Deep Flow Technique (DFT): A deeper version of NFT, but there are no cultivation channels. Additional oxygenation is still required (Kumar, 2024).

- DWC: Plant roots are submerged in a deeper layer of nutrient solution compared to NFT. Oxygen is supplied using air pumps to prevent root suffocation (Bunyuth & Mardy, 2024; Kannan et al., 2022; Kumar, 2024; Viscon Hydroponics, 2025).

- Kratky Method: Adaptation of DWC, where no pumps are used, but aeration happens when the water level drops (Jones, 2014).

- Ebb and Flow Ebb and Flow (Ebb and Flood) (EF): The root zone is periodically flooded with nutrient solution and then drained, allowing for aeration between cycles. It is different from NFT because the roots are not continuously exposed to flowing nutrients (Bunyuth & Mardy, 2024; Kumar, 2024).

- Aeroponics: Plant roots are suspended in air and misted with a nutrient solution at regular intervals (Bunyuth & Mardy, 2024; Jones, 2014; Kumar, 2024).

- Aerohydroponics: A hybrid system where the upper roots are exposed to aeroponics while the lower roots remain submerged in a nutrient solution, combining the benefits of both systems (Van Os et al., 2019).

- Drip/Pass-Through Systems: A slow-drip irrigation system delivers nutrients directly to the roots. It can be recovery (recirculates solution) or non-recovery (excess solution drains away) (Bunyuth & Mardy, 2024; Kumar, 2024).
- Wick system: A passive hydroponic system where nutrient solution is absorbed and transported to the roots through a wick (Bunyuth & Mardy, 2024; Kannan et al., 2022; Kumar, 2024). No pumps are required.
- Aquaponics: Integration of hydroponics with fish. It creates beneficial relations as the fish manure can be used as fertilizer (Mir et al., 2022). It uses the other systems as a base and then adds fish.

Schematic representations of the hydroponic systems are shown in Appendix B for a deeper explanation. Table 3.1 shows the comparison of the hydroponic systems. The comparison criteria focus on the essential key factors of hydroponic systems. Criteria specifically connected with commercial cultivation, such as automation and scale, are also included. More criteria can be applied, but they are outside the scope of this review.

Table 3.1: Comparison of Hydroponic Systems

Criteria	NFT	DFT	DWC	Kratky	EF	Aeroponics	Aerohydroponics	Drip	Wick	Aquaponics
Circulating water	Yes	Yes	No	No	Yes	No	Yes	No	No	No
Amount of water needed	Low	Medium	High	Low	Medium	Low	Medium	Medium	Low	High
Growing media needed	No	No	No	Yes	Yes	No	Yes	Yes	Yes	Yes
Complexity	High	Medium	Medium	Low	Medium	High	High	Medium	Low	High
Large-scale	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No	Yes
Automation potential	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No	Yes
Energy consumption	Medium	Medium	High	Low	Medium	High	High	Medium	Low	High

Note. Adapted from (Bunyuth & Mardy, 2024; Fuentes-Peñailillo et al., 2024; Jones, 2014; Kannan et al., 2022; Kumar, 2024; Mahajan et al., 2022; Mir et al., 2022; Van Os et al., 2019; Viscon Hydroponics, 2025).

3.2.2. Factors Influencing Design

Next to the available space, root depth, and structural requirements, several factors determine the most suitable hydroponic system for a given application. These include nutrient solutions, water management, CEA, and growth media. Each of these elements interacts with the crop to ensure optimal plant growth and yield.

Nutrient solutions

A nutrient solution, also referred to as plant food, must contain all essential elements required for plant growth (Jones, 2014). Fuentes-Peñailillo et al. (2024) added that only hydrogen (H), oxygen (O), and carbon (C) are not needed in the solution. The other elements include the six macronutrients — nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) —as well as seven essential micronutrients —boron (B), chlorine (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), and zinc (Zn) (Jones, 2014). The specific ratio and concentration of these nutrients depend on the plant species, growth stage, and hydroponic system used (Jones, 2014).

Nutrient concentration is typically measured using EC (Walters et al., 2020), which indicates the total dissolved salts in the solution. Maintaining optimal EC levels is crucial, as excessive salinity can lead to osmotic stress, while insufficient concentration can result in nutrient deficiencies (Kannan et al., 2022). Additionally, pH levels must be carefully regulated since extreme values can impact nutrient availability, leading to deficiencies even if the elements are present in sufficient quantities (Jones, 2014).

Root aeration is another critical aspect of nutrient management. In hydroponic systems, oxygen availability at the root zone influences nutrient uptake efficiency and overall plant health (Jones, 2014). Insufficient aeration can lead to root hypoxia, inhibiting growth and increasing susceptibility to root diseases (Mahajan et al., 2022). Depending on the system, there are different ways to aerate the roots, like air pumps and air stones (Mahajan et al., 2022).

Although different plants have varying nutritional requirements, one of the most widely used nutrient formulations is the Hoagland and Arnon solution (Jones, 2014). Modified versions of this solution are frequently used to meet crop-specific needs, such as half-strength solutions for sensitive plants or potassium-enriched formulations for tomato cultivation (Jones, 2014; Touliatos et al., 2016).

Water management

As stated by Walters et al. (2020), water quality and availability play a big role in hydroponic system efficiency. Factors such as water source, dissolved mineral content, and microbial load influence plant health and system longevity (Van Os et al., 2019). The ideal water source should be low in contaminants such as heavy metals, chlorine, and pathogens to prevent toxicity or disease outbreaks (Jones, 2014; Van Os et al., 2019; Walters et al., 2020). Next to this, the temperature of the water varies depending on the plant species.

Hydroponic systems vary in water usage efficiency, with closed-loop systems such as the nutrient film technique being more water-efficient compared to open systems (Fuentes-Peñailillo et al., 2024). Regular monitoring of water temperature, Dissolved Oxygen concentration (DO) levels, and potential pathogens is necessary to maintain system stability and prevent plant stress (Lubna et al., 2022; Sardare & Admane, 2013; Walters et al., 2020).

Controlled Environment Agriculture

CEA refers to the integration of advanced technologies to optimize plant growth conditions inside a controlled environment such as greenhouses, vertical farms, and growth chambers (**funk**). CEA integrates advanced technologies to improve plant growth conditions. CEA systems regulate variables such as light intensity, temperature, humidity, and CO_2 concentration to maximize yield and quality as stated by Fuentes-Peñailillo et al. (2024) and Walters et al. (2020).

Additional artificial lighting is a fundamental component of many CEA systems. LEDs, which offers multiple light spectra to match the plant requirements at different growth stages (Fuentes-Peñailillo et al., 2024; Mahajan et al., 2022). Light can influence the type of growth; for example, blue light on seedlings helps create a strong root system instead of excessive leaf growth (Stanghellini et al., 2019).

Beyond lighting, environmental control is essential. Temperature and humidity control prevent excessive transpiration and nutrient imbalances, while higher CO_2 increases photosynthesis efficiency (Jones, 2014; Mahajan et al., 2022; Walters et al., 2020).

CEA allows for year-round cultivation, which creates the opportunity to farm without the interruption of seasonal changes. CEA can be used in urban surroundings, underground, or in regions with extreme climates (Jones, 2014; Kannan et al., 2022). One of the major challenges of hydroponics within CEA is its significant energy demand. Fuentes-Peñailillo et al. (2024) highlights that lighting and climate control systems play a big part. To mitigate the energy demand, new LED lighting, passive cooling, and solar panels are explored as possibilities (Kannan et al., 2022). Using these technologies not only reduces environmental impact but also increases long-term economic feasibility.

Growth media

Growing media in hydroponics is often inert, meaning the roots use it for anchoring but not for gaining nutrients. Some media can take up water and nutrients from the hydroponic system and give it to the roots (Jones, 2014). The seedling is often transferred to the growth medium after germination; therefore, they are started in different plugs. Table 3.2 gives an overview of the commonly used growing media with their advantages and disadvantages.

Table 3.2: Comparison of Different Growing Media

Media	Advantages	Disadvantages
Perlite	Lightweight, good drainage, sterile	Expensive, big environmental impact, floats
Rock wool	Water retention, sterile, easy to use	Non-biodegradable, environmental impacts
Coconut coir	Renewable, water retention, good aeration	Potential for high salt content, inconsistent quality
Vermiculite	Water retention, nutrient-holding	Expensive, non-renewable, compaction over time
Clay pebbles	Reusable, good drainage, lightweight	High initial cost, potential for algae growth
Sand	High weight density, drainage	Could be contaminated, low water retention
Peat (moss)	Water retention and aeration	Decomposes over time, acidic pH
Black peat	High water holding retention and nutrient holding capacity	Low aeration, compaction
Pumice	Lightweight, porous, drainage, less environmental impact than perlite	less water-holding than perlite

Note. Adapted from (Fuentes-Peñailillo et al., 2024; Jones, 2014; Van Os et al., 2019)Adapted from.

Selecting the appropriate growth medium depends on the hydroponic system type, crop requirements, costs, and sustainability considerations (Jones, 2014). Next to the inert media, organic material can be added to the crops to increase microbial activity, improving nutrient cycling and root health (Fuentes-Peñailillo et al., 2024; Jones, 2014).

3.2.3. System Design

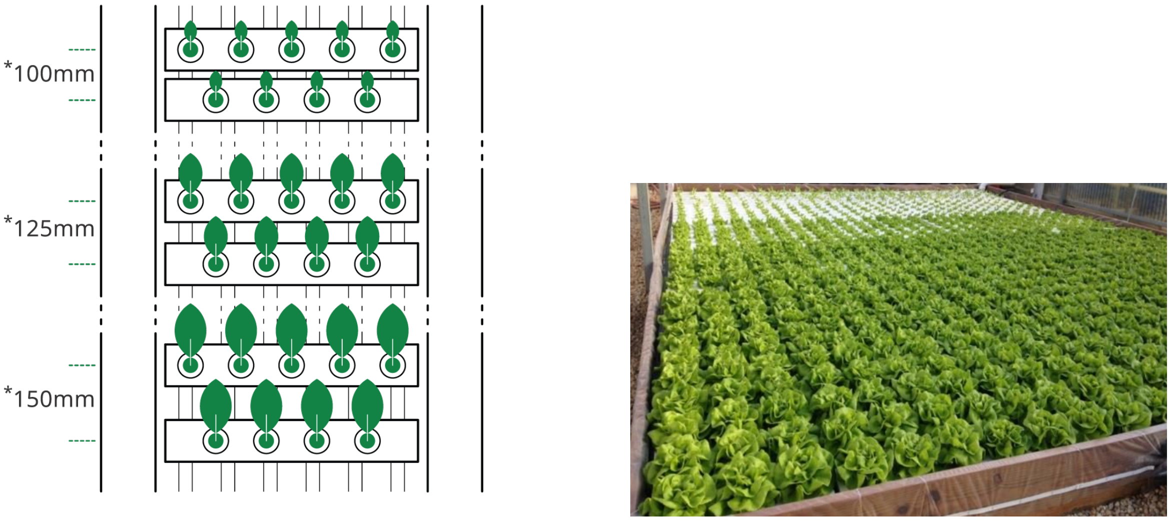
Depending on the hydroponic method, different growing systems can be used, such as trays or foam. The seedlings can be put in linear trays or in shifted trays. Linear trays are the easiest to use as they require no planning. Shifted trays are positioned to ensure plants don't overlap while limiting the space needed at the start of the plant's life cycle. The trays can be planned to create more spacing between them towards the end of a plant's life cycle. This principle is illustrated in Figure 3.6a. Figure 3.6b shows a classic DWC system with crops planted in a static position.

Vertical farming

Traditional hydroponic systems operate in a two-dimensional layout, using one horizontal layer for plant cultivation. A frequently discussed innovation in this field is three-dimensional farming, often referred to as vertical farming. This can be achieved either by stacking multiple horizontal layers Figure 1.2a or by integrating vertically connected growing sections Figure 1.2b (Lubna et al., 2022). As noted by Mir et al. (2022), vertical farming offers the same benefits as hydroponics while increasing available growing space, and thereby increasing overall yield. However, this system also presents challenges, including higher energy demands, an increased need for monitoring and automation, and substantial initial investment costs (Fuentes-Peñailillo et al., 2024; Lubna et al., 2022; Mir et al., 2022).

3.2.4. Growing Crops in Hydroponics

Certain crops are often grown in hydroponic greenhouses. These crops are economically attractive, but this still strongly correlates with the location and target market. The most common examples are lettuce and leafy greens, tomatoes, cucumbers, peppers, strawberries, and cannabis. Cut flowers and ornamentals can also be profitable, while melons or berries are sometimes rotated during seasonal



(a) Multi-Gulley System (MGS) (Organization, 2025) **(b)** Static Placement in a DWC system (Resh, 1017)

Figure 3.6: Comparison of Hydroponic Systems: (a) a Mobile System NFT and (b) a Static DWC System.

(a) Horizontal Layers (Insider, 2023) **(b)** Vertical Layers (Brandon, 2025)

Figure 3.7: Comparison of Horizontal and Vertical Layering Approaches

gaps. To illustrate the variety of hydroponic strategies, three representative crops are discussed in more detail, each highlighting different cultivation requirements and production approaches.

Lettuce

Lettuce is one of the most common hydroponic crops due to its short production cycle (around 35 – 50 days), high turnover, and clean cultivation. It is widely grown in NFT and DWC systems, where the simple growth pattern allows large-scale automation.

Propagation starts with sowing seeds into plugs made of rockwool, peat, or foam, often using vacuum drum seeders. After germination under controlled humidity and temperature, seedlings are transplanted into trays or gutters. From this point onward, little intervention is required until harvest. In NFT systems, moving gutters gradually transport the plants toward the harvesting station, while in DWC systems, new rafts push older ones forward.

Harvest is usually manual but easily automated: lettuce heads can be cut by circular blades that separate them from trays, after which the crop is packaged and trays are recirculated. Lettuce has delicate roots but tolerates minor crop losses well. In highly automated setups, the full cycle requires minimal human labor.

Tomato

Tomatoes, here represented by cherry tomatoes, are another major hydroponic crop but require more complex management than lettuce. They are typically grown in static setups using rockwool blocks, which provide stability for their extensive root systems.

Propagation begins with sowing seeds into large germination blocks. After sprouting, irrigation is provided through drip systems or NFT. As plants grow, stems must be attached to stakes or trellis wires.

This is usually done manually, but new automation options are being tested. Lighting and irrigation strategies are adjusted throughout the cycle to optimize fruit quality. The coloring and shelf life are important for the target market.

Pollination is a critical step, commonly done by bumblebees or mechanical vibration systems. Harvesting is staggered, since fruits ripen unevenly, and must be done carefully to avoid damage. This remains largely manual, although robotic prototypes exist. At the end of the six-month cycle, plants are removed and substrates replaced. Post-harvest handling and pathogen control are particularly important for tomatoes.

Strawberry

Strawberries are a high-value but delicate hydroponic crop. Due to their long germination period, growers usually start with pre-rooted plugs. These are then placed in gutters that allow fruit to hang freely, reducing bruising and improving airflow. Due to strict lighting demands, space efficiency is critical, leading to innovations such as swinging or vertically adjustable gutters. In lower-tech systems, strawberries are also grown in high tables with EF setups.

Irrigation is typically done with drip systems, though NFT and EF are also used. Ventilation and careful microclimate management are essential, as strawberries are highly sensitive to disease and humidity.

This crop requires precision during harvesting. Even slight pressure can damage the fruit, so it is usually performed manually or semi-automatically. Strawberries reproduce through runners, which can be collected and replanted. For a second cycle, dormancy must be induced, often done via cold treatments. Careful post-harvest handling is critical because shelf life is short and bruising reduces market value.

Overview

These three examples show how hydroponic cultivation strategies differ strongly depending on crop morphology and product requirements: lettuce favors speed and automation, tomatoes require structural support and precise pollination, while strawberries demand delicate handling and careful climate control. Despite their demonstrated hydroponic production systems, optimization continues through breeding, automation, greenhouse control, and system design.

Specialty crops

The research objective is the system in combination with specialty crops. There is no specific literature about this; however, the crops need to be feasible to cultivate. These can be characterized as follows:

- High market value
- Benefit from controlled environments (quality, consistency, off-season availability)
- From harvest to the target market quickly
- Compact and manageable crops
- Crops under competition of outside influences (pests, weeds, other usage of available land)
- Exotics or luxury products
- A non-food-related product

The crop choice is eventually dependent on many factors. However, some examples of a specialty crop can be: saffron, vanilla, coffee, medical herbs, bamboo, passion fruits, dragon fruits, and cocoa.

Other crops

While hydroponics has proven effective for crops like lettuce, tomatoes, and strawberries, many plant types are not yet feasible for large-scale hydroponic cultivation. These crops often are not economically feasible or have unique growth requirements that current hydroponic systems cannot easily accommodate. The mechanical and system design considerations for these crops can vary greatly depending on plant type, cultivation goals, and environmental constraints. Crops not yet feasible (economically and system design) in hydroponics can be grouped as follows:

Table 3.3: Not Often Cultivated Plants in Hydroponics

Plant group	Examples	Reasoning / Limitations
Fruit trees	Apple, citrus, mango, banana	Perennial crops with long growth cycles and large space requirements. They are also prone to algae and root rot in hydroponic setups (Russell Sharp, 2024).
Tall or heavy plants	Corn, sunflowers, sugarcane	Require significant vertical space and structural support (VicPlas Holding, 2024).
Taproot and tuber crops	Potatoes, carrots, beets	Need loose, malleable medium for root expansion, which most hydroponic systems cannot provide (Russell Sharp, 2024; VicPlas Holding, 2024).
Deep-rooted perennials	Asparagus, artichokes	Highly valuable crops, but limited by space constraints in hydroponics.
Carnivorous plants	Venus flytraps, pitcher plants	Require low-nutrient, wet substrates; cannot be fed insects in hydroponic systems (Russell Sharp, 2024).
Cereal crops	Wheat, rice, oats, corn	Require wind pollination, long growth cycles, vertical space, and specialized harvesting equipment (Russell Sharp, 2024).
Aquatic plants	Water lilies, duckweed	Can grow in hydroponics like DWC, but highly prone to algae issues (Russell Sharp, 2024).
Heavy fruits	Melons, watermelons, cantaloupes, honeydews	Large size and sprawling growth habits demand space and heavy structural support (VicPlas Holding, 2024).
Arid zone plants	Cacti, succulents	Adapted to dry environments; constantly wet roots in hydroponics are lethal (Russell Sharp, 2024).
Halophytes	Seaweed	Require saline water, prone to algae, and costly to produce hydroponically (Russell Sharp, 2024).
Bulb crops	Onions, garlic	Possible in hydroponics, but economically not feasible.

3.3. Design Methodologies

The definition of a design methodology has been given multiple times. It can be stated as: ”A systematic approach to creating a design consisting of the ordered application of a specific collection of tools, techniques, and guidelines” (Adams, 2015). Next to this, ”a design methodology can be envisioned as a framework or model that focuses the actions of human beings that are attempting to define an object, device, process, or system in order to provide the details required to effect construction, assembly, and implementation for use” as stated by Adams (2015). ”For engineering design, the methodology is a framework or model that guides the execution, tracking, and accomplishment of technical tasks required to accomplish the design of a man-made system.” also added by Adams (2015).

A design methodology provides a structured approach for creating complex systems, guiding designers through the necessary steps, decisions, and tools to develop functional and practical solutions. In engineering, it serves as a framework to organize tasks, reduce errors, and ensure that technical requirements are systematically addressed (Adams, 2015; Sreekumar, 2023). For hydroponic system design, such a framework is especially important because it must bring together mechanical design, process engineering, and the biological requirements of crops.

Effective design methodologies share several key features. They are problem-driven, ensuring that design decisions meet specific system needs. They encourage creativity and optimization, allowing alternative solutions to be explored. They are compatible with interdisciplinary knowledge, which is essential when combining aspects. Finally, they are practical, helping to reduce workload, time, and errors while guiding the design process (Adams, 2015; Sreekumar, 2023).

To identify suitable approaches for hydroponic system design, design methodologies from mechanical and industrial engineering were reviewed. These frameworks were chosen because hydroponic systems share structural and process similarities with mechanical systems. Additionally, the system can be seen as a type of factory. To better assess which methodologies are best suited for hydroponic system design, a comparative analysis of existing approaches is conducted, followed by identifying specific requirements for such a methodology. The compared methodologies are based on the selection of (Cross, 1993) in combination with field-specific methodologies. The methodologies have different scopes and levels of detail. The schematic representation can be found in Appendix C. Section 4.1.1 will compare the methodologies in a multi-criteria decision table.

- Pahl & Beitz: This methodology is a systematic and tool-supported framework focused on engineering design (Qiu et al., 2022). The methodology covers all phases of design, including planning, conceptual design, embodiment design, and detail design (Pahl et al., 2007; Qiu et al., 2022). The approach follows hierarchical phases that converge into the next step, with feedback loops allowing iteration when needed (Drăghici & Banciu, 2004; Pahl et al., 2007). A significant advantage is the inclusion of specific tools, such as function structures, morphological charts, and evaluation matrices, in all phases. The methodology promotes a holistic approach, supporting creativity while maintaining objective evaluation of concepts (Pahl et al., 2007).
- Roozenburg & Eekels: The methodology is called the basic design cycle. Design can also be compared to a trial-and-error process, which is included in the methodology by an iterative process (Annemiek van Boeijen et al., 2010). The structure follows a similar path to Pahl & Beitz. The methodology offers practical guidance through specific tools, such as functional decomposition, stakeholder analysis, and simulation techniques, supporting both creativity and systematic evaluation (Annemiek van Boeijen et al., 2010). At the end of the cycle is a decision point, where, if needed, further actions can be taken. Its accessible framework makes it widely applicable across various engineering and product design contexts.
- DFMA: This is a systematic engineering methodology that focuses on designing products to be easy, cost-effective, and reliable to manufacture and assemble (Formentini et al., 2022; Naiju, 2021). It combines Design For Manufacturing (DFM) and design for assembly Design For Assembly (DFA) principles and provides structured methods to analyze product components and processes (Naiju, 2021). While commonly applied to existing designs, DFMA principles can also be introduced during conceptual design to reduce the number of components, minimize materials and tooling, simplify product structure, and promote modularity (Formentini et al., 2022; Naiju, 2021).
- Axiomatic Design (AD): This is a systems design methodology providing a scientific framework for designing products, processes, and software (Alves & Carmo-Silva, 2009; Kulak et al., 2010). The method translates customer needs into functional requirements, design parameters, and process variables, enabling efficient design improvement and redesign (Adams, 2015; Qiu et al., 2022). It is based on two axioms: the Independence Axiom, which ensures each functional requirement is satisfied independently by a design parameter, promoting robustness and predictability, and the Information Axiom, which minimizes information content to reduce complexity and increase reliability (Adams, 2015; Kulak et al., 2010; Qiu et al., 2022).
- Theory of Inventive Problem Solving (TRIZ): This is a methodology focused on innovation (Ekmekci & Nebati, 2019; Qiu et al., 2022). It provides structured tools to guide design toward inventive solutions, based on patterns of technical evolution and problem-solving strategies (Ekmekci & Nebati, 2019). Principles include identifying and resolving technical or physical contradictions, applying inventive principles, and striving toward the Ideal Final Result, which guides the system to maximum function with minimal complexity (Drăghici & Banciu, 2004; Ekmekci & Nebati, 2019).

3.4. Synthesis, Discussion and Summary

The literature review illustrates that both greenhouse and hydroponic systems are critical for increasing food production. Greenhouses provide protection from environmental variability and allow manipulation of climate, light, CO_2, and irrigation, which directly affects crop growth and quality. Hydroponic systems increase controlled cultivation by allowing precise root-zone conditions while removing risks. Next to that, different sustainability aspects can be applied when cultivating crops. Various crops, from leafy greens like lettuce to more complex fruiting plants such as tomatoes and strawberries, are successfully grown using these systems, with cultivation strategies highly dependent on crop requirements, growth stage, and economic value.

The review of hydroponic system typologies shows that the system design is influenced by factors like nutrient solutions, water management, growth media, and the layout of the greenhouse. With the different options, it can not be stated that there is a best option. It strongly depends on the case. Understanding these fundamental differences is crucial for both researchers developing hydroponic technologies and practitioners selecting systems for specific applications. There is a strong emphasis in the literature on high-value, fast-growing, and easily automatable crops. Crops with long growth cycles, high structural demands, or specialized pollination requirements remain largely unfeasible for large-scale hydroponic cultivation.

From a design perspective, engineering methodologies provide a structural approach for complex systems. Each methodology has specific strengths. Pahl & Beitz and Roozenburg & Eekels present complete phase-based guidance and iterative design. AD focuses on the functions and reducing the system complexity. DFMA has an emphasis on modularity and product with machinery. TRIZ has a focus on innovation and removing contradictions.

The following research gaps have been identified:

- Integration of biological and mechanical aspects: Hydroponic system design needs to combine plant biology with mechanical and process engineering. Current design methodologies don't fully address this integration in a structured way.
- Specialty crops: There is limited research on growing specialty or high-value crops in hydroponic systems, and guidance on adapting systems to these crops is still lacking.
- Feasibility assessment: Deciding whether a crop is suitable for hydroponics is mainly based on economic performance or comparing it to traditional field cultivation. There are no clear guidelines or standards to evaluate crop feasibility for hydroponic systems systematically.
- Sustainability: Water, nutrient, and energy management can be considered for the design of a greenhouse. This is an ongoing process that depends on the situation and the crop.
- Automation and systems: The mechanical engineering aspect is still under development by improving system control, automation, robotics, and monitoring of the greenhouse and hydroponic systems.

The literature suggests that although greenhouse cultivation is well-studied, improvements can be made. There is a gap when considering new crops and the hydroponic system, especially considering the design and feasibility. The first three points form the foundation for the research in this thesis, justifying the investigation into developing or adapting design methodologies tailored specifically to hydroponic system design. Although more research gaps have been identified, they will not be considered for this thesis.

4

Review and Comparison of Design Methodologies

This chapter dives deeper into existing design methodologies in mechanical engineering and evaluates their applicability to hydroponic system design. The aim is to determine which approach suits hydroponics or can be adapted to meet the unique requirements of specialty crop cultivation.

4.1. Methodology Criteria

During the literature review in section 3.3, five methodologies of different scopes were identified and explained. Additional information about the methodologies can be found in Appendix C. The aim is to connect the hydroponic system to these methodologies in order to answer the first Sub-Question: *"Which existing design methodologies in mechanical engineering are relevant to adapt for the development of hydroponic systems"*. To answer this question, a comparative analysis of established design methodologies is conducted. The criteria to evaluate the methodologies are chosen by reflecting on the unique challenges of the hydroponic system. The selected criteria evaluate the methodologies on a system level, assessing their process, design effectiveness, and relevance for hydroponics.

- Flexibility: Ability to handle variations in crop physiology, system scale, and other demands. This is critical for the methodology as the aim is to support different types of crops, setups, and demands. Crops require different approaches in order to design a suitable system.
- Decision-support: Provides structured guidance for trade-offs and design decisions, including crop-specific requirements, mechanical constraints, and cost considerations. This is an important factor due to the interdisciplinary nature of the problem. Additionally, as specialty crops will probably start early in the research stage, the trajectory is long. Decision guidelines help determine whether to continue or redirect the project.
- Design from start: Supports the creation of entirely new systems for specialty crops, defining functional requirements and design parameters without relying on pre-existing designs if needed. The methodology is intended for crops not yet introduced to hydroponics. Thus, this criterion is included to ensure the methodology takes that into account.
- Adaption of reference processes: Facilitates iterative improvement or adaptation of existing systems and best practices to increase efficiency and reduce development risks. As seen, hydroponic system types are well developed, and this criterion is added, as not every project needs to reinvent such designs. The focus must lie on adaptations of the existing principles.
- Implementation speed: Measures how quickly the methodology can be applied in practice, considering both learning curve and execution time. Implementation speed may vary depending on crop complexity or specialization. This is included for the practical feasibility and allows for quick designing.

- Focus on process efficiency: Optimizes the overall design workflow, minimizing errors, redundancy, and complexity, while ensuring effective resource use. This criterion ensures focus on the novelty of the species while managing the complexity of introducing it to hydroponics.

4.1.1. Comparative Analysis

The Pugh matrix compares five design methodologies against six criteria derived from the specific challenges of hydroponic systems for specialty crops. Each criterion was scored from -2 (very poor suitability) to 2 (excellent suitability) according to insights from the literature and applicability to hydroponic system design.

Flexibility

Roozenburg & Eekels and TRIZ score the highest. Roozenburg & Eekels has a broad scope and allows for an iterative and adaptive approach. TRIZ follows a similar iterative and adaptive philosophy, enhanced by its innovation-driven focus, which encourages creative problem-solving and the handling of novel challenges. This flexibility is lacking in the DFMA methodology, where the principles are primarily focused on manufacturing and assembly optimization, leaving biological variability underrepresented. Axiomatic Design and Pahl & Beitz score moderately, as both frameworks provide structured guidance and systematic decomposition that allow some adaptability, but their rigid phase-based processes can limit responsiveness to unexpected crop-specific requirements in comparison to Roozenburg & Eekels and TRIZ.

Decision-support

Pahl & Beitz and Axiomatic Design rank highest in providing structured guidance for decision-support. Pahl & Beitz offer explicit tools such as function structures, morphological charts, and evaluation matrices that assist in trade-off analysis. Axiomatic Design supports decisions through its Independence and Information Axioms, allowing for systematic evaluation of functional requirements and design parameters. Roozenburg & Eekels provides less specific guidance, relying more on the designer's judgment. Furthermore, DFMA and TRIZ offer moderate guidance through process optimization and inventive principles.

Design from start

Pahl & Beitz and Roozenburg & Eekels are well-suited for designing completely new systems. They allow designers to define functional requirements clearly and develop concepts iteratively. Axiomatic Design and TRIZ can also support new system creation, but they often require more interpretation and adaptation to be applied effectively. DFMA, on the other hand, is less appropriate here since it focuses mainly on improving or adapting existing designs rather than guiding entirely new solutions.

Adaption of reference processes

DFMA, Axiomatic Design, and TRIZ work well when building on existing systems. They make it easier to improve or adapt designs and reduce development risks. Pahl & Beitz and Roozenburg & Eekels are moderately effective in this regard. Existing designs can be used as references, but their frameworks are not specifically built for adaptation.

Implementation speed

Roozenburg & Eekels and DFMA are generally quicker to apply. Their iterative processes and structured methods for adapting existing designs make them relatively fast in practice. Pahl & Beitz requires more time to follow its rigorous, phase-based workflow, which ensures thorough evaluation but slows early-stage implementation. Although TRIZ emphasizes innovation, its structured problem analysis and application of inventive principles can make it slower in practice than iterative or reference-driven approaches. Axiomatic Design is the slowest, as its theoretical nature requires careful analysis before practical application.

Process efficiency

Pahl & Beitz and DFMA are the most efficient, thanks to clear workflows that reduce errors and repetition. Axiomatic Design and TRIZ are moderately efficient, while Roozenburg & Eekels can be seen as less efficient because iterative cycles sometimes involve redoing steps, which can temporarily slow progress. The focus on the feedback steps is at the end of the design cycle.

The Table 4.1 contains the full comparison. Section C contains a more detailed evaluation. Overall, Pahl & Beitz and TRIZ achieve the highest total scores, suggesting a balance of structure and flexibility suitable for hydroponic system design. The lowest score is achieved by DFMA.

Table 4.1: Comparative Evaluation of Design Methodologies for Hydroponic Systems using a Pugh Matrix

Criterion	P & B	R & E	DFMA	AD	TRIZ
Flexibility	1	2	-1	1	2
Decision-support	2	1	1	2	1
Design from start	2	2	-1	1	1
Adaption of reference processes	1	1	2	2	2
Implementation speed	0	1	1	-1	0
Process efficiency	2	0	2	1	1
Total	**8**	**7**	**4**	**6**	**7**

Note. Rating scale: –2 = very poor suitability; –1 = poor; 0 = neutral; 1 = good; 2 = excellent. Adapted from (Alves & Carmo-Silva, 2009; Annemiek van Boeijen et al., 2010; Drăghici & Banciu, 2004; Ekmekci & Nebati, 2019; Formentini et al., 2022; Kulak et al., 2010; Naiju, 2021; Pahl et al., 2007; Qiu et al., 2022).

4.1.2. Justification for a New Methodology

A review of current design methodologies reveals that each offers important strengths, yet none completely address the unique requirements of hydroponic systems for specialty crops. Roozenburg & Eekels and TRIZ are notable for their flexible and adaptive methods, which help manage the biological differences among crops. In contrast, Pahl & Beitz and Axiomatic Design offer structured workflows and strong decision-support, making it easier to guide choices and systematically assess trade-offs.

However, each methodology also has limitations when applied to hydroponic systems. Flexible methods might reduce efficiency, while very structured ones may not adapt well to the needs of different crops. Innovation-focused approaches can also be too time-consuming. Since hydroponic systems have a unique mix of biological, mechanical, and economic needs, a customized approach is necessary.

Therefore, developing an adapted methodology that integrates the strongest elements of these existing frameworks can improve the process. The methodology will also include a decision guideline with clear recommendations for important choices and key design steps. This approach helps make the system reliable and adaptable for different specialty crops, adding to the academic understanding of hydroponic systems.

4.2. Summary

The Sub-Question for this chapter was: *“Which existing design methodologies in mechanical engineering are relevant to adapt for the development of hydroponic systems?”*. The analysis shows that while no single methodology fully satisfies the interdisciplinary needs of hydroponic systems, several provide valuable strengths. Roozenburg & Eekels and TRIZ excel in flexibility and adaptability, crucial for addressing crop-specific variations, whereas Pahl & Beitz and Axiomatic Design offer structured workflows and strong decision-support for guiding design choices. These key principles will form the foundation of the adapted methodology. Therefore, the three highest-scoring methodologies are incorporated into the proposed design approach, while elements from the remaining methodologies are included where appropriate.

5

System Requirements for Hydroponic Systems

This chapter decomposes the system and identifies the requirements of the system. The findings are translated into variables and performance indicators.

5.1. Analytical Approach

This chapter focuses on answering Sub-Question 2: *”What functional requirements, constraints, design parameters, process variables, and KPIs define and guide the conceptual design of hydroponic systems?”*. The focus of this chapter is to analyze the hydroponic system in a structured way to provide a solid foundation for developing the design methodology. In line with DSR principles, this analysis uses several design tools, including:

- Stakeholder analysis
- System decomposition
- Axiomatic design
- Literature comparison

With the tools, the hydroponic system and design can be mapped from a system-level perspective. Hydroponic systems combine human interaction with technical systems. Next to this, there is a biological interaction. To handle this multidisciplinary view, a holistic and integrative approach is applied, as Adams (2015) and Pahl et al. (2007) mentions for complex systems. Using the requirements, constraints, and eventually the KPIs creates a structure to test the solution to. For validation, the concept can be checked on ”Is the right thing built?” and for verification, the idea can be checked with ”Did we build the thing right?”.

Stakeholder Analysis

To keep the stakeholder analysis as inclusive as possible, a macro-level analysis is done, and some stakeholders are grouped (Fares, 2024). The focus is on stakeholders connected to hydroponic systems for specialty crops. Each stakeholder group was assessed in terms of influence and interest. This ranking is done in cases of contradictory demand, where a trade-off must be made. This process is also known as a stakeholder impact assessment (Rogers, 2025). The stakeholders are also divided into primary (directly involved) and secondary (indirectly affected) stakeholders (Min et al., 2024)

- Influence: The amount of power a stakeholder wields over other stakeholders and their opinions and actions (Negacz & Tongeren, 2023).

- Interest: The amount of focus on, concern for, or financial interest a stakeholder holds for a particular issue or industry (Negacz & Tongeren, 2023).

Primary stakeholders

- Investors, funders, and clients: Investors typically have the greatest influence, since system development depends on their capital, and as an employer. Their focus is on Return on Investment (ROI), risk reduction, and long-term financial viability. However, their priorities (minimizing Capital Expenditure (CAPEX), fast ROI) often clash with operational needs for reliability and system resilience. Additionally, the investor does not always have the most knowledge about the greenhouse and the crops to produce.
- Cultivator/operational personnel: These actors manage daily tasks such as seeding, monitoring, and harvesting. Their interest is very high, as usability, system reliability, and ergonomics directly affect productivity and safety (Paturu & Varadarajan, 2024). Yet, as employees, their influence is often moderate compared to that of investors or regulators.
- Government and regulatory bodies: Regulations vary strongly by jurisdiction but often set non-negotiable constraints on food safety, materials, and sustainability standards (Negacz & Tongeren, 2023). In some regions, regulators can exercise a significant influence, shaping both system design and operational boundaries.
- System development/project team: designers, engineers, and developers define technical solutions and translate requirements into design parameters. Their influence is high during concept development but is ultimately bounded by investor resources and regulatory demands (Paturu & Varadarajan, 2024). They find the balance between demands, regulations, and economic feasibility.

Secondary stakeholders

- Research institutions: Public and private research organizations contribute knowledge, innovation, and validation of methods (Negacz & Tongeren, 2023; Paturu & Varadarajan, 2024). Their direct influence is limited, but their findings can shape best practices and indirectly affect design parameters and strategies (Negacz & Tongeren, 2023; Paturu & Varadarajan, 2024)
- Customer: Customers expect safe, high-quality, steady demand, and reliable production. Although their direct influence on technical design is low, market expectations shape the way the crop is grown (Paturu & Varadarajan, 2024).
- Suppliers: Providers of sensors, pumps, and growing media influence system reliability and costs through quality, lead times, and availability. This also includes plant material and seeds. Their influence is usually low, though supply chain bottlenecks can hinder the production process.
- Utility providers: Suppliers of electricity, water, and waste management services shape operational costs and system sustainability. Their role is supportive, but shortages or price fluctuations can create indirect but significant pressures.
- Local communities: Communities near hydroponic facilities are indirectly affected by land use, resource consumption, and employment opportunities. While their influence is generally medium to low, public acceptance is needed, and design mitigation might be required.

Table 5.1: Influence versus Interest Mapping of Stakeholders

Stakeholder	Interest	Influence
Investors, funders and clients	High	High
Cultivators	High	Medium
Government	Medium	High
System development	High	High
Research institutions	High	Low
Customers	Medium	Low
Suppliers	Low	Low
Utility providers	Low	Low
Local communities	Medium	Medium

Conflicts can happen when influential stakeholders have different goals. Investors often seek quick returns by keeping costs low, while cultivators focus more on making the system reliable and easy to use. Regulators focus on safety and sustainability, which can raise costs. These rules may align with what the community wants, but they can conflict with what investors prefer. Customers, while low in direct influence, correlate with the regulatory demands for safe products. In addition, the customer's desire for a quality product drives the cultivation strategy, which is executed by the cultivator and made possible by the system developers. These conflicts translate into concrete design trade-offs: balancing CAPEX and Operational Expenditure (OPEX), integrating safety and sustainability, and ensuring usability without compromising financial performance.

Functional Decomposition

Functional decomposition is a systems engineering method that breaks down complex systems into smaller functional components. The approach focuses on the what, providing a foundation for design and requirement specifications (Pahl et al., 2007). In Figure 5.1, the hydroponic system is represented as a black-box model, showing primary inputs and outputs at the system level.

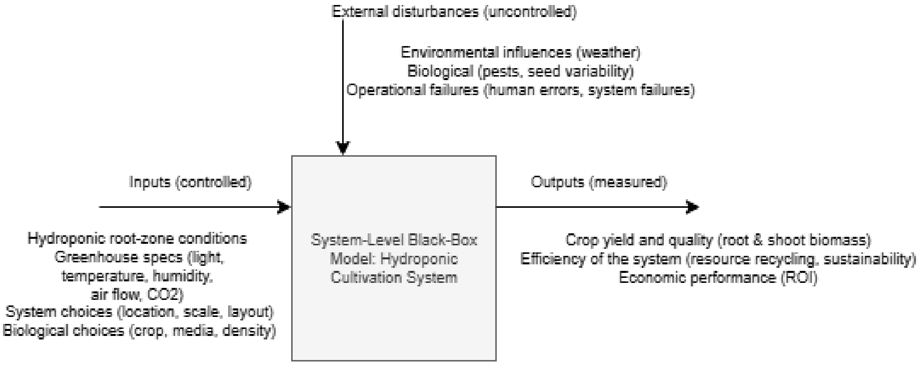


Figure 5.1: System-Level Black-Box Model

In section 3.2, the fundamental principles of hydroponic systems were introduced. Building on that foundation and the black-box model, Figure 5.2 presents a functional decomposition of hydroponic system operations at the system level. This decomposition focuses on what the system does rather than how it is physically built, providing a structured overview of the crucial process steps typically found in large-scale hydroponic cultivation. The system consists of 6 main functions to grow a crop:

1. Seed preparation: select the seeds, prepare the germination media, and trays
2. Germination: place the seeds and create a suitable environment
3. Crop transfer: transport crops and seedlings, and if needed, transplant them
4. Growth cycle: the hydroponic system is working, together with cultivation methods

5. Harvesting: cutting and storing the crop
6. System maintenance: cleaning and operational actions

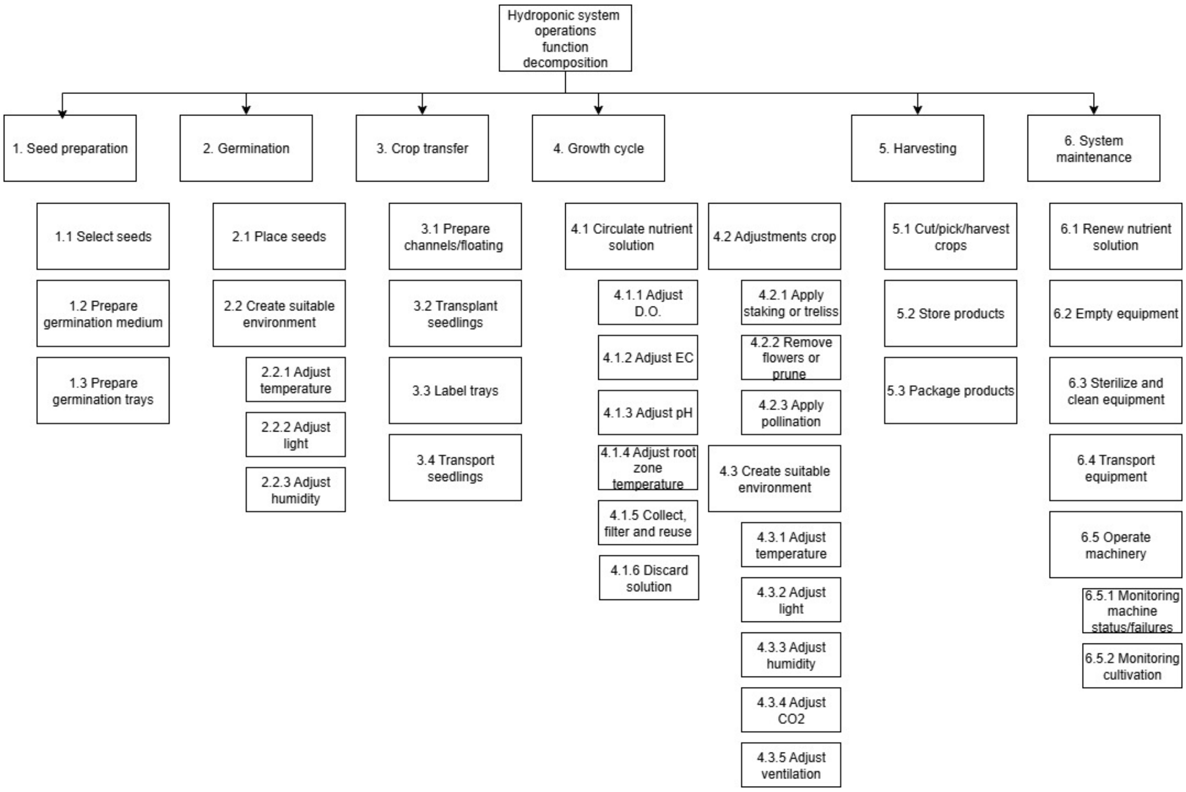


Figure 5.2: Function Decomposition of the Process Steps

This functional decomposition outlines the operational workflow, associated interventions, and system requirements at each stage. Though it appears linear, the process is adaptable: steps may repeat, with parameters varying by crop type, growth stage, and operational goals. Functions may operate in parallel, repeat cyclically, or be omitted based on crop-specific requirements. Parameters are crop-specific and must be dynamically tuned to each crop's trajectory, with some steps skipped for certain crops. Contextual factors also influence execution. Thus, the decomposition provides generic key functions and parameters for defining functional requirements in the axiomatic design process in section 5.2.

5.2. Axiomatic Design Applied

According to Adams (2015), axiomatic design distinguishes four domains in the design process: the customer domain, functional domain, physical domain, and process domain. This structure is shown in Figure 5.3, where the design flow begins with customer attributes and is gradually refined into implementable processes.

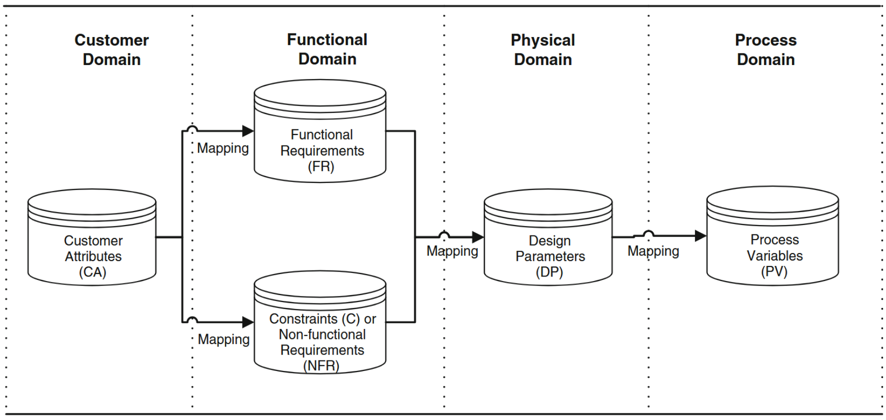


Figure 5.3: Four Domains of the Design World (Adams, 2015)

In this context, customer attributes can be understood as stakeholder requirements, both functional and non-functional (Adams, 2015). This maps the requirements for the functional domain. These later evolve into the physical domain with Design Parameters and eventually into the process domain with Process Variables. For the axiomatic design, not only are the stakeholder analysis and decompositions taken into account, but other factors are also considered. Data was also collected from literature, from experts, and from industrial cases.

- Project Boundaries (PB)
- Requirements: Functional Requirements (FR) & Non-Functional Requirements (NFR)
- Design Parameters (DP)
- Process Variables (PV)
- KPIs

Project Boundaries

System parameters are external factors that define the project's operational context. These parameters directly influence design constraints and system capabilities. To prioritize their impact, a weighting can be assigned based on their criticality to the project's success. Different parameters are dependent on the following points:

SP1 Geographic location. This influences climate conditions, regulations, resources, and the constraints of the target market, all of which affect the quality targets of the crops. This also influences the economic and business boundaries.

SP2 Available site. This influences the available area for the greenhouse.

SP3 Utility Infrastructure. The availability, capacity, and quality of connection points for electrical power, water supply, natural gas, and wastewater disposal are fixed. This determines the feasible processes for climate control and nutrient management.

SP4 Operational demands. The target level of automation.

SP5 Environmental and sustainability targets. Constraints on energy usage and footprint.

5.3. Functional Domain

The functional domain is the second phase of the axiomatic design. Requirements are divided into functional and non-functional constraints, providing a structured basis for system design. To support prioritization, the Must, Should, Could, and Won't Have (requirements prioritization method) (MoSCoW) method is used to rank requirements according to their criticality in the design process.

- Functional constraints: Specific functions the system must perform to transform inputs into outputs. These requirements can be linked directly to one or more of the system's outputs (Adams, 2015)
- Non-functional constraints: Constraints on the quality or context of system functions, such as performance limits, standards, safety, or usability. These typically apply to the system as a whole, rather than to individual functions (Adams, 2015)

Functional constraints are the limits on the system's operation, which directly affect the design to achieve the desired performance. The functional constraints for hydroponic systems differ per situation, crop, and stakeholder demand. Greenhouse and other constraints are not included in the scope. However, the general constraints can be stated as:

F1 (M) The system must support all essential crop phases: seeding (or transplanting), germination, transfer, growing, and harvesting [1,2,3]. The system must also allow for cleaning of equipment and system maintenance [1,3].

F2 (M) The system must maintain crop-specific root-zone parameters (pH, EC, DO, temperature) with continuous, non-stagnant nutrient circulation. Adjustable environmental controls (light spectrum/hours, temperature, humidity, CO_2, airflow) must accommodate varying life stages and external conditions (Shareef et al., 2024)

F3 (M) The system must ensure operational resilience through: backup power for critical systems; sensors and fail-safes for key failure points; continuous monitoring with data logging and alarms; and a central interface with manual override capability (Andreescu & Gurban, 2018; Rathor et al., 2024; Shareef et al., 2024) [1,4].

F4 (M) The system must comply with machine safety and regulations. The regulations depend on the location of the greenhouse, and the food-related regulations depend on the crops [1, 4].

F5 (S) The system should recycle the resources and materials [1, 4].

F6 (S) The system should implement integrated preventive measures against algae, pests, and pathogens. The methods depend on the greenhouse, hydroponic system, and the crop [2, 4].

F7 (S) Plant-specific maintenance should be available, like flower removal, staking, or pollination [1,4].

F8 (S) The system should ensure the quality of the crop. This quality depends on the market standard and can be, for example, color, size, taste, nutritional value, or shelf-life [2, 4].

F9 (C) The design could support modularity to accommodate different crops within the same system [1, 4].

F10 (C) The system could collect crop residues or by-products for potential value addition [1,4].

[1] Based on findings through industrial practices and observations.
[2] Based on findings through expert discussions.
[3] Based on findings through process decomposition Figure 5.2
[4] Based on findings through stakeholder analysis

Non-functional constraints define how a system must perform. These focus more on efficiency and reliability, outlining how the process should operate. Specific numbers differ per system, so the requirements are given as [X]. The non-functional requirements are shown as:

NF1 (S) The quality of the product should stay within [X] amount of %. This depends on the crop, quality demands, and production season [2].

NF2 (S) The system should achieve [X] % operational time. A specific amount of time is dependent on the machine or component in the system [2].

NF3 (S) The structural systems shall have a design service life of [X] years under continuous operational loads and environmental conditions. Per component, this differs between 10–20 years [2].

NF4 (S) The machines should be able to process [X] plants/day to ensure throughput of the system [2].

In Appendix D, the requirements are connected with the stakeholders.

Crop Specific Scenarios

To illustrate the differences between system requirements, the list is compared for the crops, analyzed in subsection 3.2.4.

Table 5.2: Requirement Relevance for Lettuce, Tomato, Strawberry

Requirement	**Lettuce**	**Tomato**	**Strawberry**
F1 (M)	Must	Must	Must
F2 (M)	Must	Must	Must
F3 (M)	Must	Must	Must
F4 (M)	Must	Must	Must
F5 (S)	Should	Should	Should
F6 (S)	Should	Should	Should
F7 (S)	Won’t	Must	Must
Lettuce is vegetative and does not flower. Tomato and strawberry are fruiting crops requiring pollination to produce yield.			
F8 (S)	Should	Should	Should
F9 (C)	Must	Could	Could
Lettuce systems can accommodate different leafy greens, sometimes even simultaneously. Tomato systems may diversify products depending on energy costs for heating or cooling. Strawberry systems are typically specialized and less flexible.			
F10 (C)	Could	Could	Could

5.4. Physical Domain

The Physical Domain defines the design parameters. These are the elements that fulfill the functional requirements. Following the independence axiom, each function is linked to a single, uncoupled parameter to ensure clarity and efficiency in design. In hydroponic systems, these design parameters guide decisions on layout, system components, sensors, and operational controls, connecting functional needs to concrete design choices. However, due to the relation of the system to the end product, not everything is uncoupled. DP2 and DP8 are not independent. Additionally, there is a coupling between DP5 and DP6. The design choices impact the preventive measures that need to be taken. A mapping of all requirements to DP can be seen in Table 5.4.

Design Variables

Table 5.4: Mapping Functional Requirements to Design Parameters

ID	Functional Requirement (What)	Design Parameter (How)
F1	Support all essential crop phases and allow cleaning and maintenance.	Layout with dedicated zones for seeding, germination, growth, harvest, and easy access for cleaning and maintenance.
F2	Maintain root-zone and environmental parameters.	Closed-loop system with sensors and controllers for pH, EC, DO, temperature, humidity, light, and CO_2.
F3	Maintain operational resilience.	Integrated backup power, monitoring, alarms, and fail-safes managed through a central control interface with manual override.
F4	Comply with machine, safety, and food regulations.	Design using certified materials and compliance with relevant safety and food standards.
F5	Recycle and reuse resources.	Recirculating nutrient and water system with filtration and reusable trays or growing media.
F6	Implement preventive measures against algae, pests, and pathogens.	Hygienic system design with filtration, UV or biological control, and cleanable surfaces.
F7	Support plant-specific maintenance.	Adjustable features for pollination, pruning, and plant training or support.
F8	Ensure crop quality.	Precision control of environmental conditions to maintain desired crop characteristics.
F9	Be modular for multiple crops.	Scalable system architecture allowing modules and root-zone conditions to be added, removed, or adapted for different crops.
F10	Collect and manage crop residues.	Integrated waste collection and handling system for by-products or residue processing.

5.5. Process Domain

The Process Domain defines the process variables. These are the actions or settings to control the design parameters. A single design parameter can have multiple PVs, each tunable independently to avoid affecting other functional requirements. Some design parameters do not have PVs, as they represent fixed properties that cannot be adjusted. The final mapping can be seen in **??**.

Process Variables

5.6. Key Performance Indicators

The selection of KPIs for this study is based on stakeholder requirements and relevant literature. It is important to note that not every system will utilize all of the listed KPIs, and some are interconnected. Additionally, the performance of a hydroponic system is often closely linked to that of the greenhouse structure itself. The KPIs can be weighted depending on the project scope and crop type. Based on these considerations, the following quantitative KPIs have been identified.

Yield and quality

$$\text{Yield} = \frac{\text{Total Harvestable Fresh Weight}}{\text{Total Growing Area}} \tag{5.1}$$

This KPI defines system productivity, expressed as the amount of marketable biomass produced per unit area per year (kg·m^{-2}·year^{-1}) (Henry Sheykin, 2025). It measures land-use efficiency and the system's core output. Since yield directly affects revenue potential, it is a primary performance indicator. However, higher yields may come at increased costs, requiring a balance between productivity and profitability.

$$\text{Quality Stability} = \frac{\text{Number of Batches within Quality Specifications}}{\text{Total Number of Batches}} \times 100\% \tag{5.2}$$

This metric describes how consistently crop quality meets predefined specifications across production cycles, expressed as a percentage. Quality stability can vary seasonally due to environmental influences and is not defined by a fixed target value. This KPI was identified as significant through expert discussions.

Energy and resources

The energy and resource indicators correlate with the greenhouse. Light is the primary energy source for plant growth and, in controlled environments, often the largest consumer of electrical energy, increasing the OPEX. Therefore, optimizing its use is essential for both biological and economic efficiency. This is often done by aiming for a dense planting density so there are no light losses. The indicators can be calculated from a biological perspective or a technical perspective. The formulas provided focus on the technical side. In addition to this, the Light Area Index (LAI) and Energy Use Intensity (EUI) can be used (Henry Sheykin, 2025).

$$\text{WUE} = \frac{\text{Total Water Consumed}}{\text{Total Harvestable Fresh Weight}} \tag{5.3}$$

The Water Usage Effectiveness (WUE) quantifies the amount of water required per kilogram of yield (L·kg^{-1}). Unlike traditional agriculture, where most water is lost, a closed-loop hydroponic system should achieve a very high WUE. For a more comprehensive sustainability assessment, the Water Recycling Rate, indicating the proportion of water reused within the system (as a percentage), can also be considered (Henry Sheykin, 2025). This metric is critical for operational cost management, environmental sustainability, and resilience in regions with limited water resources.

$$\text{LUE} = \frac{\text{Total Quality Fresh Weight (g)}}{\text{Total Photosynthetically Active Radiation (mol)}} \tag{5.4}$$

This formula calculates the light use efficiency. It is calculated as the grams of harvestable product produced per mole of Photosynthetically Active Radiation (PAR) delivered to the plant canopy. A higher Light-Use Efficiency (LUE) indicates that the system's combination of lighting strategy, climate control, and nutrient management is effectively driving photosynthesis and growth, maximizing the return on the significant investment in artificial lighting.

Operational performance

$$\text{Operational Availability} = \frac{\text{Scheduled Operation Time} - \text{Downtime}}{\text{Scheduled Operation Time}} \times 100\% \tag{5.5}$$

This KPI represents the proportion of scheduled operating time during which the system is fully functional and available for production, expressed as a percentage. It measures system reliability and resilience. Even a highly productive system can be unprofitable if frequent downtimes occur. Therefore, operational availability highlights the importance of robust engineering and preventive maintenance.

Economic feasibility

$$\text{Gross Profit Margin} = \frac{\text{Revenue} - \text{Goods sold}}{\text{Revenue}} \times 100\% \tag{5.6}$$

The Gross Profit Margin measures the financial efficiency of the production process. It reflects the percentage of revenue remaining after covering direct costs such as seeds, nutrients, energy, and labor. A strong margin is essential for covering operating expenses and ensuring long-term economic viability.

$$\text{ROI Period} = \frac{\text{capex}}{\text{Annual Net Profit}} \tag{5.7}$$

This metric represents the payback period (in years) required to recover the initial capital investment (Velosio, 2025). While the ROI period is an essential metric for commercial feasibility, it can sometimes hinder innovation by favoring short-term financial gains over long-term sustainability and technological advancement. Therefore, it is included as an optional indicator, particularly relevant during later stages of commercialization rather than early-stage technical validation.

5.7. Summary

This chapter has systematically decomposed the hydroponic system, translating stakeholder needs into a structured set of requirements, parameters, and performance indicators. Using axiomatic design as a framework, the analysis progressed through the customer, functional, and process domains, establishing traceability from high-level goals to actionable process variables.

The FRs are set up without a prioritization. However, this can be applied if a crop needs it. These FRs were then mapped to DP and PV to create an analysis for the system's physical and operational design. Additional FRs needs to be found per crop and greenhouse.

As the mapping in Table 5.4 shows, the requirements exhibit a largely uncoupled structure at a high level. In practice, however, certain inherent couplings emerge. A key example is that controlling crop quality (DP8) is fundamentally dependent on adjusting the climate and root-zone management system (DP2). Such interdependencies are characteristic of complex systems that integrate biological and technical components, and they must be acknowledged as a key consideration during the design phase.

The application of the Information Axiom, which seeks to minimize information content by maximizing the probability of success, is early at this system level. However, the defined KPIs establishes a crucial quantitative foundation for applying the axiom later in specific cases. These KPIs will enable the comparison and optimization of different design solutions against clear, stakeholder-focused metrics. It is also important to note the connections between the KPIs themselves. For example, energy usage has a direct and significant influence on economic feasibility.

6

Proposed Design Methodology for Hydroponic Systems

This chapter explains the development of the methodology. It also explains how each phase operates and how it can be applied to the design.

6.1. Introduction

This chapter addresses the Sub-Question: *"What structure and core components define a design methodology tailored to hydroponic systems?"* The aim is to synthesize the findings into a tailored design methodology for hydroponic systems, focused on conceptual design for specialty crops. The proposed approach integrates biological, technical, and economic aspects into one coherent framework.

To build the methodology, a systematic mapping was made of the three best-scoring methodologies from chapter 4: Pahl & Beitz, Roozenburg & Eekels, and TRIZ. From this mapping, their key elements were adapted and combined into a methodology suited to the uncertainties and constraints of hydroponics. In addition to this, components were added as needed. These were based on other methodologies or engineering principles. The components were also identified by the analysis conducted in chapter 5.

The resulting methodology builds on the established base of design methodology. It introduces a testing stage between the design blocks. Additionally, there are explicit feedback loops and crop-specific decision points.

6.2. Systematic Mapping

Systematic mapping was used to analyze and categorize three methodologies and relate them to hydroponic systems. The purpose of this analysis was to identify which elements of each method could be directly transferred, which required adaptation, and where new components were needed to address hydroponic-specific challenges.

Table 6.1: Systematic Mapping of Pahl & Beitz Design Steps with Hydroponic-specific Additions

Pahl & Beitz step	Generic description	Hydroponic-specific additions
Task clarification	Define objectives, stakeholders, and system boundaries. Analyze the market. Select product ideas. Elaborate a requirements list	Define objectives, stakeholders, and system boundaries. Beyond market analysis, a soil vs. hydroponics study is required. Agronomic and physiological crop data need to be found. The produce to harvest might change agronomically when growing in hydroponics, especially for special crops. If this data is not available, it needs to be tested. System boundaries need to expand to include plant physiology.
Requirement list (Design specification)	Develop the principal solution, translate needs into measurable requirements (must/should/-could). Identify the essential problem. Establish function structures	Full requirement lists cannot be created upfront because of biological uncertainties that need to be found through testing. The requirement list should be adjustable throughout the process.
Conceptual design	Generate solution principles, morphological charts, and system concepts.	The morphological chart can be made, but will include more hydroponic typologies and fewer solutions due to constraints of the crops. Key performance indicators differ from the conventional mechanical engineering view. These are for example: yield per square meter, water-use efficiency, energy per kg, or economic feasibility. However, these are also dependent on the crop. Concept trade-offs are constrained by crop behavior, which can be precisely controlled with the climate. Multiple concepts will be feasible.
Embodiment design	Develop manufacturable system and layouts (CAD, BOM, calculations).	This step is very similar. Due to the requirement list, the design might include different regulations for safety, materials, and efficiency.
Detailed design	Finalize components, tolerances, and manufacturability.	This step is very similar. The design needs to be well-connected with the greenhouse design. Focus should also include integration of the control system and the logistics for growing the crop.
Decision	Evaluate and select the final design concept.	Evaluate engineering KPIs and biological KPIs. Compare hydroponic concepts vs. soil cultivation. Determine if the system is able to produce the crop with the specific goal.

Note. Adapted from (Drăghici & Banciu, 2004; Pahl et al., 2007; Qiu et al., 2022)

Table 6.2: Systematic Mapping of Roozenburg & Eekels Methodology Steps with Hydroponic-specific Additions

R & E step	Generic description	Hydroponic-specific additions
Analysis	Formulate the design problem and establish the criteria for success. Define the functions and requirements of the system-to-be.	Map crop requirements, system requirements, and core problems.
Synthesis	Generate potential conceptual solutions that could fulfill the criteria defined in the analysis.	Focus on concepts that address critical KPIs. This is a creative step focused on the analysis findings.
Simulation	Assess concepts for feasibility and contradiction resolution.	Model the proposed solutions to predict their performance. Mainly computer or prototype-based simulations. Missing
Evaluation	Compare the simulated performance of the concepts against the criteria established during the Analysis.	Systematically evaluate how well each hydroponic concept meets the design criteria. However, still, information is missing in order to effectively evaluate hydroponic systems.
Decision	The formal outcome of Evaluation, selecting a concept for further development or implementation.	Selection of the most promising hydroponic system concept to proceed with.

Note. Adapted from (Annemiek van Boeijen et al., 2010)

Table 6.3: Systematic Mapping of TRIZ Methodology Steps with Hydroponic-specific Additions

TRIZ step	Generic description	Hydroponic-specific additions
Define	Identify the main technical contradiction, set system boundaries, and formulate the ideal final result	Define why hydroponics is chosen. Formulate contradictions such as lowest energy use vs optimal lighting, highest yield vs lowest costs. An addition is the relation between the technical contradictions and their influence on the crop.
Analyze	Analyze system functions and interactions. Identify harmful, useful, and missing functions.	Map crop requirements to system capabilities. Identify missing “soil” functions that must be replaced if needed. Evaluate energy flows, resource availability, and environmental control. Full lists cannot be created up-front because of biological uncertainties that need to be found through testing.
Generate	Translate technical/physical conflicts into solvable problems. Apply TRIZ inventive principles to resolve contradictions.	Apply TRIZ principles like modularity and flexibility to the system, or space optimization vs. ergonomic access. Focus on KPIs correlating problems. This step can be integrated but is not feasible on it’s own.
Evaluation	Assess concepts for feasibility and contradiction resolution.	Test whether proposed solutions balance crop health, efficiency, and cost. This can be integrated by validating via small-scale biological trials or mechanical tests.
Verify	Assess alternative solutions for feasibility, efficiency, and contradiction resolution.	Important step to check the soil vs hydroponic possibilities. Similar to the decision stage in Pahl & Beitz

Note. Adapted from (Ekmekci & Nebati, 2019; Qiu et al., 2022)

6.3. Methodology Development Section

The Pahl & Beitz method showed a strong first block defining the task. This was also the case for TRIZ and Roozenburg & Eekels. The objectives will be joined by an additional study comparing the soil versus the hydroponic cultivation. Additionally, the uncertainty of the produce in hydroponic systems needs to be evaluated during this step.

All approaches move to the design specifications stage, which also fits the methodology. The necessary adaptation is that the requirement list should be adjustable throughout the process.

Another implementable block is the conceptual design stage from Pahl & Beitz. The KPIs will differ and correlate with the crop, but the morphological chart is a solid step to use. The concept trade-off will be slightly different as it originally did not include the interaction between product and process, which is important for the crop and the system.

After this stage, all methodologies move towards choosing a concept to work out in more detail or generate. This does not fit the hydroponic system design. Not enough information is available to choose the most fitting concept explicitly. Next to this, it is possible that the requirement list is still lacking boundaries, as these have not been identified yet due to missing agronomic practices. For this reason, a different approach is needed before moving towards the other stages.

Only Roozenburg & Eekels proceed towards a simulation. However, this was focused on validating a product. Closing the design with a combination of the embodiment design and the Generate stages seems fitting as it combines both the conflicts and KPIs with a final design.

The last step is the decision step and the evaluation and verification of the design. These actions seem to fit for hydroponic systems. An addition to this is the connection with the requirement stage, to evaluate the biological and economic interests as well.

Although not every step includes all the objectives needed, it does show a base to build upon. However, there is a crucial element missing. This is the testing of the crop in hydroponics, together with the cultivation strategy. This testing phase is highlighted in Roozenburg & Eekels but is seen as a prototype or computational simulation.

6.4. Proposed Methodology

As explained, the proposed methodology adopts the logical structure of Pahl & Beitz. The novel implementation, in terms of phases, begins with the design phase. A main difference in comparison with TRIZ, for the proposed methodology, is the integration of two design phases instead of one.

- Conceptual Design: Focused on system level and principles, crop requirements, operational strategies, environmental influence, and biological constraints.
- Provisional Design: Focused on detailed system layouts, machinery, materials, and integration with greenhouse infrastructure.

Next to this, a dedicated Testing step is introduced. This differs from conventional engineering design as it is not a prototype at the end of the process. However, it is essential for hydroponics, where assumptions cannot be validated through calculations alone. It is thus not only a validation step but also a critical factor in providing information for the design and identifying new research gaps. Biological trials and operational experiments provide the evidence needed to refine requirements and verify feasibility before moving to full design. Testing is not before conceptual design, as choices need to be made for the cultivation process. This addition was supported by expert feedback.

Another addition is the application of decision blocks woven into the stages. These blocks need to ensure the feasibility of the crop for hydroponic cultivation and the project goals. It depends on the stage at which the feasibility is focused.

The proposed methodology also incorporates multiple feedback loops instead of a sequential movement. The feedback loops start at the Testing and Provisional design stages, back into Task, Analysis, and Conceptual design. This will create a dynamic requirement list but also ensure that more agronomical data can influence the design.

The methodology is divided into three fields. These are the biological, technical, and economic fields. Depending on the phase, different objectives are given per field. By allowing the biological perspective into the methodology, it accounts for the uncertainty of cultivation. Additionally, by allowing the economic perspective, it ensures that the end product is feasible. Instead of just putting the economic factors into the requirement list, this gives more space for different concepts and innovations within the system, which might be needed for specialty crops.

The proposed methodology is illustrated as a schematic overview in Figure 6.1. The stages are given on the left side, in combination with the feedback loops. On the right side, the main objectives are given per field. In red diamonds, the decision blocks are given, with their main feasibility check.

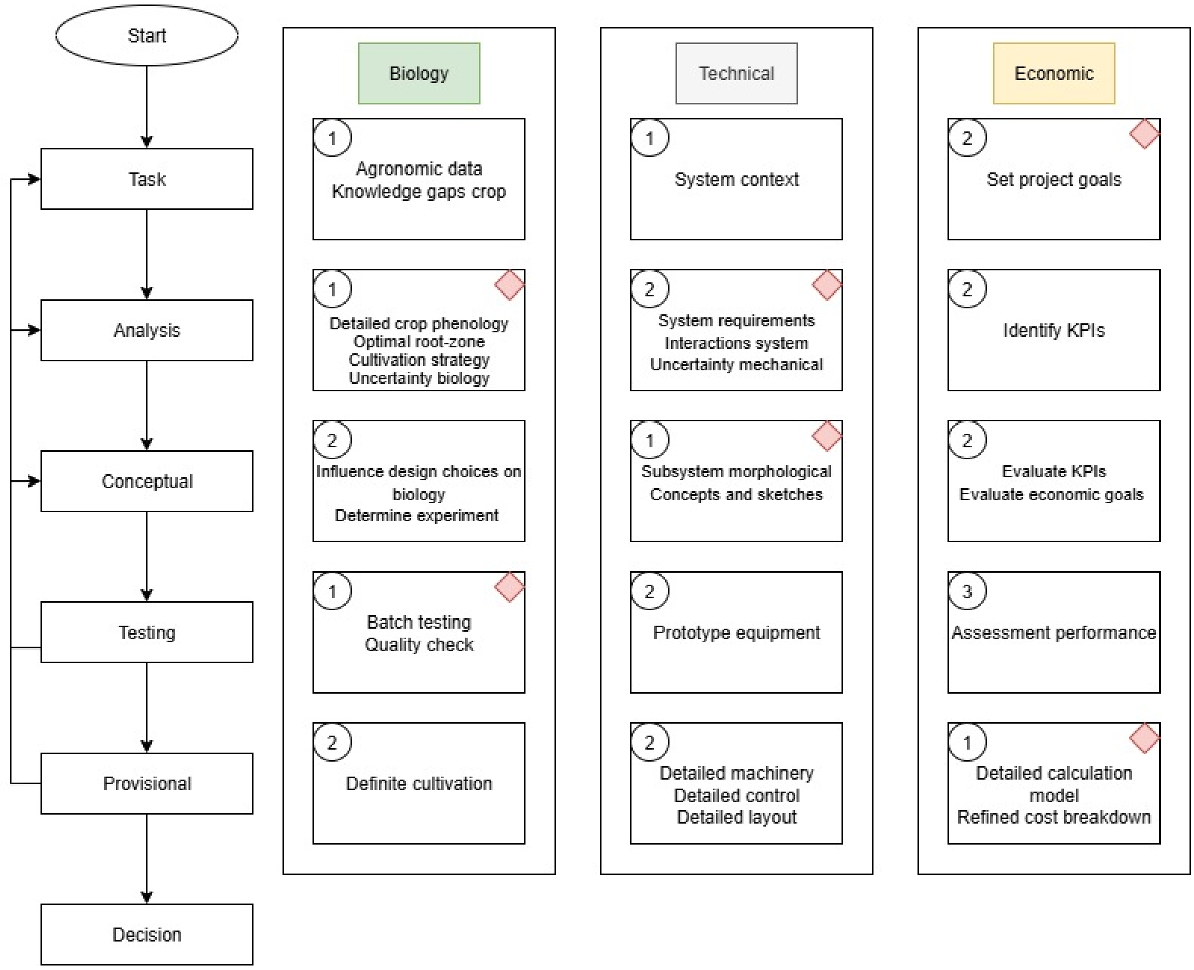


Figure 6.1: Schematic Representation of the Proposed Methodology

It is important to note that although the blocks are given as parallel, they are dependent on each other. The numbered priorities (1–3) within the circles in each field indicate the recommended sequence for initiating work. This is elaborated more per phase. However, the methodology is an iterative process. There needs to be collaborative progression within each stage, as the objectives of one field directly create, constrain, and refine the objectives of other fields.

This methodology is designed for a greenfield project, but it can be adjusted by setting the requirements differently when cultivation occurs in an existing greenhouse. The methodology does not include the design of the greenhouse, as this is outside the scope. The methodology can also be walked through with multiple crops at the same time to serve as a comparison. To create a clear overview of how the entire methodology was formed, the following notation was added:
[1] Specifically based on reviewed methodologies
[2] Created through own addition
[3] Standard methodological tool, adopted to hydroponics

Task

Objective

The Task phase defines the project's purpose and boundaries, transforming a broad idea into a concrete project description. It identifies the target crop, main objectives, and system context. A key element is evaluating whether hydroponic cultivation is preferable to soil-based methods, especially for specialty crops. Ethical, environmental, and socio-economic factors are incorporated early to frame the design challenge. In this stage, the different fields need to be addressed simultaneously. However, a detailed economic evaluation should be finalized at the end of this phase, once all preliminary information has been gathered.

What to Discover

- Primary project goal, such as to maximize yield, produce premium-quality products, or support research. Setting a goal for the system that includes biological and economic objectives.
- Baseline crop requirements and knowledge gaps (growth stages, root-zone conditions, harvestability).
- System context such as location, climate, greenhouse size, and available utilities. Explicitly connects environmental context to design constraints.
- Preliminary market and economic goals: capital expenditure, operational costs, and product price ranges. Couple the biological yield expectations to market feasibility at the Task phase.
- Stakeholders, users, and decision-makers influencing the system.

Deliverables

- Defined project objectives and constraints [1].
- Evaluate soil and hydroponic cultivation differences [2].
- Preliminary crop requirements [1].
- Initial stakeholder map and user requirements [1].
- Identified uncertainties. Find the obstacles with the specialty crop. Find the advantages that hydroponics can bring to this crop. [2]
- Early business scenarios with high-level trade-offs. Enables the go/no-go decisions before continuing research [3].

Tools / Methods

- Literature review and benchmarking against existing crops [3].
- Political Economical Social Technological Legal Environmental (PESTLE) analysis [1].
- Stakeholder mapping and interviews [1]. Extended to include interdisciplinary stakeholders that make critical demands for the system [2].
- Strengths Weaknesses Opportunities Threats (SWOT) analysis for hydroponic adoption [1].

Analysis

Objective

The Analysis phase refines the project description into a comprehensive understanding of the biological, technical, and economic conditions that shape the hydroponic system and the crop. In this stage, the technical and financial analysis is based on the biological part. This phase dives deeper into the differences between hydroponic and soil cultivation and highlights the new challenges it introduces. The outcome is a structured set of constraints, requirements, and KPIs to guide the conceptual design. An additional output is the list of research gaps that might develop during the analysis.

What to Discover

Biological

- Detailed crop phenology and optimal root-zone conditions.
- Detailed information about the desired product to harvest.
- Expected responses to system constraints (nutrient solution, light spectrum, temperature).
- Pollination, transplant, and harvest requirements.
- Integrated Pest Management (IPM) needs for target crop.
- List the missing data and research gaps for the crop.

Technical

- Describe the Ideal Final Result (IFR) to create a thorough analysis but with an end-goal.
- Availability and quality of local utilities (water, energy, CO_2).
- Waste and nutrient handling strategies (reuse, filtration, disposal).
- Automation and monitoring requirements.
- Structural and material constraints, including regulatory requirements.
- Map interaction between the system and the greenhouse.
- Design requirements based on the project objectives and requirement list. Used to find the most suitable solutions that passed the constraints.
- List the missing technology for the cultivation of the crop or investigate ways to mitigate this.

Economic / Social

- Market demand and target product quality.
- Labor availability, costs, and skill levels.
- Financial feasibility limits.
- Determine KPIs based on the project goals.

Deliverables

- Go or no-go based on the agronomic data of the crop. Also, a go or no-go based on the technical aspects [3].
- Refined crop requirements linked to project goals [1]. Set up as dynamic requirements [2].
- Full list of constraints and KPIs [1].
- Identify trade-offs and system limitations [1].
- Identify risks covering biological, technical/operational, and economic uncertainties [3].
- Determine the thresholds for the feasibility of the project. This will be used during the Decision stage [2].
- Create the research questions that need to be filled to create all the information for the other stages [2].

Tools / Methods

- Expert interviews and workshops with agronomists and engineers. Qualitative research to integrate interdisciplinary perspectives [1].
- Academic and literature research [1].
- Benchmarking against comparable crops and systems to quantify feasible ranges for biological and technical KPIs [3].
- Function-structure diagrams to accommodate biological and system interactions [1].
- Substance-field model from TRIZ [1].

Conceptual Design

Objective

The Conceptual Design phase generates and evaluates system-level solutions by combining alternative technical options into coherent concepts. The focus is on exploring configurations, not yet detailed designs. In this stage, the technical part needs to be started first, after which the biological part is connected. The developed concepts must focus on the bottlenecks identified in the previous phases, rather than redesigning the entire hydroponic system. From these concepts, the critical sub-functions that need to be tested should also be identified. Another critical step is the identification of additional tests that need to be done during the following stage.

What to Discover

- Baseline hydroponic or field system for comparison, serving as a control concept.
- Alternative solutions for critical sub-functions, focused on the identified requirements for the specialty crop. Check the hydroponic typologies with the project boundaries.
- Cultivation strategies, including seasonality and crop rotation options. This extends conventional design practice into greenhouse logistics.
- Interaction effects between subsystems, drawing on TRIZ contradiction analysis and supported by Axiomatic Design principles.
- Uncertainties requiring validation through testing. Research objectives and validation needed to be found before moving to detailed design.
- Resource recycling, informed by TRIZ resource analysis, which asks what available by-products (heat, CO_2, waste water) can be reintegrated into the system.

Deliverables

- Functional requirements categorized as must/should/could. [1].
- Morphological chart covering subsystem alternatives [3].
- 3—5 system-level concepts with sketches or block diagrams, with preliminary evaluation before selecting candidates for further development [1].
- Trade-off matrix comparing concepts against KPIs and constraints [1].
- Cultivation assumptions to be validated in testing, which is a novel addition reflecting biological uncertainty [2].

Tools / Methods

- Evaluate the feasibility of concepts before moving towards the testing phase. A technical go or no go [3].
- Morphological charts for subsystem exploration and design development [3].
- Multi-Criteria Decision Analysis (MCDA) [1].
- Concept sketches and block diagrams of the process [1].
- Contradiction matrix to resolve the conflicts [1].
- Create sub-functions with the segmentation principle [1].
- Resource evaluation [1].

Testing

Objective

The Testing phase validates the key assumptions from the conceptual design. Unlike conventional engineering, hydroponics cannot rely only on simulations or analytical models, as crop responses introduce biological uncertainty. This phase, therefore, combines plant trials, operational tests, and engineering simulations to quantify system performance, identify failure modes, and provide evidence for design refinement.

This step is mainly quantitative research. This stage needs to start with the biological trials, as their results will influence the need and scope for any subsequent mechanical tests. Results from this phase feed iteratively back into the Task, Analysis, and Conceptual Design steps.

What to Discover and Methods Biological

- Conduct small-batch growth trials using Design of Experiments (DoE) principles to test specific environmental and nutritional variables [2].
- Quantify key crop performance metrics and evaluate with the found literature in the Analysis phase [2].
- Test the end product on the requirements and target market specifications. This creates a go/no go situation if the crop does not perform in hydroponics [2].
- Potentially create a research approach for more testing [2].

Technical

- Simulations and models of nutrient flow, logistics, loads, and stresses in combination with materials and structures [3].
- Build and test functional prototypes of any novel subsystems or equipment identified in the Conceptual Design stage [3].

Economic

- Assessment of energy use, labor requirements, crop growth, quality metrics, and economic feasibility [3].

Provisional Design

Objective

The Provisional Design phase develops the selected and validated concept into a fully defined hydroponic system ready for implementation. If multiple concepts remain viable, another MCDA is required. The focus is on delivering a detailed design by integrating biological requirements with technical and economic constraints. This phase ensures manufacturability, operational efficiency, and compliance with standards. It is moving from exploration to a concrete solution. The design must fit the requirements list. The economic evaluation is prioritized to ensure viability, after which the biological and technical fields work together to finalize the design.

What to Discover Biological

- Complete cultivation strategy, including crop-specific parameters and greenhouse integration.
- Standardized crop management protocols (pruning, spacing, transplanting, pollination, harvesting).
- Finalized pest and disease mitigation strategies.

Technical

- Calculation and trade-off analysis of how the system design influences the project objectives. The design requirements identified in the analysis phase should inform the most fitting final design.

- Detailed system layout: CAD models of the hydroponic setup, greenhouse infrastructure, piping, pumps, and electrical systems.
- Logistical layout for the machinery and crops.
- Control system architecture: sensor placement, monitoring, automation level, and greenhouse integration.
- Machinery specifications, modifications, or custom equipment, including maintenance requirements.
- Structural, hydraulic, and electrical designs: sizing, flow balance, tolerances, redundancy checks.
- Sustainability assessment of materials and processes, if required by project scope.

Economic

- Refined cost breakdown (CAPEX, OPEX, maintenance, interest, sensitivity, energy usage, location).
- Financial feasibility and payback analysis linked to expected yields and product quality.
- Supply chain on the entire cycle of the product, if required by the project scope.

Deliverables

- All three disciplines evaluation for a continue or stop on the project [2].
- Final choice on the design. Based on the last setup design requirements, KPIs, and if needed, an MCDA [1].
- Functional requirements mapped to system components [1].
- Complete Computer-aided design (CAD) models, schematics, and layout drawings [1].
- Bill of materials with tolerances [1].
- Maintenance procedures [1].
- Control system design documents [1]
- Hydraulic and electrical calculations with flow balance and load checks [1].
- Operating, safety, and maintenance manuals [1].
- Updated KPIs reflecting expected performance (yield, energy, water-use efficiency) [3].
- Risk and safety documentation [1].

Tools / Methods

- Iterative reviews with crop specialists, engineers, and operators [2].
- CAD and simulation software. [1].
- LCA tools. [1]
- Tools like merging, (a)symmetry, and universality from the TRIZ principles [1].
- DFMA protocols can support the technical and logistical part of the layout of the system [1].
- Risk management frameworks (Failure Mode and Effects Analysis (FMEA), Hazard and Operability Study (HAZOP)) [1].

Decision Block

Objective

At the end of the methodology, a Decision block determines whether the project should proceed, pivot, or stop. This ensures that resources are allocated efficiently and that further work is only pursued when biological, technical, and economic evidence justifies it. With the integrated evaluation points, this risk is also mitigated. A key evaluation at this stage is whether the advantages of hydroponic cultivation outweigh soil-based methods for the specific crop and context.

Decision Criteria

Explicit criteria must be defined to guide the decision:

- Proceed Criteria (Go/No-Go): Biological, technical, and economic KPIs must meet minimum acceptable thresholds, determined during the analysis stage. This principle is adapted from system performance.
- Pivot Criteria: Conditions under which a concept must be fundamentally redesigned or a cultivation protocol significantly adjusted.
- Stop Criteria: Explicit boundaries that show project termination is needed (yield below economic break-even, seeds are not developed enough, technical infeasibility, or excessive pest susceptibility).

Proceed

The project has met all key criteria. The next phase is to finalize the design, move to engineering, and proceed with system construction and cultivation. Minor adaptations may still occur.

Pivot

The current concept is not feasible, but the overall project goal may still be achievable. This requires returning to earlier phases to reformulate requirements, explore new concepts, or conduct additional testing. The project may also be paused, waiting for new technologies or research. A research horizon can be created from the findings to ensure the project will steer in the right direction.

Stop

The project is terminated due to critical failures. This allows time to mitigate issues. This action preserves resources for more viable opportunities.

6.5. Summary

This chapter presented a tailored design methodology for hydroponic systems, focused on specialty crops, directly addressing the Sub-Question *”What structure and core components define a design methodology tailored to hydroponic systems?”* The tailored methodology is a synthesis, integrating biology, technical, and economic aspects into one methodology. The structure is an adaptation of existing methodologies. The core components are adaptations combined with assessments in various fields and experiments. It gives a flexible but also structured approach for the challenges with hydroponic system design, as due to uncertainties with the crop, a lot of knowledge is missing. The methodology is designed to accommodate a wide variety of crops and project scopes.

With a systematic mapping, the advantages and gaps were found. Key insights were the missing approach to information gathering, the lack of dynamic requirements, and the interaction between the product and the process. The approach introduces components to address the gaps, including a Testing phase between the two design stages. This is a core part of the design process. Additionally, the methodology contains multiple feedback loops to create an iterative process that allows for refinements. In addition to the schematic overview of the methodology, the decision stages are represented, as well as the priorities per stage. The methodology closes with a Decision phase, where a decision can be made to continue or stop the project.

7

Case Study: Russian Dandelion Conceptual Design

This chapter highlights the case study to test the developed methodology. It is performed on the Russian dandelion.

7.1. Introduction

This chapter aims to answer the following Sub-Question: *"How does the proposed design methodology perform when applied to the system design for the Russian dandelion?"* The Russian dandelion was selected as the test crop for this case study in order to examine the applicability of the developed methodology. This crop is selected from a list of potential crops for a new rubber source. Other crops were reviewed during the literature study, but were excluded. In most cases, they lacked data on hydroponic performance, showed weaker prospects for large-scale cultivation, or were less suited. The Russian dandelion, while not free of challenges, presented the most practical option.

This choice also comes with limitations. Research on Russian dandelion in hydroponics is still underperformed. Important agronomic parameters are missing from the literature, both in field-grown and hydroponically grown plants. As a result, this crop gives the potential to test the methodology. To continue the process, assumptions will be made to proceed to the following stage. The aim is not to create a detailed design, but to highlight how the process is influenced by the methodology. Uncertainties and risks will be mapped during the process to use as recommendations to continue the design. As fitting in the scope of the thesis, the design of the greenhouse is not taken into account.

7.2. Task

During this phase, the aim is to discover the project goals, the background of the crop, and the first set of requirements for the project. In order to do so, a literature study was conducted to understand more about the situation, the crop, and its rubber biosynthesis.

Background Crop

The supply chain for Natural Rubber (NR) is under pressure due to multiple threats. The *Hevea brasiliensis* tree, mainly located in Asia, produces the worldwide demand for latex. One major concern is South American Leaf Blight, a fatal disease that could potentially wipe out the entire Asian rubber production. Additionally, climate change is reducing the availability of suitable land for rubber cultivation (Cornish, 2019; Mooibroek & Cornish, 2000). In addition to these biological and ecological threats, the demand for NR is rising at an annual rate of 5.2%, according to Cornish (2019).

One alternative to NR is Synthetic Rubber (SR), which is made with petroleum. SR can partially replace NR; however, the quality of the rubber is different and thus not applicable for all products (Cornish, 2019). Additionally, an increase in the use of fossil fuels for rubber production contradicts sustainability efforts worldwide. Therefore, an alternative production for NR is being researched.

Given these challenges, researchers have explored alternative plant-based sources of NR. While over 2,500 plant species produce rubber, only a few have the potential for commercial-scale production (Mooibroek & Cornish, 2000). Among them are guayule (*Parthenium argentatum*) and the Russian dandelion TKS (Soratana et al., 2017; Van Beilen & Poirier, 2007). Guayule produces rubber in its leaves and grows in the Chihuahuan desert, whereas the Russian dandelion produces and stores latex in its roots and grows in a wider variety of temperatures. Previous research has shown that the rubber quality of Russian dandelions is superior to that of guayule (Van Beilen & Poirier, 2007), making it suitable for medical products.

During the Second World War, Russian dandelions were already cultivated for rubber, and had a yield up to 16% (Cornish et al., 2016; Kreuzberger et al., 2016). Following the post-war decline in rubber demand, research in this area decreased (Puskas et al., 2024). However, recent threats to current rubber production and the growing need for independent natural rubber sources have renewed scientific interest in both Europe and North America. The Russian dandelion is a promising alternative due to its suitability for diverse growing conditions and improved yield through selective modifications (Bates et al., 2019; Eggert et al., 2018; Van Beilen & Poirier, 2007).

At present, Russian dandelions are primarily cultivated in open fields, a method that presents several challenges. This traditional approach requires extensive manual labor for planting, cultivation, and harvesting, making it resource-intensive and costly (Krotkov, 1945; Seilkhan, 2024). Furthermore, field-grown dandelions are highly vulnerable to competition for light and space with weeds (Eggert et al., 2018; Ramirez-Cadavid et al., 2017). They are also vulnerable to water scarcity, which can negatively impact plant growth and rubber yield (Krotkov, 1945; Seilkhan, 2024). These limitations restrict large-scale field production and lead to inconsistencies in yield.

To address these challenges, researchers have proposed an alternative cultivation method: growing Russian dandelions in a CEA using hydroponic systems (Cornish et al., 2019; Puskas et al., 2024; Salehi et al., 2021). Proposed cultivation methods include both horizontal hydroponics and vertical farming (Cornish et al., 2019; Kopicky, 2014; Muhammad Akbar Bin Abdul Ghaffar, 2017). The design or development of the systems has not been defined yet, but preliminary testing has begun. The biggest challenge is the placement of the rubber in the roots. This makes the cultivation special and also creates uncertainty for cultivation.

Botanical Characteristics

The TKS is a perennial herbaceous crop (Seilkhan, 2024). The plant is native to Kazakhstan and is part of the *Asteraceae family*. The plant has gained scientific and commercial interest due to its ability to produce high-quality rubber in its roots. As stated by Seilkhan (2024), field-grown TKS has a shorter growth cycle compared with *Hevea brasiliensis*, is cultivated easily, and contains excellent rubber quality and content.

The Russian dandelion is characterized by a taproot system, consisting of one or multiple primary roots that anchor the plant and store energy (McNulty, 2019). The dandelion grows 20 to 50 leaves (Krotkov, 1945). The leaves can vary in shape, caused by polymorphism and the growing conditions, see Figure 1.3 (Krotkov, 1945). The rosette of the plant has a diameter of 15 to 40 centimeters according to Krotkov (1945). The rosette grows close to the ground. Depending on the environment and its lifetime, the plant will produce flowers, which will produce seeds. Flowering occurs for 2 to 4 days (Seilkhan, 2024).

During the growth cycle, winter dormancy is reported. Next to this, summer dormancy is also possible (Krotkov, 1945). The habitat preferences of the dandelion are rich but not too heavy soil. It needs to be moist but not wet (Seilkhan, 2024). The plant is most successful in less acidic soils and requires temperatures between 5 and 30°C for seed germination. Germination can occur in both spring and autumn, depending on environmental conditions (Cornish et al., 2016; Krotkov, 1945).

Root systems can be categorized into different types based on their structure. For Russian dandelions in soil, mainly taproots occur. However, in hydroponics, this changes to fibrous roots.

1. Taproot: One central thick root grows downwards. This root can split into branches or create lateral roots. This system creates deep anchorage (Ennos, 1993).
2. Fibrous roots: Multiple flexible roots stay at the soil surface (Ennos, 1993). There is no main root.

Both architectures contain root hairs. The internal structure of a taproot can be seen in Figure 7.2, showing how the vascular tissues are organized. In taproots, the xylem and phloem form a circular

Figure 7.1: Russian Dandelion (Zibek & Hahn, 2025)

pattern. This structure provides support and allows the plant to transport water and nutrients. In fibrous roots, there is no central vascular core. Instead, the vascular bundles are scattered throughout the root, which allows flexibility but thinner roots. Fibrous roots have higher root density and increased nutrient and water uptake in comparison to taproots (Kopicky, 2014).

Rubber Biosynthesis

TKS produces and stores latex in the roots. The latex contains cis-1,4-polyisoprene, which is the primary component for NR (Salehi et al., 2022). Latex is produced in laticifers within the phloem of the roots. This milky fluid is an emulsion of polymeric material combined with proteins, sugars, lipids, and resins (Bates et al., 2019; Keener et al., 2018). The primary function of latex is to act as a defense mechanism against pathogens and herbivores (Stolze et al., 2017). Rubber particles of various sizes are in the latex (Mooibroek & Cornish, 2000).

In the phloem, primary sugars are transported (Muhammad Akbar Bin Abdul Ghaffar, 2017). These sugars are glucose, fructose, and sucrose and are produced during photosynthesis, where carbon dioxide is converted into organic molecules. The roots store inulin, a polymer of fructose, which serves as an energy reserve (Stolze et al., 2017). Other carbon and sugar sources are utilized in the production of rubber (Muhammad Akbar Bin Abdul Ghaffar, 2017). There are strong correlations between carbon availability, inulin concentration, and rubber yield due to the biochemical pathways involved in NR biosynthesis (Kreuzberger et al., 2016; Muhammad Akbar Bin Abdul Ghaffar, 2017; Stolze et al., 2017). This is supported by Cornish et al. (2016) but contradicted by Hodgson-Kratky et al. (2017), who states that it is negatively correlated. The concentration of latex in roots varies based on genetic and environmental factors, influencing overall rubber yield (Cornish et al., 2016). Inulin concentration varies based on factors such as plant age, growing conditions, and genetic traits (Kreuzberger et al., 2016). The genetic traits can be adjusted to create seeds with higher yields.

In addition to the previously mentioned factors, root biomass, root architecture, and growth rate also

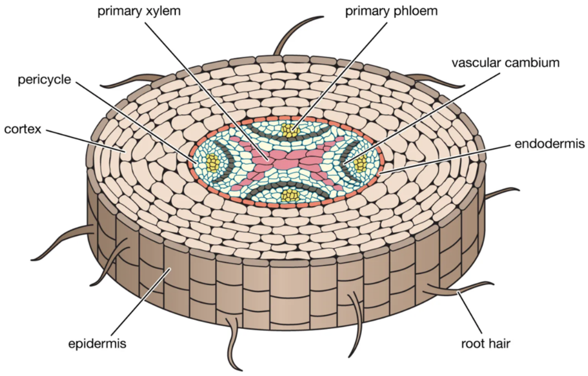


Figure 7.2: Cross Section of a Taproot (Rogers, 2025)

Figure 7.3: Rubber Prices (Trading Economics, 2025)

significantly influence rubber yield (McNulty, 2019). To extract and measure latex content, roots must be harvested and dried. Rubber quantity and quality can be determined from Dry Root Weight (DRW), with NR at least being 5% of DRW, a value that can be increased through improved growing conditions (Salehi et al., 2022). As mentioned by Salehi et al. (2021), rubber quality is determined by molecular weight, macromolecular structure, gel content, proteins, and non-rubber components, which can also be measured from the DRW.

System Context

For the purpose of this case study, the system context has been set in the Netherlands. This choice creates a concrete set of design requirements for the greenhouse and provides a realistic baseline for the calculations. While the project did not specify a geographical context, the Netherlands serves as a suitable reference due to the availability of relevant technical and economic benchmarks. This context allows for a structured assessment of the system's potential performance and costs.

At the same time, there are limitations to this assumption. The economic feasibility of cultivating TKS in a controlled environment is highly sensitive to location-specific factors such as energy prices, labor costs, climate, and the potential for the target market. The Netherlands represents a high-cost operational environment, particularly for energy and wages, which may bias the economic analysis toward a more negative outcome. This context is therefore used primarily as a reference point to demonstrate the methodological framework for assessment, rather than to present a universally applicable economic result.

The greenhouse will be assumed to be high-tech. This incorporates CEA and allows for optimal growing conditions. There is no limit on the size of the greenhouse. It is also assumed that there will be no crop rotation as the system is very crop-specific for dandelions. The last assumption is that the crops will germinate from seeds in the system. There will not be a start with already grown crops.

Market Evaluation

The primary product of interest is NR, for which global demand continues to grow (Cornish, 2019). The price per kilogram does vary as illustrated in Figure 7.3. For this case study, an indicative average market price of 1,65 euros per kilogram is taken as reference.

In addition to NR, side products are produced in the roots. Examples are inulin, sugars, and proteins, which can contribute to the business case. These compounds are of interest to the food and pharmaceutical sectors. This study does not consider these parts of the scope as they are not well studied and reported. Other side products are the flowers and leaves. They can be harvested and dried to create food-related products. For this case study, this will not be included.

The main customer of the rubber is the biorefinery that will modify the roots to the product. The downstream products are thus not defined. However, the demands and requirements are not provided and thus cannot be taken into account. The Task phase considers additional deliverables to be found during this stage. However, full analyses are limited by the available information and will not contribute to testing the case study. The market evaluation, therefore, remains indicative rather than conclusive.

7.2.1. Summary Task

The main objective of cultivating Russian dandelion in a hydroponic system is to produce natural rubber of comparable quality to *Hevea brasiliensis* while achieving improved yield consistency than field-grown dandelions. This will create supply security. The Task phase established the foundational understanding of the crop's biology, its market potential, and the system context required for future design stages.

Hydroponics presents significant advantages through controlled environmental conditions, repeatable growth cycles, and reduced dependency on climatic factors. The difference of cultivation methods is given in Table 7.1. The benefits of hydroponics must be weighed against increased capital and operational costs, especially in high-cost regions such as the Netherlands. The goal at this stage is to assess the feasibility and identify knowledge gaps that influence the go/no-go decision for continued system development.

Hydroponic cultivation of TKS supports sustainability goals by providing a renewable alternative to SR and reducing dependency on Asian natural rubber production. Nevertheless, the high energy demand of CEA introduces environmental and ethical considerations regarding energy sources and carbon footprint.

To summarize the explicit research gaps:

- Biological: Unclear effect of hydroponic root morphology on latex yield.
- Technical: Lack of a defined system design for TKS.

Table 7.1: Comparison between Soil-based and Hydroponic Cultivation of TKS

Factor	Soil-Based	Hydroponic	Relevance
Root type	Taproot system with a central thick root storing latex	Fibrous root system with a higher surface area but uncertain latex storage	Directly affects rubber yield
Labor requirements	High due to manual planting, weeding, and harvesting	Lower through automation and controlled management	Impacts operational costs
Water use efficiency	High water consumption with losses through evaporation and runoff	Efficient water recirculation and nutrient control	Sustainability and resource use
Disease and pest control	Susceptible to soil-borne diseases and weeds	Easier control in closed systems with minimal weed pressure	Improves yield stability
Environmental control	Dependent on local climate and seasons	Fully controlled via CEA systems	Enables year-round production and potentially higher yield
Capital investment	Low initial investment, minimal infrastructure	High initial CAPEX for greenhouse and hydroponic setup	Major economic constraint
Yield consistency	Variable due to weather and soil variability	Stable and repeatable under optimized conditions	Affects economic predictability
Scalability	Limited by land availability and local conditions	Modular and scalable system design possible	Relevant for commercial expansion

7.3. Analysis

The objective of this Analysis phase is to translate the findings of the Task phase into measurable conditions that can be tied to the hydroponic system design. Furthermore, this phase also needs to find the risks and uncertainties that the specialty crop brings, by diving deeper into the biological conditions. As the project goal is to produce a high yield with high-quality rubber, the analysis delves into the rubber synthesis.

Increasing Rubber Synthesis

As stated by Seilkhan (2024) and Stolze et al. (2017) rubber biosynthesis must be improved to enhance NR production in plants and make large-scale cultivation more viable. Several factors influence biosynthesis as shown in Figure 7.2. Possible solutions to increase the rubber synthesis are to adjust the environmental and growing conditions. Another approach is genetic modification and selective breeding to develop higher-yielding plants, but this is outside the scope.

Environmental changes

By using clones of the same plant McNulty (2019) tried to find the true effect of environmental influence on the root size and rubber concentration. All the other researchers used Russian dandelions starting from seed. Results from McNulty (2019) photosynthetic testing are that older plants contained more rubber. There was no clear correlation between inulin concentration and rubber concentration. There was also no clear correlation between plant and root weight with different photosynthetic rates. Significant genetic variation in photosynthesis exists, even among cloned plants, which was unexpected. One clear result was the faster growth of plants with more chromosomes.

In a separate study, Stolze et al. (2017) investigated the effects of water availability on TKS. It was found that TKS is drought-tolerant, but insufficient water decreased the rubber concentration.

Cultivation strategy

It was noted that rubber concentration depends on the harvesting time in the year (Stolze et al., 2017). This is supported by Bates et al. (2019), who shows that rubber yield increases by extending the harvest time. During late harvesting, more rubber had time to accumulate. A big contradiction in the results was that many plants died during the winter, thus decreasing the rubber yield. Another limitation of the research that was mentioned was that possible root death occurred, but it was not possible to quantify.

Another influence in cultivation strategy is the planting density (Bates et al., 2019). Because of the low rosettes, it is important that plants do not overlap to keep the best photosynthesis and reduce competition, as competition increases stress, which decreases the root development (Baiyin et al., 2021). By increasing planting density, weeds have less space to grow and are easier to eliminate (Bates et al., 2019). The importance of weed-free fields to increase rubber is also highlighted in Cornish (2019) and Kreuzberger et al. (2016). Various planting techniques have been tested by Keener et al. (2018), where depth and sewing material were reviewed. From this paper, it was concluded that soil temperature has a big influence and that a depth of 0,6 cm works best with a compost layer.

In Muhammad Akbar Bin Abdul Ghaffar (2017), cold treatment was applied to soil-grown roots, finding that rubber biosynthesis increases after 50 days, as long as the plants don't freeze to death. Older plants contained more consistent root weight and thus more rubber in comparison to younger plants. Research done by Kreuzberger et al. (2016) also confirmed the importance of cold treatment. Cornish et al. (2016) also found that cold treatment influences rubber production positively, but notices it depends strongly on the phenotype.

Although cold temperatures increase rubber formation, a warmer winter period can alter the winter dormancy according to Cornish et al. (2016). The plants with shorter dormancy do not create more rubber but create higher root biomass, and thus yield more rubber (Cornish et al., 2016). Researching both tactics with the same other parameters has not been done yet.

The flowering of the plant has an influence on the rubber concentration (Kreuzberger et al., 2016). Flowering plants produce less rubber, but the plants are usually bigger, with bigger root systems, so still contain more rubber than non-flowering plants (Krotkov, 1945).

McNulty (2019) states that not one key phenotypic trait can be used to increase the rubber yield, which means that growing bigger plants should be the most beneficial to increase the rubber yield.

Harvest

Rubber extraction processes are not included in the scope of this literature research. However, the rubber yield is influenced by the efficiency of the process. Thus, to decrease yield loss, root architecture and morphology are included, as it was mentioned in the literature that small roots lead to inefficiencies. To increase efficiency in the rubber harvesting process, the best roots are thicker, less-branched roots. This is because if roots break, latex will leak out, resulting in rubber loss (McNulty, 2019). It was mentioned that small root sizes are lost during machine harvesting, reducing the yield (Bates et al., 2019).

Root morphology

Soil-grown TKS mainly has a taproot, which can develop into one or multiple roots that branch off of the crown. This architecture development and rubber concentration are investigated by McNulty (2019), who found that branching roots resulted in larger plants than single tap-rooted plants. However, rubber concentration was not affected by root architecture.

Another perspective is given by Salehi et al. (2021), who states that more laticifers might be the answer to why bigger roots have a higher rubber concentration. Thus, focusing on increasing laticifer density can lead to a higher rubber yield.

Testing has shown that root development is influenced by environmental conditions, as demonstrated by experiments conducted both outdoors and in a greenhouse (McNulty, 2019). In better conditions, the roots develop faster and the biomass is higher, containing more rubber.

The uncertainty of the biological aspects makes finding the optimum hard, and research is not yet connected. Next to this, multiple sources show that a lot of factors can influence biosynthesis. Thus, as stated by Salehi et al. (2022), it is important that improved agronomics are found, which is also argued by Seilkhan (2024).

Difference in Rubber for Hydroponic

In the previous section, it was found that the rubber synthesis can be influenced by multiple factors. For hydroponic roots, the latex and rubber formation happens differently from both field-grown roots and the *Hevea brasiliensis*.

For the Hevea tree, the laticifers are in the tree. The latex can be taken out by tapping the tree. The latex contains between 30–50% NR. For the field-grown dandelions, the latex also contains rubber. Rubber may be only 10–20% of the latex dry matter. The rest is mostly water, proteins, resins, lipids, and sugars.

As is seen, hydroponic roots have a different structure and thickness. This means that in the fibrous roots, there is a different laticifer structure. The latex that is produced is more spread throughout the entire root. The latex is less prominent there and contains less rubber. However, rubber is still produced and stored in the root tissue. The way of measuring the rubber content is thus different from the other crops, and it is different to harvest the rubber. There is still a lot unclear about the content of the rubber in the root. Table 7.2 shows the root composition from different tests. From the hydroponic tests, there was no data available, and could not be compared. Table 7.3 shows the ranges of yield and planting densities for cultivation.

Table 7.2: Rubber and Latex Content of Field Cultivation

Age of Crop	WRW (g)	DRW (g)	Latex	Rubber	Source
-	-	0.8–1		3–28%	(Kreuzberger et al., 2016)
5 years	110	35	-	6%	(Liu et al., 2024)
-	-	-	-	5–7 mg rubber/g	(Bates et al., 2019)

Note. All Field Cultivation.

Table 7.3: Yield of Russian dandelion under Different Cultivation Conditions

Age of Crop	Planting Density	Yield (kg/ha)	Source
18 months	100–150 pl/m^2	200–300	(Liu et al., 2024)
18 months	1.24–9.88 million pl/ha	400–1000	(Bates et al., 2019; Liu et al., 2024)
18 months	1 million pl/acre	2160	(Cornish et al., 2016; Liu et al., 2024)

Note. All Field Cultivation.

Technical Analysis

The target deliverables on this topic remain unclear as they strongly correlate with the system context. Due to the focus on the methodology, the following points are not included in the scope:

- Availability of utilities
- Waste and nutrient handling

- Automation and monitoring requirements
- Structural and material requirements
- Regulatory requirements
- Interaction between the system and the greenhouse
- Design requirements based on these points

A crucial difference that the crop will have is the repeated harvests. Normally, crops are fast-growing, and if they have multiple harvests, like with fruiting plants, they are in hydroponic systems that can resolve issues. Integration with greenhouse infrastructure must ensure compatibility with the existing logistics of these long cycle times.

The technology missing for the cultivation of the crop focuses on the harvesting of the roots. This will be included in the Conceptual Design stage. This includes the method of harvesting, as well as the maintenance and cleaning of equipment. It also includes the method of capturing the roots and preventive measures that need to be taken to allow the crops to reenter the system. The system architecture must allow access to roots without disturbing the upper canopy. Modular gutters or movable trays are preferred to support multi-harvest strategies as they allow the harvest points to be stationary.

Another missing technological issue is the monitoring of the roots. There are no specific sensors in hydroponic systems to measure their growth and health. Sensors that track the growth of the shoot could be integrated at the harvest points to capture the growth of the roots. Additionally, sensors that measure nutrient quality could be implemented to detect root rot.

Economical and downstream products

The primary product will be the roots, supplied either fresh or dried. Sales may occur on demand or as part of a continuous production model. The target customer is the refinery responsible for producing rubber from the extracted latex. Depending on their processing needs, the refinery may prioritize a high-quality product, a high-volume supply, or a consistent delivery schedule. However, the specific quantity of roots required to sustain biorefinery operations remains uncertain.

KPIs

The KPIs for this project will be the rubber yield per plant and per area (g/m²). This allows the comparison to the classic harvesting of rubber. It also allows the comparison of single or multiple harvests. Additionally, energy and water efficiency will be performance indicators. However, due to missing data, they cannot be measured in this case study. The final performance indicator is the ROI. This will clearly indicate the economic viability of the system and the cultivation of the crop.

KPIs not included, but important for future research are:

- Plant survival rate after cutting (%)
- Operational time

Additionally, for this case, qualitative indicators are also added. This is done from a process and business perspective to find the most fitting solution. These indicators are system complexity and automation potential. These are added to highlight the differences between hydroponic systems and field-cultivation.

Trade-offs

The chosen KPIs are both tradeoffs and contradictions. Choosing to prefer a higher yield might increase energy costs. This will affect the CAPEX and OPEX. Furthermore, a higher planting density increases yield per area but may reduce root size and latex content. Frequent harvesting can sustain productivity but increases mechanical stress and maintenance demands. It can also cause less rubber, decreasing the yield.

Risks, uncertainties and remaining unknowns

The challenges of this crop stem from the unknown cultivation strategy, rubber biosynthesis, and agronomic influences. This leads to uncertainties in the design needs of the crop. To find the answers to these questions, a literature study was conducted in combination with consultation with crop specialists. All the research and design-related questions identified are given in Appendix E.

Functional requirements

From the findings on the rubber biosynthesis and other topics, the functional requirements of the system can be adjusted. Due to missing system boundaries, not all can be filled or specified. In the following steps, new requirements will be found or defined. The current functional requirements are identified and are stated in Appendix E.

7.3.1. Summary Analysis

The Analysis phase translates the findings from the Task phase into measurable design conditions for hydroponic cultivation of TKS. Additionally, it deepens the knowledge about the rubber synthesis. Literature shows that environmental conditions, harvest timing, planting density, and cold treatment significantly affect rubber yield, yet results are often contradictory and strongly dependent on genotype and growth conditions. Root morphology plays a role in harvesting efficiency, as thicker, less-branched roots reduce yield loss. Hydroponic cultivation introduces further uncertainty, as latex formation differs from soil-grown plants, with fewer laticifers and altered root structures. The lack of data on hydroponic rubber content highlights the need for targeted experimentation.

The findings are connected to the technical implications of the system. Also, the technical influences on the yield are stated. The challenges lie in root harvesting, monitoring, and maintaining system compatibility with greenhouse logistics. Economically, the system's success depends on achieving sufficient rubber yield and a positive return on investment. Key performance indicators include rubber yield per area, energy and water efficiency, and ROI, with survival rate and operational time suggested for future evaluation.

Overall, the analysis identifies the main research gaps, technical risks, and biological uncertainties that must guide the conceptual design phase. A full list of the research gaps is stated in Appendix E.

7.4. Conceptual Design

At this stage, key design decisions are made based on the findings from the analysis phase. The objective is to generate and compare system-level solutions by combining alternative technical options into concepts. The focus is on high-level configurations, rather than detailed engineering designs, but sufficient detail should be included regarding cultivation practices. This ensures that the conceptual designs can later be used as a basis for the Testing phase. During the Analysis phase, multiple knowledge and research gaps were identified. These gaps were taken into account for the design principles and sub-functions for the morphological chart. Functions that prove not to be an issue will be excluded from the scope. The other gaps are not taken into account, as it is not possible to make assumptions yet on the implications of the system.

Design Principles

The following points have been identified as research gaps influencing the design or logistics of the system. These factors could be included in the conceptual design. These also create sub-functions with multiple options, not yet determined and optimized:

Factors taken into account

These factors are included in the conceptual design. Some of these also create sub-functions with multiple options, which can be included in the morphological chart. These are not yet determined and optimized:

- Root anchorage
- Growing medium
- Type of container
- Transfer: horizontal movement, vertical movement
- Allowing nutrient flow
- Management: prune flowers, timing/moment of pruning, prune leaves, IPM (iterative findings)
- Harvest: location of harvest in system, identify harvest-ready roots, how to cut the roots, how to allow access to roots, amount to harvest, other parts of crop harvesting, post-harvest washing, handling waste parts, what the demand is for the product (iterative finding)

- Layout: system layout
- Practices to increase rubber in the system
- Level of automation possible in the system
- How root morphology affects choice of:
    - Hydroponic type
    - Growing medium
    - Nutrient solution
    - Longevity of substrate/system if harvested multiple times (iterative finding)

Factors not taken into account
These factors are not yet incorporated into the conceptual design because they concern knowledge gaps or uncertainties that cannot be reasonably assumed at this stage:

- How much the crop grows in length or mass for the root
- How long the crop needs to mature to produce rubber
- Influence of taproots or root morphology on rubber formation and yield
- Exact limits of root system cutting and effects on rubber synthesis and life cycle
- Dying crops after a certain number of cuts
- How to prioritize rubber synthesis/metabolism
- Effects of cutting and intervention frequency on costs and crop balance (iterative finding)
- Optimal flowering control: delaying, increasing, or cutting flowers (iterative finding)
- Break-even points for different design solutions
- Rubber content in rotten roots (iterative finding)
- Potential unexpected changes in rubber quality

Concept Generation

Concept generation was done through a morphological chart. The focus was on functional elements instead of physical parts. By decomposing the production process into discrete functional blocks, each function can be solved with a range of feasible technical options. The morphological chart can be made visual; however, it was chosen to keep it with words instead of illustrations.

From these options, various concepts can be built. In this situation, not every option fits together, so logical connections need to be made. An example of an impossible connection is to have a substrate in combination with aeroponics.

From this table, three options were selected that show the most promise for implementation. In Appendix G, the visual representation of how the concepts are built is given. A more detailed evaluation will be given for these three options. In Appendix G, other concepts are given, and explained why they were not selected for detailing. Feasibility played a big role in selecting the concepts.

Concept 1: Multi NFT

Figure 7.4 This concept is based on an adaptive NFT system, a method proven effective for leafy greens and lettuce. Its defining feature is the use of multiple, mobile growing channels that dynamically adjust their spacing throughout the growth cycle. As plants mature and require more space, the channels move apart. This passive adjustment optimizes the LAI, ensuring efficient light usage and maximizing space utilization within the growing environment.

This concept supports a multi-harvest cycle if needed. The operational philosophy is product-centric: the crops themselves are in motion on mobile gullies, while key processing stations (seeding, pruning, harvesting) remain fixed. There can be multiple stations for multiple harvest cycles. Plants are typically started in small plugs (rockwool or peat) within net pots, which are then transplanted into the main NFT channels. The substrate will also contain a similar density of potting mixture.

Harvest happens at pre-programmed moments. This ensures the correct position of all the gutters and the life cycle of crops. There can be a small overload area in case of problems. To harvest, the gully separates, and the root mass is gently pushed downward with rollers at different angles, presenting it cleanly for cutting. Depending on the growth time, the roots may have formed a mat inside the gutter. When the roots stay down, they can be harvested with two circulating blades. This principle can be seen in lettuce harvesting. For sequential harvests, only a portion of the roots external to the plug is harvested, leaving the core root system intact for regeneration. The cutting assembly may include brushes or scrapers to manage the wet root material.

As it is not known yet which harvest cycle would be most optimal, this system can accommodate the variants. The crops move, while the harvest and other stations stay static.

For the single-harvest variant, the system grows the seeds until plant maturity, creating more space when needed. To harvest, the design should create a way that can open the upper and lower parts of the final gullies. This way, access is given to the root system. As seen during testing, the roots will stay horizontal, giving less access to them when cut with the lettuce blades. The principle in rollers with steps, where the roots are pushed down, can be applied. This way, the roots will be easier to harvest in a non-complex way. The roots will be wet, so the blades will need to have some sort of brush to scrape the roots/gather them. The harvested roots are then collected. The crops that will be harvested again will be quickly sprayed in order to remove debris. Afterward, the gutter will be closed again. The gutters can start a new life cycle in the NFT system. At the end of the cycle, the plant waste is separated and removed from the system. The layout is designed as a single-layer horizontal movement.

Concept 2: Single NFT

Figure 7.5 This concept proposes a simplified, low-intervention adaptation of a standard NFT system. It is designed for a single harvest cycle where the entire plant biomass is harvested and processed together as the final product. This includes the root ball, shoot and substrate. This approach minimizes system complexity by eliminating the need for root-cutting or multi-harvest mechanisms, making it the most straightforward to implement from an engineering perspective.

Plants are cultivated in a conventional NFT setup. They are typically started in small, dense plugs (rockwool or peat) within biodegradable pots, which are then seated into the NFT channels. A continuous flow of nutrient-rich water sustains growth. The system allows the roots to develop extensively, eventually forming a mat within the channel. The system uses a standard 2D horizontal layout with single-lined gutters. The gutters space dynamically. The harvest principle is the same as concept 1. The extraction of the crops is by opening the NFT channels and then rotating the gutter. The biological material will fall out and be collected. No washing is needed, but the equipment will be cleaned. The roots will not be separated, and this is the final form of the product.

This concept offers significant advantages in terms of simplicity and low cost, as it requires minimal modification to existing designs. However, its feasibility is entirely dependent on the downstream processing requirements for rubber extraction. If the medium must be separated from the roots, this will require new process steps.

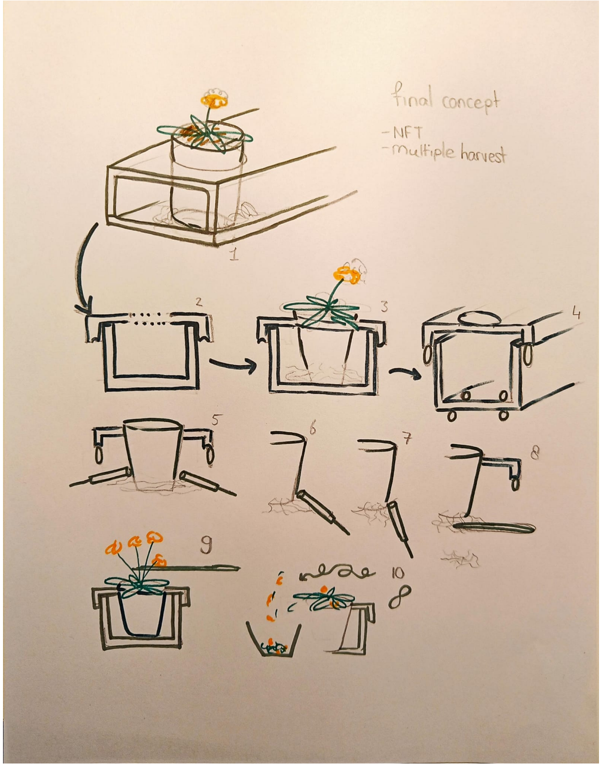


Figure 7.4: Sketch Concept 1

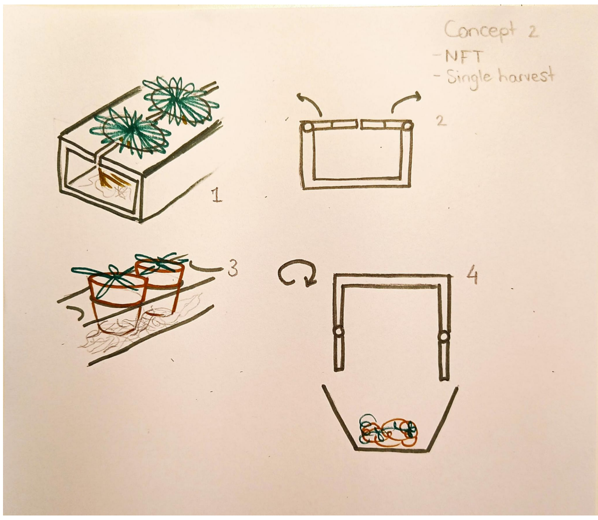


Figure 7.5: Sketch Concept 2

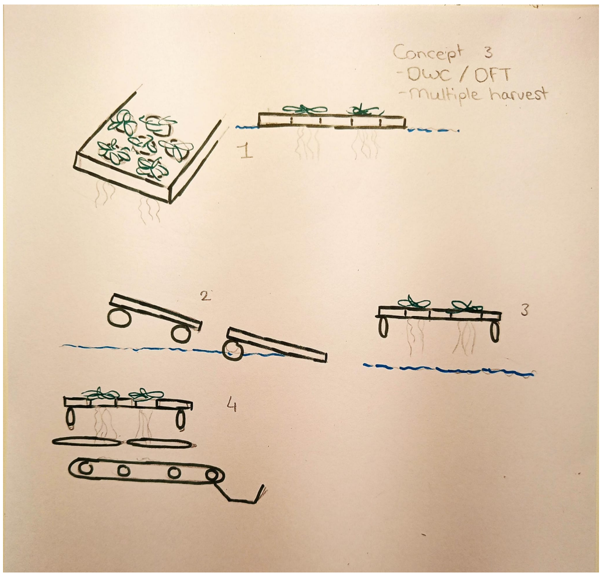


Figure 7.6: Sketch Concept 3

Concept 3: Multiple DWC

Figure 7.6 This concept utilizes a DWC or DFT system, where plants are suspended over a large, aerated reservoir of nutrient-rich water. Their roots are fully submerged and free-hanging, removing the need for a growing medium. This environment promotes quick and extensive root growth, resulting in a high biomass volume. The plants are typically supported by floating rafts or panels, with the rosette resting on the surface. Plants are started in small net pots or plugs to provide initial anchorage before being transplanted into openings in the floating rafts. Their roots then grow directly into the oxygenated nutrient solution below. The large, shared water reservoir provides a stable root environment. A key consideration of this static, non-adjustable layout is a potential inefficiency in light distribution, as the setup cannot be spaced to optimize LAI after initial placement. The system uses a 2D horizontal layout.

The system is designed for multiple harvests. By harvesting small portions of the root system at regular intervals, the shoot is maintained in a continuous state. The harvesting happens in the same way as concept 1. However, this assumes that the roots do not tangle and form a mat, but hang loosely underneath the raft. After reaching a time period in the system, the plants reach the harvest area. The rafts travel slightly up, allowing the hanging roots to be cut by circular blades. With a spray, the rafts can be cleaned underneath. After harvesting, the crops will be placed in a transition pool. A big risk of this system is the contamination of the water. Cleaning might help with the possible root rot. At the end of the plant's life cycle, the entire plant is removed. The raft is lifted, and the remaining root mass and shoot can be pulled or pressed out for disposal or as a valuable by-product.

Concept Comparison and Criteria

The evaluation of the three hydroponic concepts and traditional field cultivation is conducted against criteria specifically designed for the cultivation of Russian dandelion. The first three criteria are derived from the project's KPIs: Yield, water consumption, energy consumption, and ROI. In addition to these, there are additional criteria provided. These are based on industry comparisons and feasibility. These are system complexity and automation potential.

At this conceptual stage, direct quantitative data is limited. Therefore, assessments are made using relative rankings (Low, Medium, High) justified by reasoning from literature, expert input, and comparisons to existing hydroponic systems for other crops. This structured approach allows for a comparative analysis despite existing knowledge gaps. In a later stage of the project, these criteria can be weighted based on specific stakeholder priorities, for example, favoring maximum automation or sustainability.

A critical unknown is the trade-off between rubber content and root biomass yield across different harvest strategies. As emphasized by experts, it is currently impossible to conclude which cultivation method yields more rubber per plant per year.

Table 7.5: Comparison of Concepts and Field Cultivation

	Concept 1	Concept 2	Concept 3	Field cultivation
Yield	High	High	Low	Low
Energy usage	High	Medium	High	Low
Water usage	Low	Low	High	High
ROI	Medium	Medium	Low	Medium
System complexity	High	Medium	High	Low
Automation potential	High	Medium	High	Low

Based on this structured evaluation, Concept 1 Multi NFT emerges as the most promising candidate at the conceptual stage. It provides an optimal balance of high planting density with a high yield, high automation potential and allows for multiple harvests. Its flexibility to accommodate both single and multi-harvest strategies is a significant advantage given the current biological uncertainties. Next to this, it is suitable to look into the methodology further.

The other concepts remain valuable: Concept 2 serves as a low-risk, low-cost baseline should downstream processing accept integrated biomass. It is a balanced concept. Concept 3 represents a high-risk, high-reward alternative for maximizing root yield if the technical and biological challenges can be overcome. Field cultivation provides a benchmark but is unsuitable for achieving the consistent, high-quality supply chain required for industrial rubber production.

7.4.1. Summary Conceptual Design

The conceptual design phase translates the analytical findings into concepts. The goal was to identify technically feasible configurations that can address the identified research gaps and serve as a foundation for testing. Key design principles include single or multiple harvests, access to the roots, and efficiency.

A morphological chart was developed to explore a wide range of functional options focused on the gaps. From this, three concepts were selected for further evaluation: (1) a Multi-NFT system with mobile channels enabling dynamic spacing and multi-harvest operation; (2) a Single NFT system optimized for simplicity and one-time harvest; and (3) a Multiple DWC system focused on submerged growth and high biomass production.

Comparative analysis against field cultivation showed that the Multi-NFT concept offers the best balance between yield potential, efficiency, and automation potential. However, if more information is found, this could change and favor other concepts.

7.5. Experiments

To gain insights and a practical understanding of Russian dandelion cultivation, a series of experiments was conducted. Plants were grown and monitored in a small-scale hydroponic system. The entire setup is explained in subsection 2.2.3.

The tests served as a proof of concept for cultivating Russian dandelions hydroponically. Additionally, they aimed to investigate certain research gaps identified in section 7.3. Due to constraints of time, scale, and equipment, these studies are primarily qualitative and exploratory. Their purpose is to highlight practical challenges to inform the overall case study. Next to this, it highlights the additional step in the methodology. The specific tests conducted are summarized in Table 7.7. Beyond the direct results of these tests, broader conclusions and observations were also made.

It is critical to note that the sample sizes for these tests were small and that there is no control group for the tests. The system experienced external disruptions, including a minor thrips infestation, a small power outage, and a setting mistake with the lighting period. Consequently, the results should be interpreted as indicative trends and observations rather than definitive quantitative conclusions.

Table 7.7: Overview of Experiments

Test Number	Description
Test 1	Effect of Repeated Root Trimming on Plant Health and Regrowth
Test 2	Determination of Dry Root Weight
Test 3	Observation of Flowering Behavior

(a) NFT Crop Setup

(b) Plug with Roots

Figure 7.7: Setup Climate Chamber

Test 1: Effect of repeated root trimming on the plant health and regrowth

Objective

The purpose of this test was to determine the effects of repeated root trimming on plant health. Previous studies like Cornish et al. (2019) and Kopicky (2014) suggest that roots can be trimmed up to 75% for multiple times. However, the maximum feasible number of cuts under current growth conditions remains uncertain and must be established empirically. This experiment sought to explore that limit through direct testing. However, because of a time constraint, the number of cycles could not be reached within the timespan of this thesis. However, how the trimming would work in combination with NFT system and the reaction of the plant could be tested.

Hypothesis

It was hypothesized that after cutting around 75% of the roots the remaining roots and plant would show visible signs of stress, for example, wilting or stunted growth. Next to this, there was a possibility that the remaining roots would rot. However, it was expected that the root regrowth would be back to the original size in 6 weeks.

Method

Healthy plants were randomly selected from a group of test subjects. Root trimming was treated as the independent variable, while crop health served as the dependent variable. The plants were kept under controlled environmental conditions to isolate the effects of root trimming. The measurement of plant health was done visually, comparing the cut plants with the crops that were not cut. Which plants were cut was noted in a spreadsheet containing the data of all plants. During a second round of root trimming, all previous plants were taken again so that multiple trimmings could be tested. This is done in combination with a variety of older and younger plants. In Appendix F are the pictures of the roots, plants, and initial measurements.

Procedure

1. Grow plants.
2. Select plants.
3. Record initial measurements and pictures.
4. Trim approximately 75% of the roots outside of the growing container with clean scissors.
5. Monitor the growth, variations and stress. Record in the logbook and pictures.
6. Repeat trim.
7. Compare the behavior of trimmed plants with the control group plants.

(a) Crop R1H1 before Cutting the Roots

(b) Crop R1H1 1 month after Cutting the Roots

Figure 7.8: Test 1

Results Test 1

Severe root trimming (approximately 75%) caused significant stress responses in all tested plants. Growth was stunted, leaves browned, and in some cases, plants died. Contrary to the hypothesis, trimmed roots did not return to their original size within six weeks. Next to this, several crops showed signs of root rot. The crops with root rot did show reemerging roots from the pot. After a second trimming, crops died, while others only lost the size of the rosette. The flowering crops slowed down their production of flowers. The specific results per plant are given in Appendix F.

Test 2: Determining the dry root weight

Objective

According to Salehi et al. (2022) rubber makes up 5% of the DRW, of field-grown dandelions. The literature on the hydroponic study with Russian dandelions showed only the weight of fresh field-grown roots, which differ in structure, density, and water content (Kopicky, 2014). However, the rubber in the DRW was 30 percent for field-grown dandelions (Krotkov, 1945). It was found that rubber is present in the Wet Root Weight (WRW) of hydroponic dandelions. However, the test subjects were field-grown dandelions, put into hydroponics after germination (Kopicky, 2014; Muhammad Akbar Bin Abdul Ghaffar, 2017). If the estimation is that hydroponic roots produce the same amount of rubber as field roots, there needs to be an estimation on what the dry weight is of hydroponic roots.

Hypothesis

The hypothesis was that the DRW would be less than 10% of the fresh roots' weight for hydroponically grown roots. This is based on the idea that hydroponically grown roots contain more water and are thinner than field-grown roots, which are typically thicker and more developed due to different environmental conditions.

Method

Roots were taken from previously trimmed hydroponic plants. Fresh weights were measured immediately on a precise scale. Roots were dried between paper towels at room temperature (19–23 °C) until weight stabilized. To confirm, they were re-weighed after several days.

Procedure

1. Grow plants.
2. Select plants.
3. Trim approximately 75% of the roots outside of the growing container with clean scissors.
4. Measure the fresh weight with a precise scale
5. Let the roots dry in a couple of days.
6. Measure the dry weight with a precise scale
7. Measure the dry weight one more time to be certain it is the end value

Methodological note

DRW was determined by air-drying, not oven-drying (the standard). Residual moisture may be slightly overestimate DRW.

(a) Measuring Trimmed Roots

(b) Sample in Process of Drying

Figure 7.9: Test 2

Results Test 2

The dry matter content of hydroponically grown Russian dandelion roots was determined. The results of the wet and dry weight measurements for six root samples are presented in Table 7.8. The average dry weight was calculated to be 9.4% of the wet weight. A notable observation was that root morphology influenced the results. Thicker roots contained a higher percentage of dry matter compared to finer roots. It is likely that this was caused by drying errors. The specific results per plant are given in Appendix F.

Table 7.8: Wet and Dry Weights of Root Samples with Percentage Dry Weight

Sample	Wet Weight (g)	Dry Weight (g)	Dry Weight (%)
1	1.807	0.266	14.72
2	10.946	0.494	4.51
3	9.460	0.655	6.92
4	5.569	0.427	7.67
5	0.957	0.073	7.63
6	1.343	0.201	14.97

Test 3: Flowering of the dandelions

Objective

The goal of this test was to observe the impact of flowering within the hydroponic system. This included monitoring any negative side effects, such as seed spread, system contamination, or potential disease. In addition, the timing of flowering after germination was recorded to better understand the plant's development cycle under controlled indoor conditions. Since flowering had not been documented extensively in hydroponic setups for this species, the test also aimed to determine whether it would follow the same timeline and behavior as in field grown dandelions what was documented by Krotkov (1945).

Hypothesis

It is expected that the plants will produce seeds in a similar way to those grown outdoors. Depending on airflow and ventilation settings, these seeds may scatter throughout the system, potentially leading to contamination or interference with other crops. Seed development will happen as Russian dandelions are not dependent on outside pollinators.

Method
No manual interference was made during this experiment. A batch of germinated Russian dandelion plants was placed into the hydroponic setup and observed over several weeks. Flowering behavior and its timeline were recorded, along with any visible effects on the surrounding environment. Humidity, temperature, and nutrient levels were kept stable to avoid introducing additional variables. The life cycle of the flowers was identified. After initial observations, minor interventions were introduced such as removing seed heads to protect nearby crops and prevent spread within the system.

Procedure

1. Grow plants.
2. Monitor the plants
3. Observe and record flowering and seed set.
4. Allow some natural development.
5. Intervene (cutting seed heads) when necessary to maintain system hygiene.

(a) Difference in Flowering

(b) Crop after Flowering for 1 Month

Figure 7.10: Test 3

Results Test 3
Flowering behavior in the hydroponic environment was observed to be highly variable and asynchronous. Out of eight mature plants, three individuals produced flowers, with the timing of flowering initiation varying from one to three months after germination. The remaining five plants did not flower during the five-month observation period. Individual flowering plants produced up to 30 active flowers simultaneously, and kept producing new ones after others died. The seeds formed successfully but remained

attached to the flower head rather than dispersing. The manual removal of flowers was required to manage plant debris within the system. Although the seeds did not fall, the dead flowers became moldy and collapsed into other crops. The specific results per plant are given in Appendix F.

7.5.1. Discussion Findings

Test 1

The hypothesis was partially supported: the predicted stress response was confirmed, but root regeneration to the original size within six weeks did not happen. The observed stunted growth directly illustrates the principle of the root and shoot behavior. This is as expected, because 100% of the roots allows the nutrients for 100% of the shoot, so removing one has consequences for the crop. Leaving the 25% was insufficient for the crop to support the shoot, leading to wilting leaves and stunted growth.

This finding indicates the possibility of harvesting multiple times, but not at the rate that was expected. This presents a potential trade-off between plant health and the efficiency of rubber collection.

It is thus important to include the option of harvesting less than 75% of the roots multiple times or not to cut the roots multiple times. It also shows that if the concept were to be harvested multiple times, root rot should be mitigated where possible.

Test 2

The hypothesis that the DRW would be less than 10% of the WRW was supported by the data, with an average of 9.4%. This confirms that hydroponically grown roots have a very high water content. This is a critical parameter for estimating rubber yield.

The variation in dry matter content correlated with root thickness. It suggests that the morphology of the harvested roots will be a factor in determining the final dry yield. If the rubber content is similar in all thicknesses, it would be best to focus on heavier roots instead of the fibrous roots. The findings of this study can also influence the post-harvest method.

A limitation of this study is the use of air-drying at room temperature instead of a standardized oven-drying protocol. This method may have left residual moisture, potentially leading to a slight overestimation of the dry matter percentage. Despite this, the results provide a benchmark for design calculations. Another limitation is the relatively small sample group. It would be better to take the standard deviation of the weights instead of the average.

Test 3

The flowers appeared unpredictable. In many plants, flowering is triggered by environmental cues such as photoperiod, temperature, or stress. It is possible that because of the climate chamber settings, the crops experienced a form of stress.

A clear finding is that the crops do flower in the hydroponic system, and also quickly after planting, meaning within one to three months of transplanting to the climate chamber. This can mean two things for the business case:

- The flowers take away energy from creating the rubber
- The flowers show a form of secondary metabolism, meaning more rubber is created

Only with testing can this be found. It was seen that relatively large plants flowered. The effect of flowering on the leaf growth was not measured.

The retention of seeds on the flower head is a positive finding. This reduces the risk of uncontrolled seeds throughout the system. However, the dropping flower heads posed a mold risk. There can be three options for the business case:

- A quick life cycle, where if the crop flowers, and eventually it gets moldy, it will not be long enough to create problems
- Structured and often deflowering of a crop that is longer in the system
- Occasional deflowering for a medium time in the system

This will have an influence on the needed machinery and operational costs.

Additional Findings

Several additional observations beyond the main hypotheses were recorded, each with implications for system design and plant management:

- Low germination and high transplant mortality: Russian dandelion showed very poor germination ($\leq$10%), and nearly half of the seedlings that did emerge failed after transplanting. In contrast, companion crops such as basil and lettuce achieved $>$90% germination with minimal transplant loss. Germination was a bottleneck in this experiment. It should be noted that the seeds used were eight years old, which causes a poorer germination rate.
- Algal contamination: Algae quickly spread over the surface of the growing medium in larger pots, especially around vulnerable seedlings. This highlights the need for light-blocking measures to prevent algal growth that competes with young plants. How this will develop if a crop is in the system for a long time is uncertain.
- Material degradation: The cardboard pots deteriorated rapidly under constant moisture and handling, shedding debris into the nutrient solution. This underscores a critical design requirement: cultivation equipment must be durable enough to withstand hydroponic conditions without compromising hygiene.
- Distinct root architecture: Russian dandelion developed roots mainly from the bottom of the pot, forming a compact mass rather than a dense, spreading root ball. This contrasted with basil, whose roots became tangled throughout the container and started from a higher point. Such differences affect container spacing and system design. Next to this, the roots stayed horizontal after picking up the crops.
- Potential for vegetative propagation: Multiple rosettes were observed in plants that had undergone root trimming, suggesting possible regrowth from root fragments. While this phenomenon is well known in other crops, it has not yet been confirmed in Russian dandelion. If validated, it could provide new propagation opportunities but also introduce risks within a recirculating system. Due to the new rosettes, the crops ripped open the pots and blocked light from the main plant.
- The crops inspected on the root growth were taken out of the NFT-channels. Some roots were torn due to the limited sizing of the structure. This should be mitigated in the design of the system.
- The root ball of the cut plants regenerated underneath the pot. While still able to hydrate the crop due to enough water flow, it pushed the crop up in the system. The pots were no longer leaning and were stable on the bottom of the gutter.

7.6. Iterations and Feedback Loop

The experimental work provided several practical insights. Although the tests were exploratory and limited in scope, they revealed key challenges and opportunities that would not have been found from a literature review alone. The results influenced the creation of the DoE, which is elaborated in subsection 7.7.5. The most important conclusions can be summarized as follows:

- Severe root trimming disrupts the root–shoot balance; plants showed stress, dieback of leaves, and high mortality after repeated cuts. Shoots die back after trimming, leaving withered leaves that accumulate as debris and increase the risk of mold. Additionally, rosettes decreased in size.
- Biodegradable pots proved unsuitable for multiple harvest cycles, tearing under handling and allowing roots and new rosettes to break through.
- Dry root weight was consistently less than 10% of fresh weight, confirming a high water content in hydroponically grown roots. This needs to be taken into account for the economic viability.
- Mold, debris, and general system hygiene emerged as recurring challenges. Algae strongly affected transplanted seedlings, leading to early losses.
- Root rot occurred after trimming, but plants were capable of regenerating new roots from the pot area.

- Roots accumulated underneath the pots and pushed plants upward in the system
- When picking up the crop, the roots stayed horizontal.
- Flowering was unpredictable; once initiated, it halted further vegetative and root growth. However, the crops that flowered were relatively large.
- Evidence was found of new rosettes/pups emerging from root fragments, indicating possible vegetative reproduction.

Implications for the Analysis Phase

The results provide answers to some of the research questions identified earlier. This opens up new gaps for research on:

- Flowering management
- Crop modeling and growth rates
- Propagation of the crop

At the same time, several questions remain unanswered and must be carried forward. These are stated in Appendix E.

Implications for the Conceptual Phase

From a design perspective, several practical lessons were drawn:

- Container design needs to take into account the longevity of the cycle
- System hygiene after multiple cycles might need to be integrated during the cycle
- Root support or root ball behavior needs to be
- Maintenance tasks are needed to mitigate risks of root rot and loose roots

The unanswered and newly found gaps influence the Analysis and Conceptual design phases. It has already been indicated in the previous sections how this was applied.

Further Steps

In a full project lifecycle, these experimental results would trigger a return to the Analysis phase. A new, more targeted literature review would be conducted to investigate the observed phenomena. This would generate new, refined research questions for the following cycle of small-scale testing, creating an iterative loop between analysis, experimentation, and design. For the purpose of validating this methodology, the project will now proceed to the provisional design phase. However, the findings have been applied. Based on the concept evaluation and experimental insights, Concept 1 has been selected for further development.

The concept has been redesigned slightly, with the new findings. The flowers will be cut and taken away from the crops. The pots will not be made out of biodegradable material. The crops need to be washed after cutting the roots to ensure loose roots will not clog the system and to let the crops acclimate to the new ratio of roots. One important addition to the design is the separation of nutrient solutions and tanks at different points in the cycle. For example, after roots are harvested, the crops can be watered until all the loose roots are washed away. Then the crops will continue to receive the basic nutrient solution. This mitigates the risks of extensive clogging of the filters.

7.7. Provisional Design

The objective of this stage is to develop and validate the concept. For the case study, the scope is to highlight the research gaps and identify how the concept should evolve. As too much information is still missing, it is not useful to conduct many of the steps stated in the methodology.

Remaining Research Questions

The influence of root morphology on rubber yield remains a critical factor in system design. Depending on whether taproots are essential for maximizing rubber production, different considerations apply:

1. Substrate: A dense substrate mixture is needed to provide adequate pressure on the roots. More research needs to be conducted on this subject.
2. Container size: Larger containers might be necessary to accommodate the taproot structure.
3. Hydroponic system adjustments: The water and nutrient distribution must meet the structure with substrate, so DWC might not be an option anymore.
4. Harvest: If the taproot needs to be harvested, the roots within the substrate need to be cut. This will change the design and approach of the system.

If taproots are not essential for maximizing rubber production, the focus can be on creating the highest volume of roots. The hydroponic system needs to be chosen accordingly. Nutrient solution composition also influences root morphology. Literature comparisons between Krotag and Hoagland solutions show visual differences in root thickness, though rubber content was not quantified (Kopicky, 2014; Kuluev & Berezhneva, 2017). Substrate influence on hydroponic roots remains uncertain, requiring further research.

It is assumed that the fibrous roots will contain the same amount of rubber as the taproot. This means the NFT system can be used with a medium-density substrate. Potting size and a specific nutrient solution will not be taken into the design.

Root trimming affects the growth and plant balance, as was seen during the experiments. If more stress creates the most rubber content, repeated harvest might be the best option. From this, the following research questions are the most crucial to answer:

- What root system is needed?
- How can the root system be optimized?
- How many roots can be trimmed?
- How often can the roots be trimmed?
- How much does the cutting stun the crop?
- What situation creates the highest yield for volume or rubber yield?
- Will repeated trimming create stress, which will increase the rubber content?

Maximizing rubber synthesis relies on stimulating secondary metabolism. How this can be achieved in hydroponic systems is still unclear. Factors to investigate include:

- Plant age and size: Larger and older plants typically contain more rubber.
- Stress triggers: Environmental stress, including cold, may improve rubber production.
- Dormancy cycles: Seasonal temperature variations affect rubber content in field-grown plants.

In hydroponic setups, introducing cold periods through a cooled nutrient solution may increase rubber synthesis. However, this could slow root growth and change harvest cycles. Design adaptations, such as incorporating water-line cooling systems, should weigh cost versus expected improvements in rubber quantity and quality. For this provisional design, no additional modifications have been included.

7.7.1. Calculation

In order to test the provisional design, a calculation model was built. In here, different scenarios of Concept 1 were tested. In the model, the chosen KPIs were added to create an overview of different options. However, due to multiple assumptions and limitations in this stage of the crop research, the model is not a feasible business case but highlights potential opportunities and identifies areas for further research.

Assumptions, Limitations and Inputs

This section explains all the numbers and assumptions that went into the model. It also explains the limitations of the model.

Growth Model Assumptions

As explained in subsection 3.1.2, the growth pattern of a crop goes in an S-curve. The data on the growth of TKS is not documented, and cannot be implemented into the model. Additionally, the behavior cannot be assumed similar to other crops, as it is unknown how the S-curve behaves for the roots, and how this behaves for cut roots. As was seen during the experiments, a stunned response seems likely. To highlight the uncertainty and effects, illustrative graphs were created in Figure 7.11. The red dotted lines indicate the harvest points. The growth weight does not correlate with the Russian dandelion. The setup of the graphs is explained in Table 7.9.

Table 7.9: Growth Setup

Model	Description / Differences
Every model	Has the same S-curve until day 60.
Base Model	Harvest occurs every 30 days. A stunted growth is implemented by restarting the S-curve after each harvest.
Different Cycle Lengths	No specific cycle times are applied.
Steeper S-Curves	Follows the base model setup but with a different, steeper growth pattern.
Decrease Cutting	Follows the base model setup but exhibits decreased growth after each harvest.

Key growth dynamics include average daily growth (trendline slope), periods of acceleration or slowdown (growth rate), and responses to interventions. The exploratory analysis confirms that factors like cycle length, curve steepness, and the effect of cutting significantly impact growth dynamics and total yield. The behavior of the roots in combination with cutting can be expected to be in a similar S-curve, as was seen during the experiments. However, this can also not be estimated for the calculation. That is why the model will use two linear growth rates for the crop. The first one is during the germination and transplanting phase, and the second one is for the harvesting and regrowing cycles. These values are determined on the S-curve of lettuce, which is 5 – 6 grams/day of growth for the shoot of the crop. It is also known that the root-shoot ratio is 1:2. To apply a safety factor to account for the effect of a slight stunting growth, the model uses the lowest value of 2 g/day. It is also acknowledged that a system designed explicitly for root growth could achieve higher rates. Therefore, to conduct a sensitivity analysis, a range of 2 – 4 grams/day was used in the model. The assumption for the calculation is that the rubber and the second metabolism do not spike after a time or cultivation strategy. If more information is found, this can be implemented into the model.

Once the correct values are determined, they can be incorporated into the model using Equation 7.1, which provides the formula for modeling the crop's growth.

$$L(t) = \frac{C}{1 + A \cdot e^{-B \cdot t}} \tag{7.1}$$

where:

- $L(t)$ is the size (height, biomass) of the plant at time t.
- t is the time (days).
- C is the maximum capacity, the maximum possible size or weight.
- B is the growth rate, controlling the steepness of the curve.
- A is a scaling constant that sets the initial condition.
- e is Euler's number.

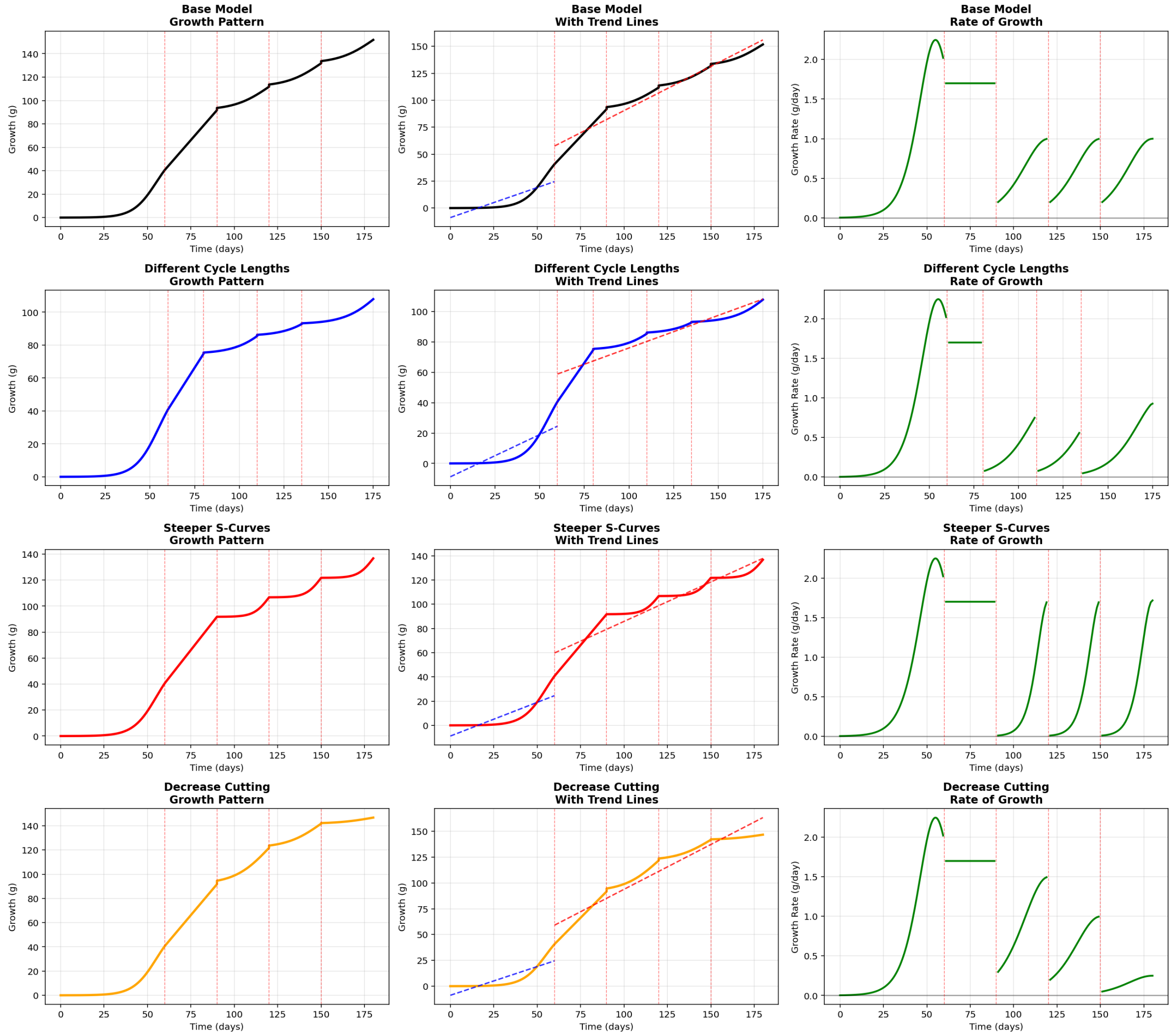


Figure 7.11: Illustrative Overview of Growth Patterns for Different Scenarios

The parameters A, B, and C are crop-specific and highly dependent on the environment. These can be found through estimations, measurements, and with non-linear regression analysis. In order to find these, experiments should be done. Recommendations of these experiments can be found in subsection 7.7.5.

Product Assumptions

As shown in Table 7.2 the latex and rubber content are different for hydroponic roots. With these roots, the rubber is also in the form of rubber particles, so outside the laticifers (Salehi et al., 2022). That is also the reason articles skip latex content when determining the rubber content. Due to missing precise data, the rubber content is taken as 10% of the DRW, which is 10% of WRW. This is in range with the field-grown dandelions. For hydroponic roots, it is also unclear how the quality of the rubber will vary. For this calculation, it is assumed to be of the same quality as the Hevea tree. As the price was identified as 1.65 euros per kilogram, this will be the minimum price. The model has a maximum price of 1.80 euros to implement sensitivity.

System Design and Operational Assumptions

The root harvesting is taken as a repetitive action, but it does not affect the calculation. The linear growth is taken as growth times the number of days in the system. This is also because it is assumed that during the last harvest cycle, all outside roots are harvested, as that is most productive. As the harvesting is not taken into account, it also does not influence the amount of roots to be cut.

This assumption limits the influence it has on the crop dying and the leaves browning, stunting the growth as seen in the experiment. If more roots are cut, this can imply a denser planting density, as the rosettes will stay smaller. However, it is not known how this will influence the rubber yield, so it will not be implemented. This assumption also limits another factor, which is not in the model. If the roots grow to long and are not cut enough, it might clog the system. In the design, this should be taken into account, with, for example, bigger gutters. This influences the planting density, and thus the area and costs.

The assumption is that with multiple small harvests, the dying shoot can be controlled. This would mean no measures need to be taken to remove plant material. The assumption for flowering is that these can be cut and collected with a system used for lettuce harvesting. This can be included in the harvest for the roots or added during the growing stage. This depends on the cycle time. The assumption is that it is needed for a multiple-harvest cycle, but is not further implemented in the calculation.

Planting density is determined by the balance between individual root space requirements and system throughput. The aim is for the rosettes to have light access, without wasting light on the system. An average rosette size is known (15–40 cm), but more information is needed to make a precise planting density schedule. However, due to the root cutting, it is assumed that the rosette will not reach the maximum size. The planting density is estimated based on similar crops. The starting density is 160 plants per square meter and will decrease to 40 pl/m^2. All plants are assumed to start from a uniform initial weight (S_0) after germination.

It was assumed that there were no limitations on available land. With the calculation, the effective used area is calculated. However, the greenhouse and the surroundings of the hydroponic system require more space. This is taken as an additional 5% on top of the effective area. This number is used to calculate the costs associated with the area. With this, the input of plants per day is 5000, based on documents provided by the company.

The lifetime of the greenhouse is taken as 25 years. This is based on **amiraubedzoubi<empty citation>**. With this, it is assumed that the greenhouse to be built will be of a high quality and thus be operational for 25 years.

To mimic different greenhouse scenarios, there are three options in the calculation. These directly influence the growth rate of the crop, and thus the yield. The values to increase and decrease the growth are arbitrary until further values are found through experiments. It was implemented to highlight the trade-off between yield and costs. However, as this is an illustrative case, it does not represent real designs. The values for the economic side are chosen based on three classified cases, provided by the company. These are given in subsection 7.7.2.

Sensitivity

The independent variables in the calculation are:

- The linear growth rates (S_2).
- The duration of harvest cycles (D_n).
- The number of harvests per plant (R_n).
- The market price of rubber (P_{rubber}).
- The cost structures associated with different automation levels and their effect on growth.

These variables also create the sensitivity of the calculation. The earlier-mentioned values will be considered constant values.

The input of plants per day is also taken as a constant. This is taken as an estimation of what the scale would be to produce rubber. Increasing this number directly increases the area. If needed, the calculation can be changed around, with the area as a constant and the input of crops as a variable.

Model Limitations

The following elements are explicitly excluded from the current model scope, representing primary limitations and avenues for future work:

- Plant mortality, detailed post-harvest regrowth dynamics (additional growth or shock), and seasonal effects in non-closed greenhouse scenarios are not modeled.
- Maintenance downtime, cleaning periods, energy consumption calculations, and the detailed engineering of root harvesting to prevent clogging are not included.
- Losses during the process for harvesting are not accounted for. Additionally, if these effects are not in the scope.
- Financing costs (interest), land value appreciation, land preparation costs, insurance, and other business hazards are outside the model's scope. Precise energy, water, and other utility costs are estimated and could be improved on.
- The rubber content could be estimated higher if it is taken into account that the modified seeds in a few years will produce more rubber.

7.7.2. Summary of Assumptions and Limitations

The core assumptions and their implications for the model are summarized in Table 7.11.

Table 7.11: Summary of key model assumptions and their inherent limitations.

Category	Assumption / Input	Rationale / Limitation
Growth Model	Simplified two-phase linear growth.	Lack of documented S-curve data for TKS roots; response to cutting is unknown and likely stunted.
	Growth rates based on lettuce S-curve, using a lower-bound value (2–4 g/day)	A pragmatic estimate; a safety factor accounts for potential stunting.
	Seasons not included.	Not in the scope of the current research stage.
	A fixed number of harvests (1–6).	Based on literature.
	Fixed cycle days and planting densities.	Based on approximations from experiments and comparable hydroponic crop models (lettuce).
	All plants are assumed to start from a uniform initial weight after germination (outside weight 10 g).	Simplifies model initialization and avoids introducing biological variability.
Yield & Content	Rubber content is 10% of DRW.	An optimistic assumption within the range of field cultivation.
	DRW 10% of WRW.	Based on the average from hydroponic studies and experiments.

Continued on next page

Category	Assumption / Input	Rationale / Limitation
	Content is unaffected by cutting stress, cycle length, or other stressors; assumed linear but correlated with greenhouse scenario.	A significant simplification; quality and quantity may vary in reality. See subsection 7.7.5
	Temperature and dormancy effects are not considered.	Cold-induced stress could influence rubber yield, but is excluded from this stage of modeling.
System Design	No clogging from root growth; harvesting does not affect calculations. Root architecture and mechanical design are not modeled, which may affect density and yield.	Functional constraint.
	Input of 5000 plants per day is constant. The scale chosen to reflect a potential commercial scenario affects the total required area directly.	Appendix H
	Rosette size of 15–40 cm.	Based on literature values, precise size dependent on growth conditions and cutting frequency.
	Planting density decreases from 160 to 100 to 80 to 40 plants/m^2.	Based on the provided company data and comparable crop systems.
	No spatial limitations assumed.	Land availability is not considered a constraint in the conceptual model.
	Effective area +5% for system infrastructure.	Allows for walkways, tanks, and structural components; used for cost estimation.
	Gutters are manufactured to fit the rosette size.	Considered technically feasible within current greenhouse design standards.
Economics	Greenhouse lifetime of 25 years.	Based on high-quality greenhouse construction standards.
	Three automation scenarios with associated cost and yield factors.	Conceptual classification to compare potential cost-yield trade-offs.
	Option 1: CAPEX 660, OPEX 100, growth rate = 0.8	Appendix H
	Option 2: CAPEX 1200, OPEX 150, growth rate = 1	Appendix H
	Option 3: CAPEX 1700, OPEX 200, growth rate = 1.3	Appendix H
	Rubber price is constant (€1.65–1.80/kg).	Based on long-term market range.
	CAPEX and OPEX based on European greenhouse data.	Closest available reference; actual values for TKS may differ.
Excluded Factors	Mortality, maintenance downtime, harvest losses, energy calculations, land, interest, and insurance.	Scoped out to maintain a conceptual, high-level model. These are critical for a detailed feasibility study.

7.7.3. Formulas

The variables are summarized in Table 7.12. The additional system parameters are given in the code in Appendix J. The additional economic parameters that were used as a guideline are given in Appendix H.

$$Y_n = S_0 + (G \cdot D_n \cdot R_n) \tag{7.2}$$

The total yield of a plant in stage n is modeled as the initial weight plus the product of the daily growth rate, growth duration, and the number of harvests.

$$DY_n = \frac{Y_n}{D_{\text{total}}} \tag{7.3}$$

Average daily production per plant is calculated by dividing the total yield by the total growing cycle duration. This value is used for comparing short and longer system options.

Table 7.12: Derived / Calculated Variables

Variable	Meaning	Unit
G	Growth per day	g/day
Y_n	Total yield per plant in stage n	g/plant
A_{total}	Total area with margin for infrastructure	m²
A_{growing}	Total growing area (sum of all stages)	m²
A_{harvest}	Total harvest area (sum of harvest stages)	m²
DY_n	Daily yield per plant in stage n	g/plant
S_n	Growth rate of plant (nth option)	g/day
R_n	Number of harvests (nth option)	No unit
D_n	Duration of growing cycle (nth option)	days
S_0	Initial plant weight after germination	g
P_{rubber}	Price of rubber	€/kg
ρ_{harvest}	Final planting density in harvest stage	plants/m²
N_{harvest}	Total plants in harvest stage	plants
T_{years}	Lifetime of the system	years
I_{plants}	Input plants per day	plants/day
m_{area}	Additional needed area factor	No unit
D_{total}	Total cycle duration including all stages	days
C_{variable}	Variable cost per kg yield	€/kg
C_{fixed}	Fixed operational cost per m²	€/m²/year
$C_{\text{Capex per m}^2}$	Capital expenditure per m²	€/m²

$$\text{Actual Daily Yield per Plant} = \frac{DY_n \cdot \text{DRW} \cdot \text{Rubber}}{1000} \tag{7.4}$$

The yield is multiplied by the DRW and rubber fraction to get the actual rubber yield. Conversion to kilograms.

$$\text{Daily Yield per m}^2 = \text{Actual Daily Yield per Plant} \cdot \rho_{\text{harvest}} \tag{7.5}$$

The actual yield is multiplied by the final harvesting density.

$$\text{Annual Yield per m}^2 = \text{Daily Yield per m}^2 \times 365 \tag{7.6}$$

This formula converts plant-level yield into yield per square meter of production area. Multiplying by 365 days provides the expected annual productivity under continuous operation.

$$N_{\text{harvest}} = I_{\text{plants}} \cdot D_n \cdot R_n \tag{7.7}$$

Total plants in the harvest stage equals daily plant input multiplied by cycle duration and number of harvests.

$$A_{\text{harvest}} = \frac{N_{\text{harvest}}}{\rho_{\text{harvest}}} \tag{7.8}$$

The harvest area required is determined by dividing the total harvest plants by the final planting density.

$$A_{\text{growing}} = A_{\text{germination}} + A_{\text{first}} + A_{\text{second}} + A_{\text{harvest}} \tag{7.9}$$

$$A_{\text{total}} = A_{\text{growing}} \cdot m_{\text{area}} \tag{7.10}$$

The total cultivation area is the sum of stage-specific areas calculated from the growing bays divided by their respective planting densities. A_{growing} represents the productive area, while A_{total} includes additional space for machinery and walkways.

$$\text{Revenue per m}^2 = \text{Annual Yield per m}^2 \times P_{\text{rubber}} \tag{7.11}$$

This computes income generation potential per unit area based on yield and market price.

$$\text{Total Revenue} = \text{Revenue per m}^2 \times A_{\text{harvest}} \tag{7.12}$$

Revenue is calculated by multiplying the annual yield density by the product price and then scaling by the effective growing area. This links biological performance directly to financial outcomes.

$$\text{Variable Cost per m}^2 = \text{Annual Yield per m}^2 \times C_{\text{variable}} \tag{7.13}$$

These are the additional costs that scale with rubber production.

$$\text{Total Variable Cost} = \text{Variable Cost per m}^2 \times A_{\text{harvest}} \tag{7.14}$$

This calculates total yield-dependent operational expenses across the facility.

$$\text{Fixed Opex Cost per m}^2 = C_{\text{fixed}} \tag{7.15}$$

This represents constant operational expenses that occur regardless of production level.

$$\text{Total Fixed Opex Cost} = \text{Fixed Opex Cost per m}^2 \times A_{\text{total}} \tag{7.16}$$

This scales fixed operational costs to the entire facility footprint.

$$\text{Capex Cost per m}^2 = \frac{C_{\text{Capex per m}^2}}{T_{\text{years}}} \tag{7.17}$$

This formula calculates the CAPEX per square meter per year.

$$\text{Total Annual Capex Cost} = \text{Capex Cost per m}^2 \times A_{\text{total}} \tag{7.18}$$

This calculates the yearly capital cost burden for the entire facility. €/year

$$\text{Total Capex Investment} = C_{\text{Capex per m}^2} \times A_{\text{total}} \tag{7.19}$$

Operating costs are divided into variable costs, which scale with production, and fixed costs, which scale with total area. Capital costs are annualized over the system lifetime and expressed per unit area for consistency with yield and revenue metrics. €

$$\text{Profit per m}^2 = \text{Revenue per m}^2 - \text{Variable Cost per m}^2 - \text{Fixed Opex Cost per m}^2 - \text{Capex Cost per m}^2 \tag{7.20}$$

This calculates the net earnings per square meter after accounting for all cost categories.

$$\text{Total Annual Profit} = \text{Total Revenue} - \text{Total Variable Cost} - \text{Total Fixed Opex Cost} - \text{Total Annual Capex Cost} \tag{7.21}$$

Profit is determined by subtracting all cost categories from revenue. Expressing this on both a per square meter and total basis allows for evaluation of profitability at different scales of operation.

$$\text{ROI} = \frac{\text{Annual Profit}}{\text{Total Capex Investment}} \times 100\% \tag{7.22}$$

This measures investment efficiency by comparing annual returns to total capital outlay.

$$\text{Payback Period} = \frac{\text{Total Capex Investment}}{\text{Annual Profit}} \tag{7.23}$$

This estimates the time required to recover the initial investment through annual profits.

The full calculation and code can be found in Appendix J. Additional steps are provided. For context, a comparative analysis with traditional Hevea tree plantations and a practical calculation of rubber per medical glove are also provided in Appendix I.

7.7.4. Calculation Results

The model is built with the current information and assumptions. This leads to only indicative results instead of a true business case for the case study. However, these results can still be used to evaluate how variables interact. This is done by comparing the KPIs and independent variables. This calculation is rather a structured tool for scenario exploration and identifying critical research gaps. To highlight two cases, the low cost with the lowest level of complexity is compared with the high cost with the highest level of complexity and cycles. This comparison is given in Table 7.13.

Key observations from this comparison are that both scenarios result in significant losses. This indicates that under current model assumptions, the system is not economically viable. Additionally, it is observed that the high-performance system requires a much larger total area due to the repeated low-density bays. This is a primary driver of its escalated capital and operational costs. The area of case 2 is still within commercial greenhouse scale, meaning the setup of the operation would be an option. From the ROI,it can be seen that the High-Performance operation is slightly less bad from a percentage loss perspective, but it’s still a terrible investment that destroys

Table 7.13: Comparison of Model Outcomes for Low- and High-performance Scenarios

Parameter	Case 1: Low-Performance	Case 2: High-Performance
Rubber price (€/kg)	1.65	1.80
Growth rate (g/day)	2.0	4.0
Cycle days	30.0	90.0
Number of harvests	2	6
Total cycle duration (days)	120.0	600.0
Total area (m²)	11,484	74,484
Annual yield (kg/m²)	0.1290	0.6857
Total revenue (€)	1,596	83,314
Total costs (€)	1,451,770	19,966,441
Annual profit (€)	-1,450,126	-19,883,127
ROI (%)	-19.1	-15.7
Payback period (years)	-5.2	-6.4

Figure 7.12: Yield vs Profit by Cost Level

capital. The operation is so costly to run that even the significantly higher revenue in Case 2 cannot come close to covering the enormous expenses.

Yield vs profit by cost level

To understand the relationship between biological output, technological investment, and economics, a multivariate analysis was conducted. Graph Figure 7.12 illustrates the trade-off between achieved yield and annual profit under the three cost structures.

- Option 1: Blue markers represent the lowest costs, resulting in the least negative profits. However, this configuration assumes an 80% reduction in growth efficiency, hindering potential yields.
- Option 2: Orange markers show the baseline configuration. Profitability declines non-linearly as yield increases. Due to the higher yields, the system requires larger areas, which amplify area-dependent costs faster than revenues.
- Option 3: Green markers represent a high-cost system with a 130% base growth rate. Despite achieving the highest yields, profitability is the worst due to the needed area.

No configuration achieves positive profitability. The analysis demonstrates that higher yield, driven by larger areas and higher costs, does not lead to better financial outcomes under the given cost structure and market prices.

Rubber price vs area vs profit

In Figure 7.13, the interaction between market price, scale, and profit is given. It can be seen that:

- An increase in rubber price only improves profit slightly, insufficient to offset the high fixed-cost base. This indicates that waiting for favorable market conditions is not a viable strategy. Even if the range of rubber prices is set as 10 times the highest value of the last 5 years (Figure 7.14), it does not create a positive profit.

- While higher growth rates (warmer colors) improve revenue, their positive impact is small compared to the associated cost increases, especially in large-area scenarios. The operational variable costs that correlated with the yield are thus negligible when determining the best case.

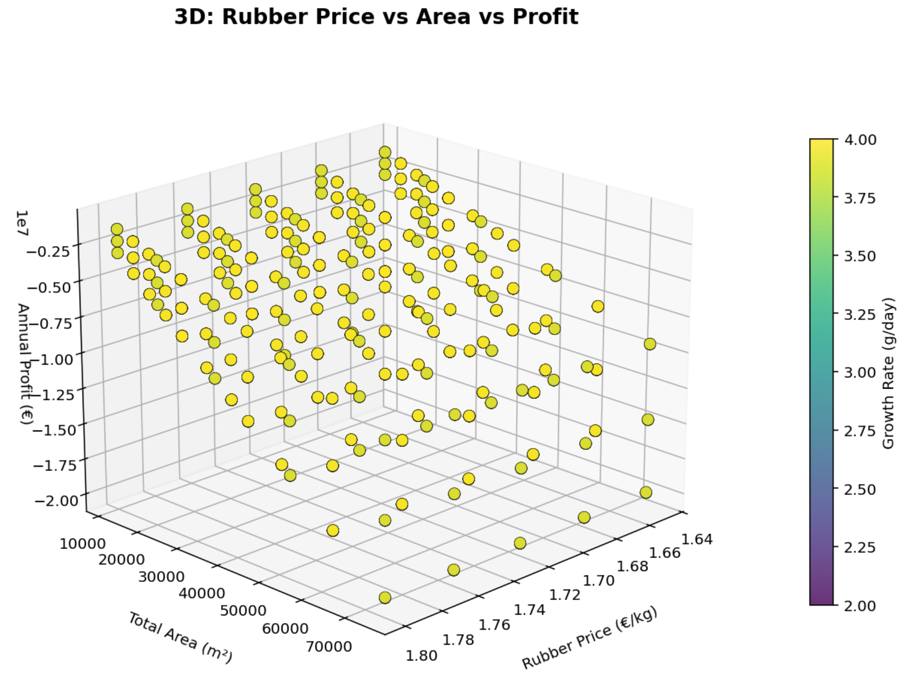


Figure 7.13: Rubber Price vs Area vs Profit

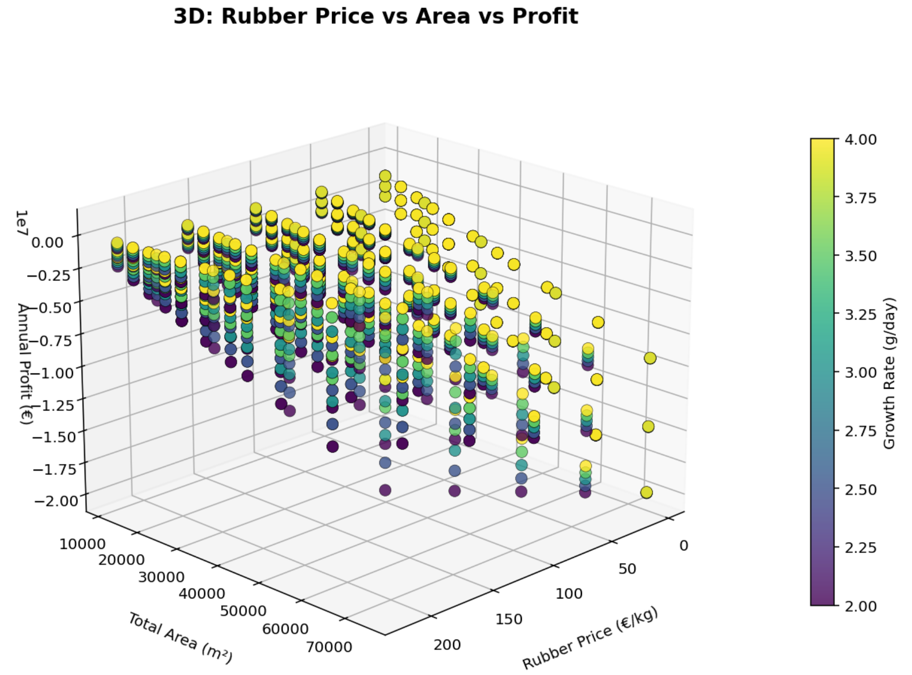


Figure 7.14: Rubber Price Extreme vs Area vs Profit

Sensitivity of profit

A tornado plot was constructed to isolate and rank the impact of individual parameters on annual profit. The independent variables were used, except for the levels of greenhouse costs. The tornado plot in Figure 7.15 reveals the level of influential independent variables of this model for option 2:

- Number of Harvests & Cycle Days: These operational parameters have the most effect on profit, with potential swings of several million euros. They directly and non-linearly affect both revenue (by determining annual throughput) and costs (by influencing the required total area and operational intensity). An optimal balance is critical: too few harvests or long cycles underutilize capital, while too many harvests or short cycles increase operational costs and reduce yield per cycle.
- Growth Rate: This biological factor has a moderate, but only positive impact on profit. Improving growth directly increases yield and revenue, but is insufficient alone to achieve profitability.
- Rubber Price: This market factor shows the least sensitivity, also seen in the previous plots. Its limited leverage confirms that internal cost structure, not external market price, is the primary barrier to viability.

This is a logical result as the growth rate affects only the yield term and some additional costs per kilogram. The rubber price only affects the revenue, as harvest and cycle days interact with both yield, revenue, and profit.

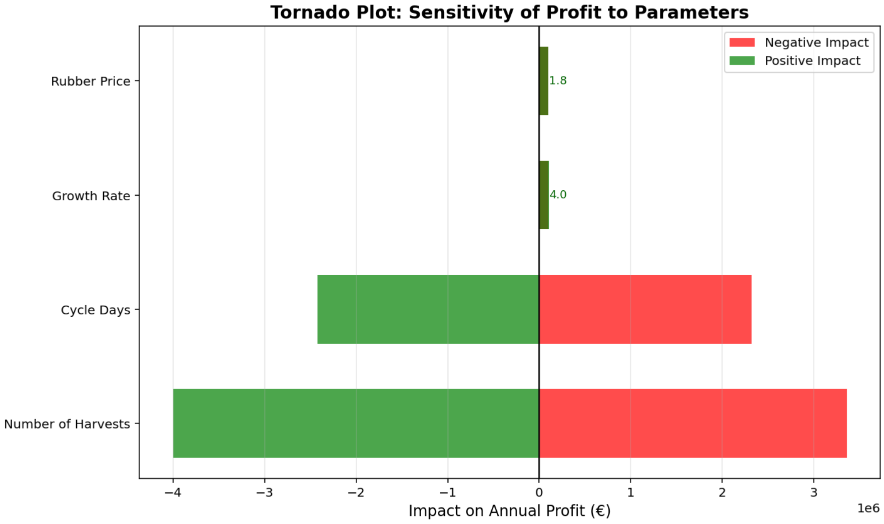


Figure 7.15: Sensitivity of Profit to Independent Variables

Implications and Conclusion

The yield for option 2 is $0.6857kg/m^2$. Compared with a Hevea plantation (..) this is incredibly low. The results clearly indicate that the current production concept is not economically viable. The path to profitability lies not in minor improvements but in fundamental redesign and optimization. Strategically, the results suggest that the two parameters related to system design need improvement. Options for improvement can be a smaller plant density or, for example, a low automation level of the system, which will reduce the CAPEX and OPEX. However, these optimizations are dependent on additional research and specific location-based design.

With additional research, the calculation can be improved by integrating specific utility costs, providing a more in-depth cost scenario linked to biological growth. However, this all depends on the growth curve of the dandelion and how the rubber quantity and quality potentially improve over time in the system.

Additional variables to add to the model are the trade-off between planting density and yield. Another option is to model vertical farming methods with the considered costs to decrease the area of the greenhouse. Another variant to consider is the growth of the crop over a longer period, as seen in field cultivation, if that means drastically improving the yield.

In conclusion, profitability is most sensitive to factors within direct operational control. The focus must be on biological performance in isolation to create an accurate model, while also optimizing the entire process, with an emphasis on cost reduction and cycle efficiency.

The model's reliability was assessed through verification (confirming correct implementation) and validation (ensuring outputs are meaningful and plausible).

Several checks were performed to ensure the equations were implemented correctly:

- Cross-checks were made between manual calculations and code output. In particular, scenarios that should theoretically result in an identical growing area (halved planting density combined with doubled area) were confirmed to yield the same results.
- Numerical plausibility was tested by running extreme scenarios. This also revealed where assumptions break down at unrealistic inputs.
- Performed sensitivity checks to see the behavior of the results. These checks were done per independent variable.
- Units and dimensions were checked across all formulas to prevent dimensional inconsistencies.
- The model was first constructed deterministically in Excel and then implemented in Python, which enabled the detection of coding or transcription errors.

To validate the model, the outputs were compared against external benchmarks:

- Plant handling speed of 5000 plants a day seems to be within the machine handling speed for greenhouses.
- Required greenhouse area was compared to industry data on commercial greenhouse sizes (Knaupp, 2024), and the values were within an order of magnitude that is reported.

Overall, the verification checks confirmed that the model was implemented consistently and without obvious coding errors. However, although the validation on the mentioned parts seems correct, due to many uncertainties and estimations, the model cannot be declared validated. Additional validation is needed after the precise values are found for the model. These validation points should include:

- Accurate business case profit and revenue.
- Testing the yield output with an experiment.
- Comparing the yield of the greenhouse with Hevea plantation, integrating both operational lifetime and economic factors.

7.7.5. Design of Experiment

Multiple subjects have been mentioned throughout the case study that need further study. It has also been stated that addressing certain research gaps will lead to more accurate information for the development of the system. The entire list of research questions has been stated in Appendix E. This section will explain what experiments need to be done in order to get results for the short-term steps in this project. subsection 7.7.5 gives the summary of the proposed tests. Test 1 is included in Table 7.7.5, and test 2 in Table 7.7.5. The other tests can be found in Appendix E. A further project horizon is also provided in Appendix E.

Biological tests

For each test, the purpose, approach, data analysis, and outcome are stated. A summary of tests is given in Table 7.14.

Table 7.14: Summary of Priority Tests

Test Number	Objective	Method
1	Determine rubber content	Measure the rubber quantity and quality under different settings.
2	Analyze S-curve	Change environmental parameters and measure the growth of biomass and roots.
3	Examine S-curve after cutting	Keep environmental conditions steady, cut the roots, and measure the resulting S-curve.
4	Investigate rubber content change	Measure differences in rubber yield when environmental factors are altered.
5	Study root rot and system effects	Determine whether root rot contains rubber and assess storage methods if latex drips from roots.

Test 1: Determining rubber content

Table 7.16: Test 1: Rubber Content

Component	Description
Purpose	To validate key assumptions about rubber accumulation in TKS roots under hydroponic cultivation and assess the feasibility of scaling up production.
Approach	• Cultivate multiple crops under varied nutrient conditions in a hydroponic system. Preferably NFT. • Nutrient level low = 1.2 mS/cm and high = 2.2 mS/cm • Harvest root samples from each experimental condition. Harvest 50% of the pruned crops. • Analyze harvested roots for rubber content. • Experimental groups will include both continuously cut plants and uncut controls to quantify the effects of harvesting via cutting on rubber yield and plant regrowth. • Experiment for at least 120 days to measure rubber accumulation over time. • Over 20 crops per run. Potentially more for the pruned crops.
Data Analysis	• Quantity of Rubber: Measure the mass or concentration of rubber extracted per unit of root biomass. • Quality of Rubber: Analyze properties.
Outcome	Data set containing the analysis and values. Determine whether hydroponically grown TKS can produce latex yields comparable to traditional soil-based cultivation, and evaluate whether further optimization and large-scale scaling is feasible. Also connects directly to the KPI yield.

Table 7.17: Factorial design for Test 1 (2^2 full factorial)

Run	Nutrient Level	Cutting Treatment	Replicate
1	–	–	1–20
2	+	–	1–20
3	–	+	1–20+
4	+	+	1–20+

Test 2: S-curve

Table 7.18: Research Plan for Determining Baseline Growth Dynamics and Parameterizing the S-Curve Model

Component	Description
Purpose	To determine the baseline growth dynamics of the crop and parameterize the S-curve model (maximum growth rate, inflection point, and carrying capacity). These parameters will serve as the foundation for modeling biomass and root development under different environmental conditions.
Approach	• Cultivate multiple crops under controlled environmental conditions. • Employ two main variable sets: – Constant light intensity with varying nutrient levels. – Constant nutrient levels with varying light intensity. • Monitor plants daily. • Record non-destructive parameters (e.g., plant height, leaf area from imaging) and destructive parameters (e.g., dry biomass from sampled plants). • Track root development separately to relate above- and below-ground growth.
Data Analysis	• Fit collected growth data to an S-curve model using nonlinear regression. • Compare derived S-curve parameters between the shoot and root components.
Expected Outcome	• Comprehensive growth datasets (height, biomass, root mass) for each environmental condition. • Plots of raw growth data with fitted S-curves for analysis and visualization.

Runs 5 to 8 are destructive measurements, so to create more replications, additional crops need to be added. The exact replications and number of crops to test should be determined with the guidance of an expert. This is also the case for the specific values to test. It will also be dependent on the availability of resources and growing space. The factorial design for test 2 is 2^3 full factorial.

7.7.6. Summary Provisional Design

The implications of the Testing phase were added, and the conceptual design with iterations moved to the Provisional Design phase. In this section, a calculation model is presented to assess the feasibility of the selected concept. The model serves as a scenario exploration tool rather than a definitive business case, highlighting critical dependencies and research gaps.

A simplified linear growth model is used due to the unknown S-curve of the crop, with growth rates estimated from lettuce data. Rubber content is assumed at 1% of fresh root weight. The model calculates yield, required area, and profitability based on variables like growth rate, number of harvests, cycle length, and rubber price. Results consistently show the system is not economically viable under current assumptions, with all scenarios generating significant losses. Sensitivity analysis reveals that operational parameters like harvest frequency and cycle days have the greatest impact on profit, while rubber price has the least. The primary economic barrier is the high cost structure due to the needed area.

The analysis directly informs a DoE plan, prioritizing biological tests to replace key assumptions with empirical data. The required tests focus on measuring the actual rubber content in hydroponic roots and establishing the plant's true growth S-curve under different conditions.

7.8. Decision

The provisional design lacks important parts due to missing information. Based on the current design and calculation, it is not feasible to cultivate the dandelions for large-scale rubber production. The methodology would transition from the provisional detailed design to the decision-making stage, where the project will be determined to continue. Based on the current findings, the project should move towards a new Testing phase. The proposed DoE experiments should be considered. Based on the information, the design needs to be reevaluated. After these numbers have been found, they should be implemented in the model. From there, another decision needs to be made for the continuation of the project. The decisions and thresholds can be made with this composed list of criteria:

- Biological criteria: The crops need to produce rubber in a quantity and quality high enough
- Biological criteria: The rubber needs to be harvestable in a short amount of time
- Biological criteria: High survival rate and seeds with a good genotype for rubber
- Biological criteria: How much the rubber can increase by applying technological measures
- Technological criteria: Feasibility of automation of harvest
- Technological criteria: Roots storage to biorefinery
- Technological criteria: Possible to apply rubber-enhancing measures to the greenhouse system
- Economic criteria: Is it feasible to build the greenhouse, aiming for a return on investment within 10 to 15 years

7.9. Application, Verification and Validation of Proposed Methodology

The purpose of this section is to evaluate whether the methodology applied during the case study was appropriate, correctly implemented, and effective in supporting the project objectives. The emphasis lies on assessing rather than the specific findings. Validation focuses on whether the chosen methods achieved their intended purpose, while verification ensures that the methods were applied in accordance with good research practice. The following table 7.20 summarizes this evaluation.

This traceability confirms that all methodological stages were followed systematically. The reporting was linear; however, the feedback loops were applied and deemed important. The inclusion of the Testing phase proved particularly valuable, validating its need as a distinct methodological component.

The proposed methodology showed:

- Structuring the design process through iterative feedback loops between biological, technical, and economic fields.
- Generating feasible and comparable system concepts for a specialty crop with limited data.
- Generating a business case setup for the feasibility.
- Identifying knowledge gaps and translating them into research questions.
- Translating the research questions into a future research setup.
- Not every tool or method needs to be achieved in order to move towards the next stage, but it will hinder progress.

The applied methodology demonstrated internal consistency. Each phase produced outputs that informed the next, confirming the operational logic of the framework. Due to the limitations in the information, it was also clear how gaps hindered the performance of upcoming phases.

Despite the application, there are several limitations that emerged for this specific case:

- The experiments could not quantify the KPIs.
- Due to limited time, feedback loops could not be repeated.
- Not every tool or method was performed at all stages, as not all information was available. However, these still hold value that could influence the system or design, and recommendations.

Next to these limitations, the general limitations of the case study are:

- The methodology was not tested alongside Pahl & Beitz, Roozenburg & Eekels or TRIZ. This could highlight the differences and identify improvements.
- The methodology was only tested with one crop. Multiple crops with different project boundaries could identify improvements.

- The methodology was not validated through expert opinions. This external validation can improve the robustness and strengthen the methodology.

The verification confirms that the methodology was correctly and structurally applied. The validation proved that it functions as intended, by showing the limitations as well. The case study thus serves as a proof of concept, demonstrating both the applicability and developmental potential of the methodology.

Table 7.20: Methodology Verification Framework for Hydroponic TKS Cultivation

Methodology Phase	Intended Purpose	Implementation	Verification Evidence
Task	Define project scope, crop biology, market context, and feasibility of hydroponic vs. soil cultivation.	Comprehensive literature review of TKS botany, rubber biosynthesis, and market drivers; preliminary comparison of soil vs. hydroponic cultivation.	Documented crop background, system context (Netherlands), market evaluation, and initial research gaps.
Analysis	Translate biological and market insights into measurable design requirements, constraints, and KPIs; identify risks and unknowns.	In-depth study of rubber synthesis factors (environment, harvest timing, cold treatment); technical implications for system design; identification of functional requirements and critical unknowns.	Detailed biological analysis, technical implications report, list of functional requirements, and prioritized research questions (root architecture, latex yield in hydroponics).
Conceptual Design	Generate and evaluate system-level concepts that address key research gaps and cultivation strategies.	Developed morphological chart; created and evaluated three distinct concepts (Multi-NFT, Single NFT, Multiple DWC) against KPIs (yield, ROI complexity, automation); integrated cultivation strategies.	Morphological chart, concept sketches, comparative evaluation matrix, and selection of Multi-NFT as the most promising concept.
Testing	Empirically validating key assumptions from conceptual design, especially biological responses and system interactions.	Conducted small-scale experiments: root trimming stress tests, dry root weight measurement, and flowering behavior observation under NFT conditions.	Experimental logs, quantitative results (9.4% DRW, stress responses to trimming), qualitative observations (flowering variability, material degradation), and documented feedback to earlier phases.
Provisional Design	Refine selected concept using experimental data; assess technical and economic feasibility through modeling.	Developed a computational model to simulate yield, area, and profitability under varying growth rates, harvest cycles, and cost structures; performed sensitivity analysis.	Growth and economic model output, scenario comparisons, sensitivity analysis (tornado plot), and a structured DoE plan to address critical gaps.
Decision	Make a go/no-go/pivot decision based on integrated evidence from all phases.	Evaluated model results against viability thresholds; concluded system was not economically feasible under current assumptions; recommended pivot to further biological testing.	Decision to pivot, supported by negative ROI, high area-driven costs, and unresolved biological unknowns (rubber content, optimal harvest strategy).
Feedback Loops and Interactions	Enable iterative refinement by feeding results from later phases back into earlier decisions and assumptions.	Used test results to update conceptual design (pot material, hygiene measures); revised research questions and DoE based on model sensitivities and new gaps.	Updated concept features, refined DoE plans, and documented iterative learning cycles (from testing back to analysis and conceptual design).

8

Discussion

The objectives of this study were to first define a methodology for the conceptual design of hydroponic systems for specialty crops. Secondly, it was to ensure this methodology provides support for both academic research and practical industry applications. Lastly, it was to demonstrate its applicability through a case study on Russian dandelions. The evaluation of the methodology was conducted by examining the feasibility of cultivating the crop for large-scale rubber production. This chapter reflects on the meaning of the results and implications. It also discusses the limitations of the study.

8.1. Interpretation of Results

Hydroponics is a cultivation method that reshapes agronomic practices by replacing soil with inert growing media and a controlled nutrient solution. Although the systems are well developed, it is still mainly applied to a small set of crops such as lettuce, tomato, and strawberry. Wider adoption is limited by the high investment costs of greenhouses and the lack of knowledge about how other crops perform in hydroponic systems. Additionally, the design for specialty crops is limited in both research and guidance. Due to high system complexity, knowledge gaps, and crop-specific requirements, it remains difficult to integrate new crops into hydroponic systems.

Hydroponic system design needs integration of biological, technical, and economic considerations. When reviewing mechanical engineering methodologies, it was highlighted that although many contain good aspects, there was still a challenge when applied to hydroponic system design. By combining the advantages of Pahl & Beitz, Roozenburg & Eekels, and TRIZ, a new design methodology could be created.

The identification of design requirements highlighted the importance of trade-offs and provided a rationale for design choices. The core strength of the proposed methodology lies in the explicit and parallel integration of the three identified fields. The introduction of a dedicated Testing phase between Conceptual and Provisional Design is a novel and critical adaptation. It acknowledges that for specialty crops, key parameters cannot be found in literature and must be empirically determined during the design process, not just for validation at the end. The methodology's iterative feedback loops and continuous cycles make it highly adaptable to new information. The inclusion of specific go and no-go decision points provides a structured way to manage the feasibility of the projects. This makes it suitable for small-scale purposes, but also for commercial system design.

The methodology was applied to a case study, focused on Russian dandelions. This specialty crop is grown for the rubber in its roots. This is highly unconventional for a hydroponic crop, but due to field-grown limitations, hydroponic cultivation is proposed. The case study successfully served as a ”proof of concept” for the methodology, demonstrating its ability to structure a complex problem, generate distinct concepts, and systematically identify knowledge gaps. The value of iteration was clearly seen after the experiments, allowing for a deeper Analysis, Conceptual design phase, and proposal for further research. The case study also clearly showed the methodology's limitations when faced with biological unknowns.

The experiments confirmed that Russian dandelion could be grown in a NFT system, although it showed signs of stress and root rot. However, it also revealed significant challenges and research gaps. When applying the root cutting experiment, the crops showed stress, leading to wilting of the leaves. There was also a clear sign of stunted growth for the regrowth of the roots. This finding deviated from the statements of Cornish et al. (2019) and Kopicky (2014). The deviation from these findings suggests a different cultivation strategy than was anticipated from the literature review. The variation needs to be researched more, as it can be explained by the differences in cultivation methods.

Additional issues emerged, including unpredictable flowering behavior and long-term system limitations related to biodegradable materials, mold, and algae. These aspects were reintegrated into the conceptual design as topics for further research, as they will hinder the cultivation strategy. The findings contribute to a deeper understanding of the system requirements and highlight how hydroponic methods influence operational design. System choice affects harvesting methods, downstream and side products, and ultimately product quality. Mechanical design choices, therefore, have significant impacts on biological variables.

Several critical research gaps identified are related to the optimal cultivation strategy and rubber content. The actual quantity and quality of rubber in hydroponically grown fibrous roots remains the single biggest unknown, making any economic evaluation hard. Further study is required to understand root growth rates, the effects of cutting, and their relationship to rubber yield. The fundamental trade-off between a single harvest of large roots versus multiple harvests of smaller roots could not yet be resolved.

Moreover, the second metabolism of the crop, triggered by stress, cold, light, and other causes, might need to be triggered in hydroponics to create rubber. This is a big contradiction, as CEA focuses on minimizing the stress for consistent growth. This might create a crop with optimal biomass but minimizes the rubber yield. Additionally, a question remains how to create a system that favors root over shoot growth, as they are in equilibrium. It is unknown which strategy yields more rubber per plant per year. This means that in order to proceed with the project, the agronomic data needs to be found. This is recommended as the first set of tests for future research.

Despite the assumptions, the calculation model delivered a clear conclusion. Under the current conditions, the system is not economically viable. The sensitivity analysis showed that profitability is most sensitive to operational parameters (harvest number, cycle days) and cost structure, not to small improvements in growth rate or rubber price. The increasing costs were mainly tied to the area needed for the end planting density, which rapidly increases due to multiple harvests. The system was set at a high-cost baseline that may have negatively influenced the outcome. With research breakthroughs and well-defined project boundaries, the economic model can be reevaluated.

Overall, the results demonstrate that while hydroponic cultivation is technically possible, economic viability depends on further research. For example, if the findings show that the rubber content is too low in fibrous roots, or that it takes months to emerge, it might be better to continue field-cultivation. Conversely, if stress factors are proven to enhance rubber yield, hydroponic cultivation becomes a more attractive option. These contradictions highlight the need for additional research.

The identified research topics, together with the Design of Experiment setup, contribute to finding the potential of a viable design. It structures the following steps of the project.

8.2. Limitations

It should be noted that the scope of this study was restricted to hydroponic system design in combination with biological and economic influences. This was also the case for the methodological focus. Additionally, the aim was to develop a conceptual design methodology, rather than a methodology for the detailed design. Greenhouse design was also outside the scope of this review. Throughout the study, several limitations were identified that influenced both the proposed methodology and the case study results.

Proposed Methodology Limitations

The proposed methodology remains conceptual and has so far been validated through a single case study. While the Russian dandelion offered a challenging and illustrative example, broader testing across multiple crops is necessary to establish generalization. This can identify additional deliverables, discoveries, and eventually additional tools and methods to apply.

During the process, experts were consulted. However, the methodology has not yet been discussed with external expert validation or independently applied by other practitioners, which would provide essential feedback for improvement.

Furthermore, the objectives, deliverables, and tools & methods are subjective and dependent on crop and situation. The application is a guideline, and it is up to the practitioner to decide which ones to use. This is also an advantage, as it is not necessary to apply all the tools when specific areas need additional information.

Another limitation of the proposed methodology is the dependence on resources. The effectiveness of the Testing phase relies heavily on available time, budget, and facilities, which may not always be accessible.

The final limitation is the lack of guidance in trade-off decision-making. The moments and tools are provided, but because every situation is different, it was decided not to incorporate them. However, this would be a valuable addition to the methodology and design.

Overall, while the methodology provides a useful conceptual structure, further validation, refinement, and testing across diverse cases are required to establish its robustness and generalizability.

Case Study Limitations

The case study was constrained by data availability. Many parameters were taken from field-grown studies, related crops, or preliminary experiments, rather than from controlled hydroponic trials with Russian dandelion. In addition, many biological processes remained unclear. Due to these processes remaining unanswered, the design was hindered, and the focus stayed on the ”Proof of Concept” instead of an in-depth design proposal.

Additionally, the project boundaries remained vague. This was the case for the biorefinery and the demands in products, but also in the precise location of the system. Additionally, the byproducts were not taken into account for the cultivation strategy and design, nor for the business case.

There were several limitations concerning the experiments. The crops were hindered by low seed quality, pest interference, and power interruptions. The small sample sizes reduced data reliability. The aim of the experiment was not to measure the rubber content, but this created a consequence for the project. Another limitation was the limited knowledge about cultivation at the start of the project. This potentially led to stressful cultivation strategies. Additionally, checking the roots created some destruction to the root ball. This should be mitigated in the future. Although these experiments were not sufficient to support statistically robust conclusions, they provided valuable preliminary insights into this under-researched crop. The limited experimental results were nevertheless included in this report for completeness and to document the practical challenges encountered during cultivation and testing.

The calculation model also contained several simplifying assumptions:

- Growth of the roots was independent of cutting and taken as linear
- Growth and rubber content were not connected with stress factors
- Crop losses were ignored
- Economic parameters were not directly connected with energy usage, although they were estimated based on existing business cases

These factors collectively limit the depth and generalizability of the case study's conclusions. It also limits the accuracy of the output. Due to the unviable economic evaluation, a comparison between Hevea brasiliensis production and a Russian dandelion greenhouse could not be made. However, this would be an insightful comparison for both economic evaluation and sustainability considerations. This comparison should include water and energy usage, land usage, and supply chain factors. The additional biological and economic factors should be added after identifying the agronomic practices to re-evaluate the case. Through this, the optimal case can be found for single or multiple harvests. Field cultivation should also be considered in the comparison.

The absence of data limits the definitive conclusion regarding the final feasibility of growing Russian dandelions for rubber. However, it does allow for an elaborate research proposal.

Contribution to Academic Purposes

The academic literature on hydroponics is currently dominated by research focusing on automation, artificial intelligence, and sustainability improvements within well-established crops. Despite this progress, there remains a distinct gap in the literature concerning design and system choices for introducing new or unconventional crops into hydroponic systems.

This thesis contributes to filling that gap by developing a novel design methodology grounded in proven engineering baselines and adapted to the unique requirements of biological systems. It positions hydroponic system design as a discipline in its own right. Beyond the methodological innovation, it also presents a structured case study that explores the hydroponic cultivation of a root-based specialty crop. This case study expands the limited academic understanding of such crops and provides a foundation for future research in bio-integrated system design.

The work, therefore, not only proposes a new methodology for integrating biological, technical, and economic factors in system design but also demonstrates its applicability through practical experimentation. The case study provides a realistic assessment with a research-oriented perspective, potentially guiding both future academic research and experimentation.

Contribution to Practical Purposes

From a practical perspective, the proposed methodology serves as a design guideline for exploring new hydroponic crops. It allows growers, engineers, and industry stakeholders to evaluate risks, trade-offs, and feasibility in a structured way. From an industry perspective, the methodology can be used as a risk mitigation tool for the design of new systems. This allows for considering new crops, design transparency, expanding knowledge, and identifying design problems early on.

Furthermore, the work highlights the potential of hydroponics beyond food production. By demonstrating how the same principles can be applied to produce materials such as rubber, bamboo, or pharmaceutical compounds, it shows how hydroponics could support more diverse, resilient, and innovative agricultural sectors.

Integrating hydroponics into high-tech greenhouses also contributes directly to increased food production in regions where field cultivation is limited, enabling greater crop diversity, stability of supply, and regional self-sufficiency.

While this research focused primarily on technical feasibility and system design, it also became clear that environmental assessment should form an integral part of future development. Evaluating the sustainability of greenhouse systems, on both the high energy demands and supply chain implications, was beyond the current scope but remains essential for determining the real-world viability of hydroponic rubber production. Considering that Russian dandelions could strengthen supply chain resilience for a critical material, future research should therefore aim to balance these potential benefits against the local environmental and economic costs of production.

9

Conclusion

This thesis proposed a methodology for the conceptual design of a hydroponic system, with a focus on introducing special crops to hydroponics. This research addressed the methodological gap in designing hydroponic systems for specialty crops, where biological uncertainty and system complexity require an adaptive design approach. The objective was to produce a methodology that can structure and guide the development of such conditions. In addition, the methodology was validated through application to a case study on the Russian dandelion.

Sub-Question 1

"Which existing design methodologies in mechanical engineering are relevant to adapt for the development of hydroponic systems?

Hydroponic systems are simultaneously technical installations and crop-specific processes, strongly influenced by greenhouse conditions. The hydroponic system can be seen as a process or product designed to be tailored to the crop requirements. Because specialty crops often lack well-defined requirements, the design methodology must be flexible, iterative, and supportive of decision-making under uncertainty. A comparative analysis of five engineering design methodologies showed that the Pahl & Beitz, Roozenburg & Eekels, and TRIZ offered the most relevant foundations for hydroponic system design. These methodologies scored highest in a Pugh matrix evaluation, excelling in criteria critical for biological systems: flexibility to handle crop variations, strong decision-support for trade-offs, and the ability to guide design from the start. However, they required adaptations to accommodate the incomplete knowledge of crop requirements and did not focus on the multiple fields. The outcome of this analysis provided the methodological basis for the proposed framework. Together with the findings of Sub-Question 2, this was synthesized in Sub-Question 3.

Sub-Question 2

"What functional requirements, constraints, design parameters, process variables, and KPIs define and guide the conceptual design of hydroponic systems?"

The system requirements vary by crop, project, and production goals. From literature sources and stakeholder analysis, the following findings were identified. A general set of functional and non-functional requirements was identified, linking design variables to process parameters, using an axiomatic design approach, creating a traceable link from customer needs and functional decomposition to technical solutions. Because crop requirements shift, the methodology must support the redefinition of these requirements as knowledge improves throughout the development.

Several KPI were highlighted to guide system evaluation. Crop yield and quality provide biological performance measures to evaluate the greenhouse and hydroponic system. Additionally, energy and economic performance indicators were identified. They KPIs strongly correlate with the greenhouse. For special crops, the financial indicator should be evaluated with caution to ensure the option for innovation and system design. Other indicators will be chosen per situation. Together, these requirements and indicators define the design space, providing both constraints, gaps, and opportunities for hydroponic system development.

Sub-Question 3

"What structure and core components define a design methodology tailored to hydroponic systems"

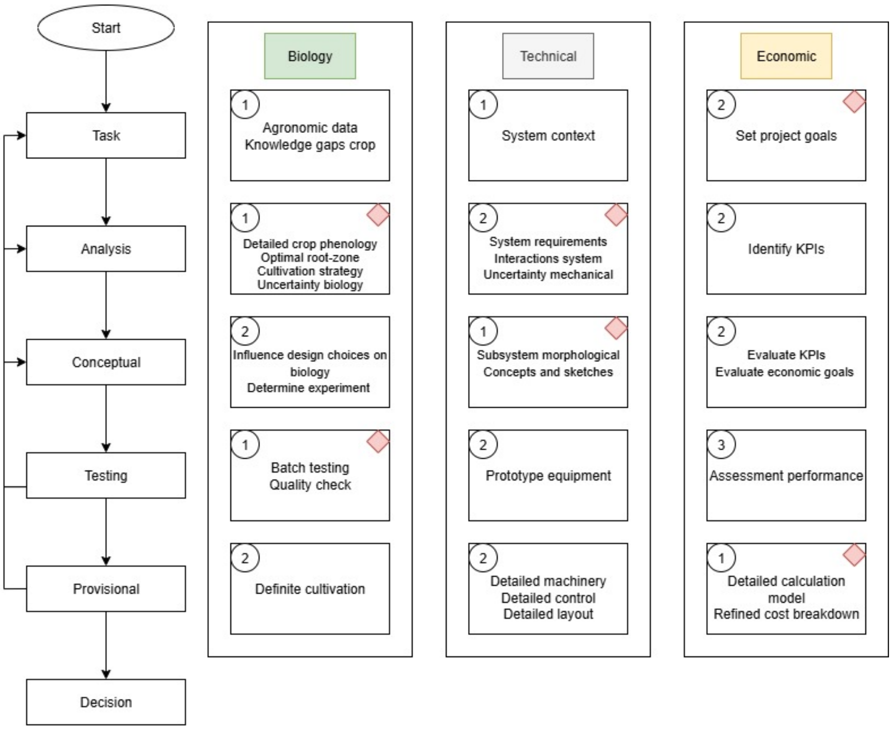


Figure 9.1: Proposed Methodology

The most significant adaptation is the introduction of a dedicated Testing phase between Conceptual and Provisional Design, which serves not for final validation but to provide the critical biological data needed to make informed design decisions. The proposed methodology builds on the Pahl & Beitz design cycle but introduces feedback loops and new phases to manage crop-specific uncertainty. This is essential for the unknown requirements of the specialty crops. The methodology incorporates the biological, technical, and economic insights at every stage. This ensures that crop requirements, engineering feasibility, and economic viability are connected.

The methodology defines objectives, deliverables, and suggested tools per stage. This creates a structured process with flexibility. The iterative character is particularly critical with new research gaps found or answered. The schematic overview is illustrated in Figure 9.1.

Sub-Question 4

"Case study: How does the proposed design methodology perform when applied to the system design for the Russian dandelion?"

The application of the proposed methodology to the Russian dandelion case study served as a test, demonstrating its performance and value in a context of high biological uncertainty. The methodology successfully provided a clear structure that guided the entire process, from initial task clarification to a provisional design and a final decision point.

Key strengths observed during the application include that the methodology showed critical research gaps effectively. Particularly for rubber content in the roots, the development of rubber, the optimal cultivation strategy, and the influence of stress on rubber production. This led to iteration and reevaluation of previous stages. The feedback loops proved essential. Findings from the Testing phase, such as plant stress from root trimming and unpredictable flowering, were directly fed back to refine the Analysis and Conceptual Design. Furthermore, the methodology highlighted the trade-offs, such as harvest strategy and design choices.

The case study did not yield a definitive, economically viable system design. Due to many biological uncertainties, the system design could not be improved further. It demonstrated that the methodology's role is a practical guideline and design-support tool. It proved that the methodology is not about guaranteeing a successful outcome, but about ensuring a structured and informed journey, clearly outlining what is known and what must be discovered before further investment is justified.

Main Research Question

"How can a conceptual design methodology be developed for hydroponic system design and validated through a case study on Russian dandelions"

This research has demonstrated that a conceptual design methodology for hydroponic systems can be developed by adapting established mechanical engineering approaches and integrating them with continuous biological and economic evaluation. The resulting methodology progresses through the stages of Task clarification, Analysis, Conceptual Design, Testing, Provisional Design, and Decision-making, with iterative feedback loops connecting these stages to manage uncertainty. It also contains specific go and no-go points per phase.

Validation through the Russian dandelion case study confirmed the methodology's practical use. It proved effective in structuring a complex problem, identifying requirements, guiding iterations, and, crucially, systematically exposing the knowledge gaps that ultimately determine project feasibility. However, the methodology can be improved by expert additions and conducting more case studies with different crops.

This thesis extends engineering design theory by proposing a novel methodology. This addresses a research gap in the design of hydroponic systems.

From a practical perspective, it provides a guideline for research on new crops, ensuring transparent design while mitigating research risks.

9.1. Future Work

Future research should focus on refining the proposed methodology and applying it to other crops. Validation with additional specialty crops and structured expert reviews would provide valuable feedback on its strengths and weaknesses. This would also test its robustness across diverse cultivation requirements. A critical next step may be developing digital decision-support platforms, where the methodology is translated into interactive tools such as trade-off diagrams, templates, or even digital twins. This can improve the combination of disciplines and inform choices.

With respect to the Russian dandelion, further investigation is needed to clarify the biological and agronomic parameters that most strongly influence rubber synthesis in the roots. An important part of this is the S-curve related to multiple cuttings. These tests should be conducted using the latest developed seeds, which are bred for the highest rubber production. A critical research focus will be the influence of root morphology on rubber yield, studied in combination with different nutrient solutions. Comparative studies between single- and multiple-harvest strategies would provide critical insights into the overall crop feasibility. This includes investigating not only the optimal amount of root biomass to harvest but also the required cycle times between harvests. Establishing a definitive cultivation strategy will require controlled experiments on nutrient solutions, substrates, lighting, and growth cycles. At the technical level, research into mechanized harvesting and processing requirements from biorefineries will determine whether hydroponic cultivation can be realistically scaled to commercial production. Furthermore, valuable future work should include a LCA of Russian dandelion rubber versus Hevea brasiliensis rubber, including a full supply chain analysis and an evaluation of potential side products.

Beyond this specific crop, broader research directions should address sustainability improvements in hydroponic systems through energy optimization and enhanced nutrient recycling. The integration of automation, robotics, and AI-driven monitoring with smart sensors represents another significant opportunity to transform both research and commercial practice. This approach could also be expanded to explore hydroponic cultivation for a wider range of non-food, high-value products.

This thesis concludes that hydroponic system design for specialty crops can be systematically structured by adapting engineering design methodologies and introducing biological and economic evaluations at every stage. The Russian dandelion case study demonstrated the methodology's capacity to reveal trade-offs, highlight uncertainties, and guide the iterative development. While challenges remain, the methodology offers a basis for both academic research and industrial application in the design of innovative hydroponic systems.

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A

Scientific research paper

Design Methodology for Hydroponic Systems A Case Study on Russian Dandelion Cultivation for Natural Rubber

Rhea Hugens
Department of Maritime and Transport Technology, Faculty of Mechanical Engineering
Delft University of Technology

***Abstract*—The increasing interest in hydroponic cultivation requires systematic design approaches for the systems under high biological uncertainty. This is lacking in existing design methodologies. This paper develops a conceptual design methodology for hydroponic systems, tailored to crops with incomplete agronomic knowledge, and validates it through a case study on Russian dandelion (Taraxacum kok-saghyz). This crop is a potential alternative source of natural rubber, which can be produced from the rubber in the roots. The methodology adapts mechanical engineering frameworks by incorporating iterative feedback loops, decision points, and integration of biological and economic constraints. Functional requirements, design constraints, and performance indicators are formalized to guide systematic and flexible system development. In the case study, the methodology structured the evaluation of cultivation strategies, highlighted trade-offs between single- and multiple-harvest approaches, and exposed knowledge gaps in root rubber content, harvesting, and crop management. The application of the methodology confirmed the iterative design approach. The current results present an economically unviable system but demonstrate technical feasibility while also revealing limitations for large-scale cultivation. Additionally, the crucial tests are suggested for future work. The proposed methodology helps bridge engineering design with controlled-environment agriculture, providing a guideline for innovation in non-traditional hydroponic crops and potentially opening the door for new crops.**

I. INTRODUCTION

With a projected global population of 9 billion by 2050, food and resource security have become pressing challenges [1]. Traditional open-field cultivation is increasingly constrained by climate change, soil, and resource availability, driving the adoption of Controlled-Environment Agriculture (CEA) and greenhouse systems [2] [3]. Within these systems, hydroponics offers significant advantages. These include reduced land and water use, improved yields, and year-round production. Compared to field cultivation, hydroponic systems minimize exposure to pests and weather risks while enabling automation and the optimization of resources [4]. However, hydroponics also introduces challenges, particularly related to high energy demand and economic viability, with trade-offs depending on local conditions, the crop, and the target market [3].

Although hydroponics is widely applied to conventional crops such as lettuce and tomatoes, other crops have not been introduced for commercial-scale production yet. Current research largely focuses on control systems, robotics, and nutrient management, and also on the greenhouse in combination with sustainability topics. Formal design methodologies for hydroponic systems are lacking in both academic and industrial contexts. This gap becomes more critical for specialty crops, which often have unique cultivation requirements and limited prior agronomic data. One such crop is Russian dandelion (Taraxacum kok-saghyz), a promising alternative source of natural rubber due to the quality of latex in its roots. Unlike above-ground food crops, Russian dandelion requires cultivation systems tailored to root harvesting, which conventional hydroponics does not address. The efforts to create a new source of rubber must be guided. Without a structured design methodology, efforts to adapt hydroponic systems to such crops face inefficiencies, economic risks, and slow innovation.

The aim of this study is to develop a systematic methodology for the conceptual design of large-scale hydroponic systems tailored to specialty crops within CEA environments in a greenhouse. The objectives are to define the structure for the biological, mechanical, and economic aspects of the hydroponic system design. In addition, the objective is to ensure applicability to both academic and industrial contexts. Alongside this, the aim is to validate the proposed methodology with the Russian dandelion, identify research gaps related to cultivation, and conceptually design the system.

The study addresses the main research questions: *"How can a conceptual design methodology be developed for hydroponic system design and validated through a case study on Russian dandelions?"*

Four sub-questions have been defined to guide the research:

SQ1 Which existing design methodologies in mechanical engineering are relevant to adapt for the development of hydroponic systems?
SQ2 What functional requirements, constraints, design parameters, process variables, and Key Performance Indicators (KPIs) define and guide the conceptual design of hydroponic systems?
SQ3 What structure and core components define a design methodology tailored to hydroponic systems?
SQ4 Case study: How does the proposed design methodology perform when applied to the system design for the

Russian dandelion?

This study adopts a Design Science Research (DSR) approach to develop a conceptual hydroponic system design. DSR emphasizes creating solutions for practical problems while iteratively evaluating their effectiveness [5]. The methodology was adapted to incorporate principles from axiomatic design and systems engineering, supporting structured decision-making and trade-off analysis. The research follows an iterative design-based approach, combining literature review, methodological adaptation, and industrial insights. First, principles from engineering design methodologies are reviewed and adapted for hydroponic applications. Next, the functional requirements, system boundaries, and KPIs are identified for hydroponic systems. From these findings, the proposed methodology is created. To validate the methodology, a case study is conducted, focusing on every phase of the methodology. Experimental trials in a climate chamber provide proof-of-concept data, informing system-level design considerations, showing the iterative steps to take. The methodology is then applied to generate conceptual hydroponic system designs and an economic evaluation of cultivation strategies.

The scope is limited to macro-level conceptual design of hydroponic systems in greenhouse environments. Greenhouse architecture, detailed machine design, and advanced control systems are excluded. The focus is on specialty crops feasible for hydroponic cultivation, excluding trees, cereals, and heavy fruiting plants. The Russian dandelion case study serves as proof of concept rather than a fully optimized design.

The paper first reviews relevant literature on hydroponics and engineering design methodologies. The proposed methodology is then developed and presented, followed by its validation in the Russian dandelion case study. Results and implications are discussed before concluding with contributions and future directions.

II. LITERATURE SYNTHESIS

A. Hydroponics

Hydroponics is the soilless cultivation of plants in nutrient solutions, with roots supported by inert media or directly suspended in water [4] [6]. Hydroponic systems can be classified into different types. For large-scale cultivation, the feasible strategies are:

- Nutrient Film Technique (NFT): a thin layer of nutrient solution circulates over sloped channels and is widely used for leafy greens due to its efficiency and low water consumption [7] [8] [4].
- Deep Water Culture (DWC): plant roots hang directly in aerated nutrient solutions, offering simplicity but requiring a large basin of water and additional oxygenation [7] [9].
- Aeroponics: a nutrient mist sprayed to exposed roots. Quickest shoot-root method, but also technically complex and expensive [9] [7].
- Drip: a nutrient film is dripped onto the substrate with the crops [9] [7].
- Ebb and Flow (Ebb and Flood) (EF): the root zone is periodically flooded with nutrient solution and then drained, allowing for aeration between cycles. [9] [7].

System design is influenced by several biological and technical factors. Vertical farming systems optimize the space, but are not yet feasible due to the lighting requirements of the crops, strongly increasing the energy consumption and increasing the costs [10]. Other design influences are maintaining the root-zone conditions of the crop [6] [4]. This includes the nutrient solution in combination with the Potential of Hydrogen (pH) and Electrical Conductivity (EC). Growth media acts as root supports and can influence water and nutrient retention. The root zone management also includes water and oxygen control. Controlled-environment parameters such as temperature, humidity, CO_2, and light spectrum directly affect growth rates and yield [6].

Commercial hydroponic production has focused on crops with short growth cycles and high value-to-weight ratios, such as lettuce, basil, tomatoes, cucumbers, and strawberries [11] [6]. These crops are well-suited to hydroponic conditions due to established cultivation protocols and efficient harvesting methods. The quality of the product strongly depends on the crop and target market.

B. Design methodologies

Design methodologies provide structured frameworks for developing complex engineering systems. They combine tools, processes, and decision points to ensure systematic exploration of design alternatives, alignment with functional requirements, and transparent evaluation of trade-offs. While widely applied in mechanical engineering, their application to agricultural systems and hydroponics remains limited. The hydroponic system can be seen as a product or process, and even a factory-type system. The following methodologies and approaches are considered:

- Pahl & Beitz: The systematic approach of Pahl and Beitz structures design into phases: clarification of tasks, conceptual design, embodiment design, and detail design. Its strengths lie in structured functional decomposition, iteration, and the integration of evaluation tools at decision points [12] [13] [14].
- Roozenburg & Eekels: This methodology emphasizes the conceptual stage, treating design as an iterative and creative process rather than a strictly linear sequence [15].
- Design For Manufacturing and Assembly (DFMA): DFMA prioritizes simplicity, cost efficiency, and ease of production. While developed for industrial products, DFMA principles are relevant to hydroponics, especially for designing modular systems that can be scaled and maintained at low cost [16] [17].
- Axiomatic design: Axiomatic Design formalizes the relationship between functional requirements and design parameters, emphasizing independence and robustness. Its mathematical structure is valuable when dealing with complex systems where multiple constraints interact [18]

[12] [19]. This is applicable to the hydroponic system in combination with the greenhouse.

- Theory of Inventive Problem Solving (TRIZ): TRIZ is based on patterns of innovation and systematic resolution of contradictions [12] [20] [14]. For hydroponic system development, TRIZ can support the options when conventional hydroponics cannot meet the design requirements.

Each methodology offers distinct strengths: Pahl and Beitz provide structure, Roozenburg and Eekels encourage creativity and trial-and-error, DFMA targets manufacturability, Axiomatic Design addresses complexity, and TRIZ supports innovation. However, all these design methodologies lack consideration of biological uncertainty and structured decision-making tools. The methods form a base but need to be adapted in order to fit the hydroponic system design.

C. *Research Gap*

Hydroponics research provides extensive knowledge of cultivation strategies, cultivation systems, typologies, and technical components. Current research also focuses on sustainability, automation, and the control system. However, research lacks a structured framework for system-level design, particularly for non-traditional crops. In parallel, engineering design methodologies offer powerful tools for structured problem-solving, but they have not yet been applied to hydroponic systems.

III. METHODOLOGY DEVELOPMENT

A. *Comparison methodologies*

The methodologies are evaluated on six design criteria that fit the hydroponic system design. This comparison is illustrated in Table I. The criteria are at the system level and include the process, the methodology design, and its effectiveness.

- Flexibility: Ability to handle variations in crop physiology, system scale, and other demands. The methodology needs to support different types of setups.
- Decision-support: Provides structured guidance for trade-offs and design decisions, including crop-specific requirements, mechanical constraints, and cost considerations.
- Design from start: Supports the creation of entirely new systems for specialty crops, defining functional requirements and design parameters without relying on pre-existing designs if needed.
- Process from reference: Facilitates iterative improvement or adaptation of existing systems and best practices to increase efficiency and reduce development risks. The base hydroponic system does not need to be redesigned for every crop
- Implementation speed: Measures how quickly the methodology can be applied in practice, considering both learning curve and execution time. Implementation speed may vary depending on crop complexity or specialization.
- Focus on process efficiency: Optimizes the overall design workflow, minimizing errors, redundancy, and complexity, while ensuring effective resource use.

TABLE I: Comparative Evaluation of Design Methodologies

Criterion	**P&B**	**R&E**	**DFMA**	**AD**	**TRIZ**
Flexibility	1	2	-1	1	2
Decision-support	2	1	1	2	1
Design from start	2	2	-1	1	1
Adaption of reference processes	1	1	2	2	2
Implementation speed	0	1	1	-1	0
Process efficiency	2	0	2	1	1
Total	**8**	**7**	**4**	**6**	**7**

TABLE II: Influence vs Interest of stakeholders

Stakeholder	Interest	Influence
Investors, funders and clients	High	High
Cultivators	High	Medium
Government	Medium	High
System development	High	High
Research institutions	High	Low
Customers	Medium	Low
Suppliers	Low	Low
Utility providers	Low	Low
Local communities	Medium	Medium

B. *Requirements system*

The requirements of the system are analyzed through multiple angles. Through a functional decomposition of the cultivation process (Fig. 2, Fig. 1) and a stakeholder analysis (Table II), a set of clustered functional and non-functional requirements is derived, prioritized using the MoSCoW method. The four Must functional requirements are:

- F1: The system must support all essential crop phases: seeding (or transplanting), germination, transfer, growing, and harvesting. The system must also allow for cleaning of equipment and system maintenance.
- F2: The system must maintain crop-specific root-zone parameters (pH, EC, Dissolved Oxygen, temperature) with continuous, non-stagnant nutrient circulation. Adjustable environmental controls (light spectrum/hours, temperature, humidity, CO_2, airflow) must accommodate varying life stages and external conditions [21]
- F3: The system must ensure operational resilience through: backup power for critical systems; sensors and fail-safes for key failure points; continuous monitoring with data logging and alarms; and a central interface with manual override capability [21], [22], [3].
- F4: The system must comply with machine safety and regulations. The regulations depend on the location of the greenhouse, and the food-related regulations depend on the crops.

The general KPIs of a hydroponic system are:

- Yield: Crop productivity per area or crop.
- Energy usage: Light interception efficiency and water usage
- Return on Investment (ROI) period (years): Optional economic metric

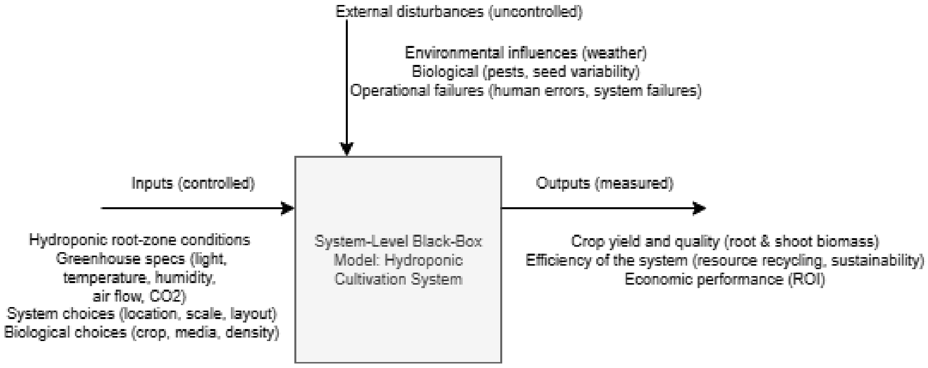

Fig. 1: System-Level Black-Box Model: Hydroponic Cultivation System

C. Proposed methodology

The proposed methodology is mainly based on Pahl & Beitz, Roozenburg & Eekels, and TRIZ, as these showed the most potential in the comparison. The structure is illustrated in Fig. 3. The methodology is structured into two main design phases: Conceptual Design and Provisional Design, separated by a dedicated Testing phase. The novelty implemented is the Testing phase between the two design phases. This ensures information, instead of only validation of the design. The methodology addresses limitations in iteration steps, particularly in combination with crop testing. Although it looks parallel, the different fields are dependent on each other. The iterative structure ensures that biological responses, operational constraints, and economic feasibility inform the design before moving to final implementation. Included decision points allow the process to continue, pause, or pivot depending on trade-offs between KPIs.

Task Definition

The Task phase establishes the project scope, objectives, and system boundaries. It transforms a broad idea into a concrete project description, identifying the target crop, main objectives, and system context. For specialty crops, this phase also evaluates whether hydroponic cultivation is preferable to soil-based methods, incorporating ethical, environmental, and socio-economic factors. Stakeholders, users, and decision-makers are mapped, and preliminary crop requirements and uncertainties are identified. This initial analysis informs high-level business scenarios and provides the foundation for subsequent design phases. Key tools include literature review, PESTLE, and SWOT analysis, and expert interviews.

Analysis

In the Analysis phase, the project description is refined to capture biological, technical, and economic conditions affecting the hydroponic system. Biological analysis focuses on crop phenology, root-zone requirements, and responses to environmental variables such as nutrient solution composition, light, and temperature. In this phase, the quality of the produce should also be determined. Technical analysis evaluates the availability of utilities, waste handling, automation needs, and structural constraints. Economic and social considerations include market demand, labor availability, and financial feasibility. The outcome is a structured set of constraints and key performance indicators that guide conceptual design. It may also structure a set of research gaps. Methods employed include agricultural data, benchmarking against comparable systems, and function-structure analysis.

Conceptual Design

The Conceptual Design phase generates and evaluates system-level solutions. Multiple configurations of hydroponic subsystems are explored. Baseline systems are included for comparison, and interactions between subsystems are identified. Assumptions that cannot be analytically validated are flagged for the subsequent Testing phase. Deliverables include a set of system-level concepts, morphological charts, and trade-off matrices comparing performance against defined KPIs. The decision should be made whether the Testing phase should be started or if the project is not feasible.

Testing

The Testing phase provides missing agronomical or technical data. Additionally, it gives information about the assumptions identified in the Conceptual Design phase. Biological trials, operational experiments, and engineering simulations quantify system performance and identify potential failure modes. Results iteratively feed back into the Task, Analysis, and Conceptual Design phases, refining requirements and clarifying targets. Deliverables include test reports documenting KPIs and validated models providing evidence to support concept selection.

Provisional Design

The Provisional Design phase transforms the validated concept into a fully defined hydroponic system. It integrates biological, technical, and economic considerations to ensure manufacturability, operational efficiency, and regulatory compliance. Biological elements include detailed crop management protocols, cultivation strategies, and pest mitigation. Technical elements cover system layout, CAD models, control systems, machinery specifications, and hydraulic and electrical designs. Economic aspects address cost breakdowns, financial feasibility, and expected performance. One specific deliverable is the proposal of a Design of Experiment, based on the identified research gaps. This will provide a guideline for future work.

IV. CASE STUDY

Task Defintion

The Russian dandelion is selected as a crop to test as the case study. Large-scale cultivation of the crop is being researched as a potential natural rubber source. The supply chain for Natural Rubber (NR) is under pressure due to multiple threats. The Hevea brasiliensis tree, mainly located in Asia, produces the worldwide demand for latex. One major concern is South American Leaf Blight, a fatal disease that could potentially wipe out the entire Asian rubber production. Additionally, climate change is reducing the availability of suitable land for rubber cultivation [23] [24]. In addition to these biological and ecological threats, the demand for NR is rising at an annual rate of 5.2% [23]. Synthetic Rubber (SR) cannot be used as the only alternative for rubber. Thus, new cultivation options are being researched. Field cultivation addressed challenges like excessive labor, light competition and competition with weeds [25] [26] [27] [28]. These can be mitigated by growing the crops in hydroponics [29] [30] [31] [32] [33].

The latex is located in the roots of the crop. Latex is produced as a secondary metabolic product. While the dandelion naturally forms a taproot, hydroponic conditions induce a fibrous root system. The harvest is thus unconventional for hydroponics, but leads to the research question of whether multiple harvests are possible.

Analysis

The biosynthesis of the rubber remains unclear, but it is estimated to be 10% of the Dry Root Weight (DRW). The primary product is NR for the biorefinery sector, with inulin and proteins considered as potential co-products [26].

Biological: Rubber yield remains uncorrelated with the cultivation strategy, so the focus will be on root biomass. Soil-grown Taraxacum Kok-Saghyz (Russian Dandelion) (TKS) develops taproots, whereas hydroponics induces fibrous root systems. Key uncertainties include how hydroponic conditions affect latex content, growth rates, and harvestability. Next to this, an uncertainty is the ability to harvest the roots multiple times, and whether this influences the rubber content and quality.

Technical: Hydroponic cultivation requires integration of root-zone management, nutrient solution circulation, and environmental control. Automation is necessary for seeding, monitoring, and harvesting to offset labor intensity. Major risks are system complexity, energy demand, and pathogen management in recirculating systems. Especially when doing multiple harvests.

Economic and social: The primary buyer is the biorefinery, which requires a consistent supply in terms of both quality and quantity. NR is priced at approximately €1.65/kg, with inulin and proteins representing additional revenue streams. Profitability depends on yield per area (g/m^2) and operational costs. ROI is a critical KPI, alongside system complexity and automation potential. In future work, yield consistency and post-harvest survival rates could be added.

Conceptual design

The previous phases identified the main bottlenecks in cultivation. A series of sub-functions focused on the challenges of cultivation was made into a morphological chart. From this, three concepts emerged as the most promising options in terms of feasibility and KPIs.

- Concept 1: Multi-NFT: This concept adapts a moving gutter NFT system, similar to lettuce production. Channels adjust spacing during crop growth to optimize light interception and space use. Crops move through fixed processing stations for seeding, transplanting and harvesting, enabling both single- and multi-harvest cycles. Harvesting relies on rollers and blades to expose and cut roots, with options for partial harvesting that enable regrowth. Although more complex, the system provides flexibility and supports sequential harvests.
- Concept 2: Single-NFT: This concept applies a simplified NFT setup designed for single-cycle cultivation. Plants grow in standard NFT channels until maturity, after which the entire biomass (roots, shoots, and substrate) is harvested. Roots form mats inside the channels, which are opened and rotated for crop removal. The main advantage is low engineering complexity and cost. However, feasibility depends on the downstream processing's ability to handle whole-plant biomass without prior separation.
- Concept 3: Multiple-DWC: This concept applies a DWC system where plants grow on floating rafts above an aerated nutrient solution. Roots are fully submerged, promoting rapid biomass formation without the need for substrate. The layout is static and horizontal, with limited flexibility for adjusting plant spacing. Harvesting is designed for multiple cycles: roots are periodically trimmed with blades while shoots remain intact, allowing regrowth. At the end of the life cycle, the full plant is removed from the raft. The main advantage is high root productivity from continuous submersion. However, water contamination and root disease are significant risks, requiring careful system management.

Through a comparison in Table III, Concept 1 was chosen to move forward with. The field-cultivation was also considered in the comparison.

TABLE III: Comparison of Concepts and Field Cultivation

	Concept 1	Concept 2	Concept 3	Field Cultivation
Yield	High	High	Low	Low
Energy usage	High	Medium	High	Low
Water usage	Low	Low	High	High
ROI	Medium	Medium	Low	Medium
System complexity	High	Medium	High	Low
Automation potential	High	Medium	High	Low

TABLE IV: Overview Tests

Test	Focus
1	Effect of repeated root trimming on plant health and regrowth
2	Determination of dry root weight
3	Observation of flowering behavior

Experiments

Small-scale tests were conducted in a climate chamber (Fig. 6). The experimental conditions are given in Table V, and the tests are summarized in Table IV. These experiments served as a proof of concept.

Fig. 6: Climate Chamber Crop Cultivation

Test 1: Root Trimming

Objective: To assess the effects of repeated root trimming (up to 75%) on plant health and regrowth.

Findings: Trimming induced strong stress responses, including stunted growth, leaf browning, and, in some cases, plant mortality. Contrary to the literature, roots did not regenerate to their original size within six weeks, and a second trimming was lethal in most cases. Root rot was common, although new roots occasionally re-emerged from the pot. These results suggest that multiple harvests are possible, but at reduced intensity and frequency, requiring additional measures to mitigate root disease.

Test 2: Dry Root Weight

Objective: To estimate the DRW ratio of hydroponically grown roots, a key parameter for rubber yield calculations.

TABLE V: Standard Environmental Conditions Maintained within the Climate Chamber

Parameter	Value
Chamber size	9 m^2
Hydroponic system	NFT
Photoperiod	07:00–19:00
Light source	Light Emitting Diode (LED), full spectrum
PPFD (μmol m^{-2} s^{-1})	700
Relative humidity (%)	70–85
Temperature (°C)	20–24
Airflow	Continuous (2 fans)
Irrigation (light period)	Every 2 hours
Irrigation (dark period)	Once
EC (mS/cm)	1.2–2
pH	5.5–6.6
CO_2 concentration (ppm)	600–700

TABLE VI: Wet and Dry Weights of Root Samples

Sample	Wet Weight (g)	Dry Weight (g)	Dry/Fresh (%)
1	1.807	0.266	14.72
2	10.946	0.494	4.51
3	9.460	0.655	6.92
4	5.569	0.427	7.67
5	0.957	0.073	7.63
6	1.343	0.201	14.97

Findings: Six samples produced an average dry matter content of 9.4% of fresh root weight (Table VI). Variation correlated with root thickness, suggesting morphology influences yield. Air-drying, rather than oven-drying, may have slightly overestimated the values; however, these results provide an initial benchmark for design calculations.

Test 3: Flowering

Objective: To document flowering behavior in hydroponic Russian dandelions.

Findings: Three out of eight plants flowered within 1–3 months after germination, producing up to 30 flowers simultaneously. Seeds developed but remained attached to the flower head, reducing risk. However, wilted flowers became moldy, requiring manual removal. The unpredictability of flowering poses risks of energy diversion from root development, but may also signal secondary metabolism pathways relevant for rubber synthesis. It remains unclear how flowering correlates with rubber synthesis, as no rubber was measured from the experiments.

Additional Observations

Beyond the three planned tests, several broader findings emerged:

- **Algal contamination:** Algae colonized growth media rapidly, highlighting the need for light-shielding measures. It also highlights the risk of growing a crop for a long period of time in the system.
- **Material degradation:** Cardboard pots deteriorated, shedding debris into the system. This indicates the need for different cultivation containers if multiple harvests are wanted.

TABLE VII: Key Variables used in Yield and Economic Modeling

Parameter	Value(s)	Unit / Notes
Growth rate (G)	2–4	g/day (slow / fast)
Cycle duration (D)	30–90	days
Harvest cycles (R)	1–6	cycles
Initial weight (S_0)	10	g
Planting density	40–160	plants/m^2
Rubber price (P_{rubber})	1.65–1.80	€/kg
Lifetime (T)	25	years
Additional area (m_{area})	5%	percentage
Input per day	5000	plants/day
GH: Option 1	CAPEX 660, OPEX 100, growth rate = 0.8	–
GH: Option 2	CAPEX 1200, OPEX 150, growth rate = 1	–
GH: Option 3	CAPEX 1700, OPEX 200, growth rate = 1.3	–
Yield (Y)	-	g

- **Distinct root architecture:** Roots grew compact and remained horizontal after removing them from the system. This has implications for harvesting design.
- **Potential vegetative propagation:** New rosettes emerged from trimmed plants, suggesting possible regrowth from root fragments. These crops then ripped through the pots.

Iterations

Exploratory experiments provided practical insights that would not have emerged from the literature review alone. This highlights the need for practical experiments after the conceptual design stage. The experiments addressed some research questions while opening new ones. Priorities include finding the correct root trimming amount, increasing the amount of rubber content, and optimizing cultivation strategies. Additional gaps were identified, which should be addressed in a subsequent analysis stage. From a design perspective, lessons include the need for flowering management, cultivation materials, and protective measures against mold. These findings informed the concept evaluation and led to refinements. Incorporating these insights into the provisional design resulted in a more refined conceptual design.

Provisional Design

The conceptual design was refined by removing the biodegradable pots. The design now also includes additional flower trimming. The last addition is to create a different nutrient solution plus buffer to water the plants separately after root cutting, to mitigate the risk of root rot and filter clogging. If multiple harvests are done, the rosette size might shrink, allowing for a higher plant density.

Calculation

Root growth was modeled linearly based on exploratory tests and literature values. Rubber yield was assumed to be 10% of dry root weight, and economic parameters were based on market values and scaled according to three greenhouse types. The key variables are summarized in Table VII. To highlight the sensitivity in the calculation, the values contained a range.

The model links growth dynamics to economic outputs through the following key equations:

$$Y_n = S_0 + (S \cdot D_n \cdot R_n) \tag{1}$$

The total yield of a plant in stage n is modeled as the initial weight plus the product of the daily growth rate, growth duration, and the number of harvests.

$$\text{Actual Daily Yield per Plant} = \frac{Y_n \cdot \text{DRW} \cdot \text{Rubber}}{1000 \cdot D_{\text{total}}} \tag{2}$$

The yield is multiplied by the DRW and rubber fraction to get the actual rubber yield. Conversion to kilograms. The unit is $kg/day/plant$. Eventually, this is multiplied by the harvest density, which creates a yield per square meter.

$$\text{Revenue per m}^2 = \text{Annual Yield per m}^2 \times P_{\text{rubber}} \tag{3}$$

This formula calculates the revenue. This can be combined with the CAPEX and OPEX, which gives the profit per square meter:

$$\begin{aligned}\text{Profit per m}^2 = {} & \text{Revenue per m}^2 - \text{Variable Cost per m}^2 \\ & - \text{Fixed Opex Cost per m}^2 - \text{Capex Cost per m}^2\end{aligned} \tag{4}$$

$$\text{ROI} = \frac{\text{Annual Profit}}{\text{Total Capex Investment}} \times 100\% \tag{5}$$

Finally, the Return on Investment can be calculated.

V. RESULTS AND DISCUSSION

Table VIII shows the numerical outputs of two cases, the low cost with the lowest level of complexity is compared with the high cost with the highest level of complexity and cycles.

Results shown in Fig. 7 show that the model is not economically feasible. The analysis demonstrates that higher yield, driven by larger areas and higher costs, does not lead to better financial outcomes under the given cost structure and market prices.

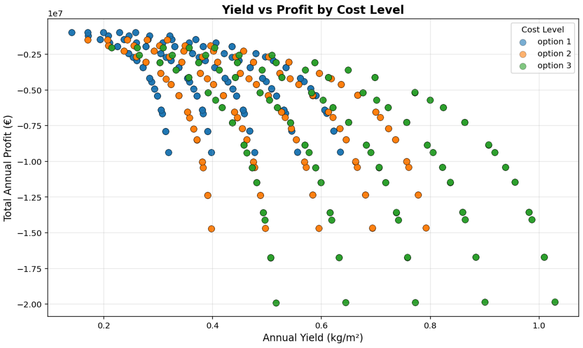

Fig. 7: Yield vs Profit by Cost Level

The conceptual design will change according to the following research gaps:

- If the stunted growth of the multiple harvests is not mitigated by cultivation practices, the tradeoff will likely be that a single harvest is the most efficient.

TABLE VIII: Comparison of Model Outcomes for Low- and High-performance Scenarios

Parameter	Case 1: Low-Performance	Case 2: High-Performance
Rubber price (€/kg)	1.65	1.80
Growth rate (g/day)	2.0	4.0
Cycle days	30.0	90.0
Number of harvests	2	6
Total cycle duration (days)	120.0	600.0
Total area (m^2)	11,484	74,484
Annual yield (kg/m^2)	0.1290	0.6857
Total revenue (€)	1,596	83,314
Total costs (€)	1,451,770	19,966,441
Annual profit (€)	-1,450,126	-19,883,127
ROI (%)	-19.1	-15.7
Payback period (years)	-5.2	-6.4

- If fibrous roots do not contain a similar amount of rubber, the focus should be on taproots. This will likely happen in a different substrate and hydroponic system. This will only allow a single harvest option.
- If rubber can be increased by stress-inducing measures, the cultivation method should be adapted. This can be, for example, lighting changes, temperature changes, or different nutrients.

The most critical research gaps to solve in order to improve the accuracy of the economic evaluations are:

- The growth and S-curve of the crop, in combination with the effects on the S-curve after harvesting.
- The rubber content and improving methods.
- Crop losses and mitigation strategies.

The case study did highlight the stages of the proposed methodology. The methodology is inclusive of multiple disciplines and shows the interaction between the steps. Further improvements on the methodology can be made by validating it with other specialty crops. The methodology has not yet been evaluated through external expert validation or independent application by other practitioners. This would provide necessary feedback on the methodology. This feedback could then be used to refine the methodology.

The case study was constrained by limited data availability. Many parameters were derived from field-grown studies, related crops, or exploratory experiments, rather than from controlled hydroponic trials with Russian dandelion. Biological processes, particularly rubber biosynthesis, remain insufficiently understood and represent a major knowledge gap. Experimental challenges remain. Thus, the results provide directional insights for the case study but cannot yet be generalized to broader agricultural contexts.

Future work should incorporate the elements that still need research and a sensitivity analysis to capture biological and economic uncertainty more accurately.

VI. CONCLUSION

This thesis developed a methodology for the conceptual design of hydroponic systems, integrating biological, technical, and economic evaluations. Its application to Russian dandelion demonstrated the framework's value in structuring decision-making under uncertainty and identifying key trade-offs, research gaps, and iterative cycles. Despite remaining uncertainties, the methodology provides a solid foundation for future hydroponic system development.

Sub-Question 1

Relevant design methodologies from mechanical engineering

Hydroponic systems combine technical installations with crop-specific processes, requiring flexible and iterative design approaches. Pahl & Beitz systematic design and TRIZ were identified as the most suitable bases, but adaptations were needed to address incomplete crop knowledge and the absence of experimentation steps.

Sub-Question 2

Functional requirements and KPIs

Requirements vary by crop and production goals and must be updated as knowledge improves. Key KPIs include biological performance (yield, Light Area Index (LAI)) and economic metrics (ROI), which guide evaluation while highlighting gaps and opportunities in hydroponic system design.

Sub-Question 3

Structure and core components of the methodology

The methodology extends Pahl & Beitz with feedback loops and testing phases to manage crop-specific uncertainty. Biological, mechanical, and economic evaluations are integrated throughout, with defined objectives, deliverables, and tools for each stage.

Sub-Question 4

Case study on Russian dandelion

Application revealed trade-offs between multiple-harvest NFT systems and single-harvest substrate systems, and highlighted gaps in rubber content, quality, and optimal cultivation strategies. While the methodology structured analysis and experimentation, it did not produce a finalized system design, validating its usefulness rather than the crop system itself. This can be done with future research.

Main Research Question

Developing and validating a hydroponic design methodology

The study shows that a structured methodology can support hydroponic system development under uncertainty, combining engineering principles with crop-specific evaluation. Contributions include extending design theory to controlled-environment agriculture and providing a practical guideline for developing specialty crops. Limitations include a lack of external validation and a restricted case study scope.

Future work

Future research should focus on refining the methodology and testing its applicability across multiple specialty crops. Structured expert reviews can improve the validation of the method. Introducing digital decision-support tools and interactive platforms to help with tradeoffs could improve robustness and interdisciplinary integration.

For Russian dandelion, research is needed to clarify factors affecting rubber synthesis, root morphology, and optimal harvest strategies. Experiments should test nutrient solutions, substrates, lighting, and growth cycles, including comparisons between single- and multiple-harvest strategies. The application of rubber-enhancing methods in a hydroponic system should be researched. Mechanized harvesting and processing feasibility must also be investigated. Finally, a Life Cycle Analysis and supply chain analysis versus *Hevea brasiliensis* would support sustainability evaluation.

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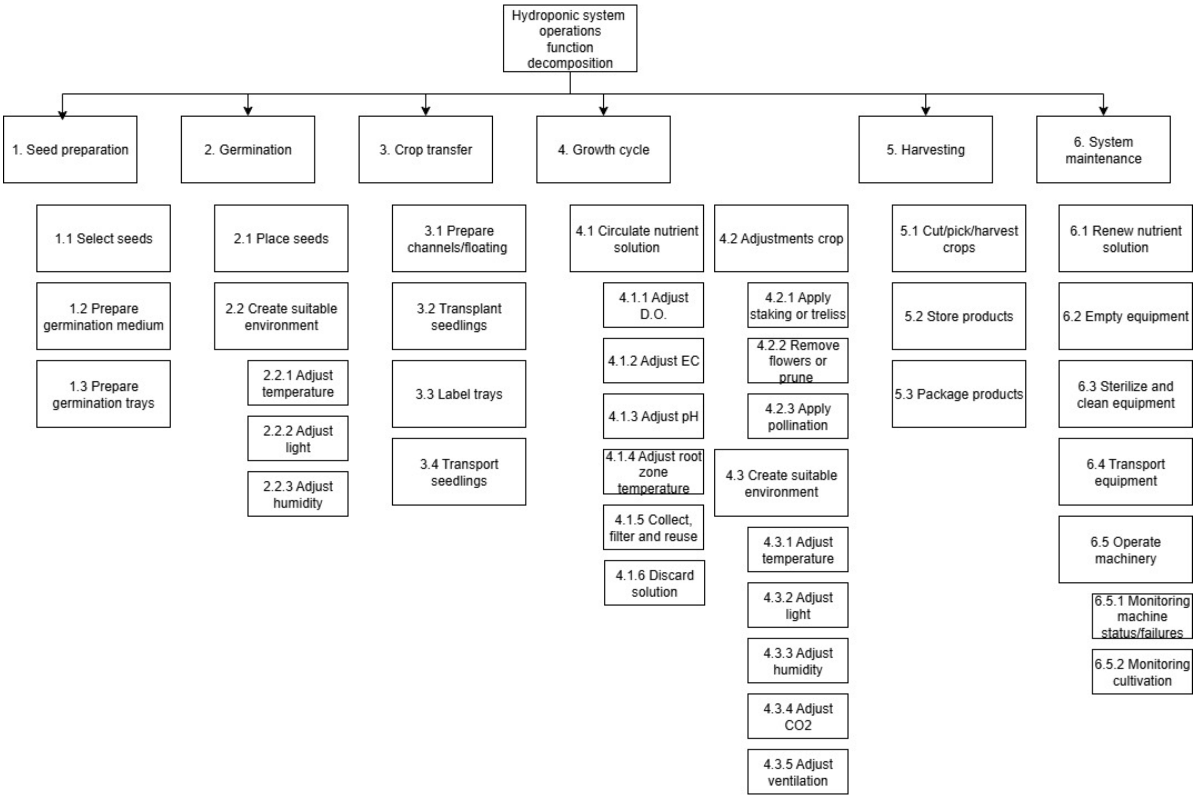


Fig. 2: Functional Decomposition of Hydroponic System Operations

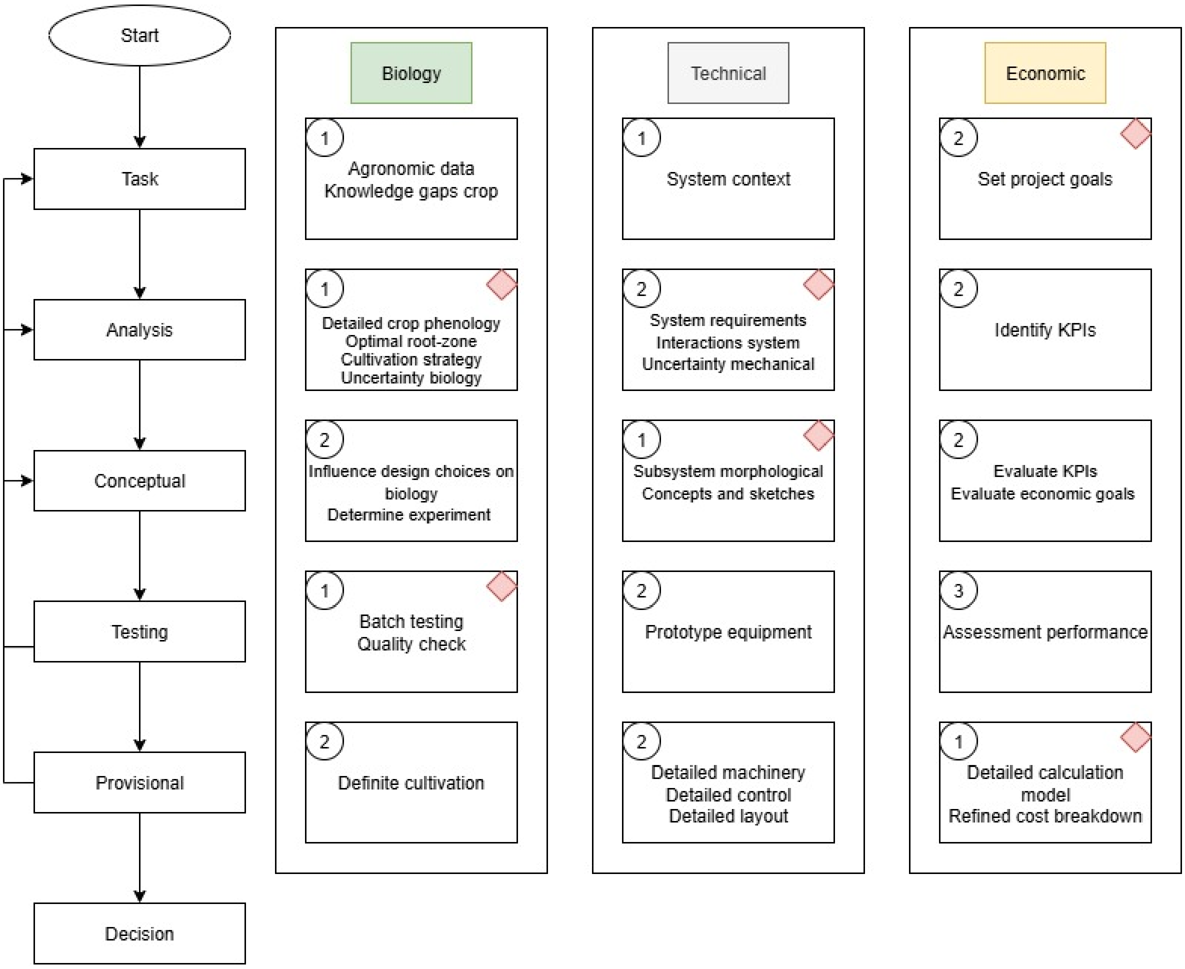


Fig. 3: Proposed Methodology

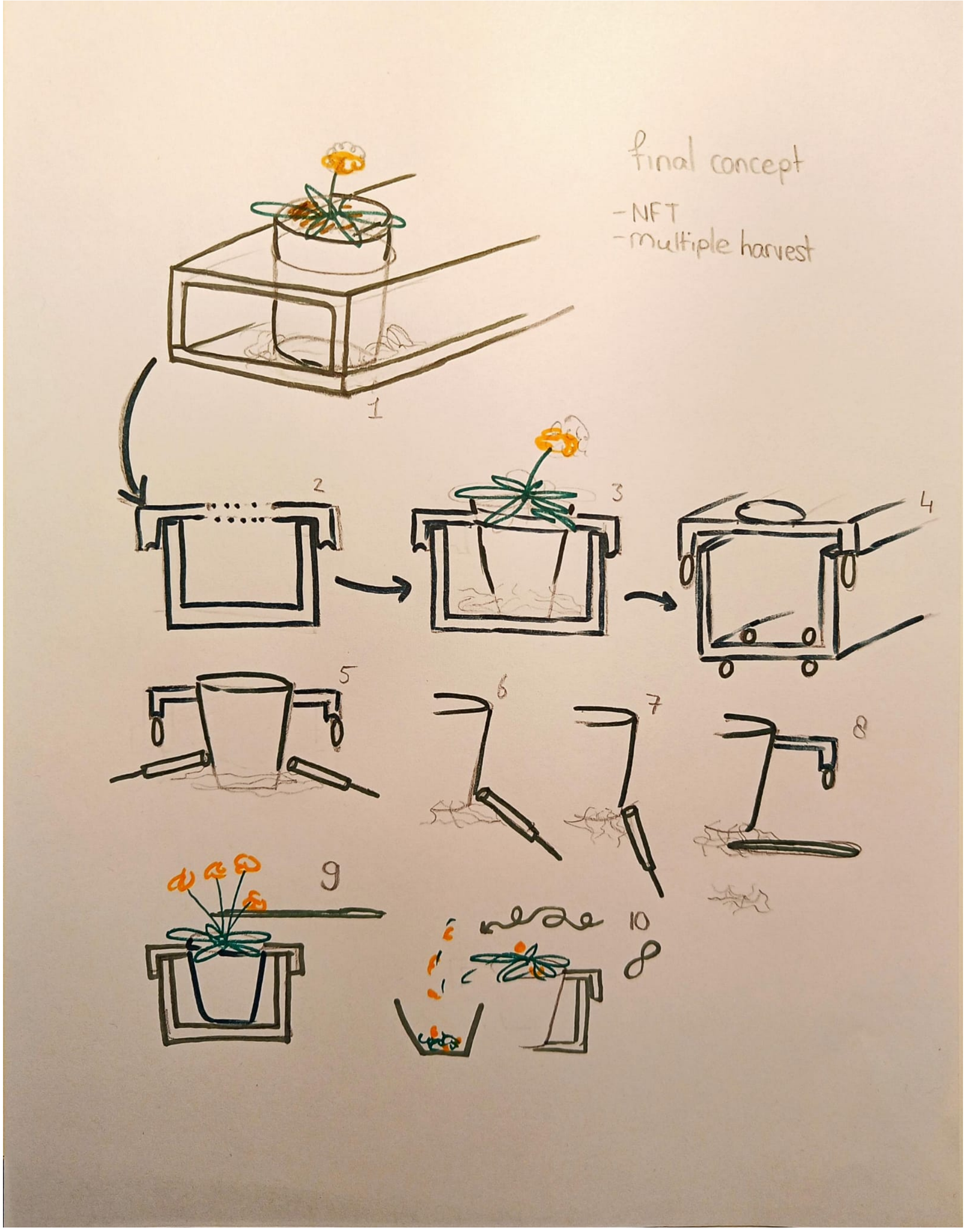
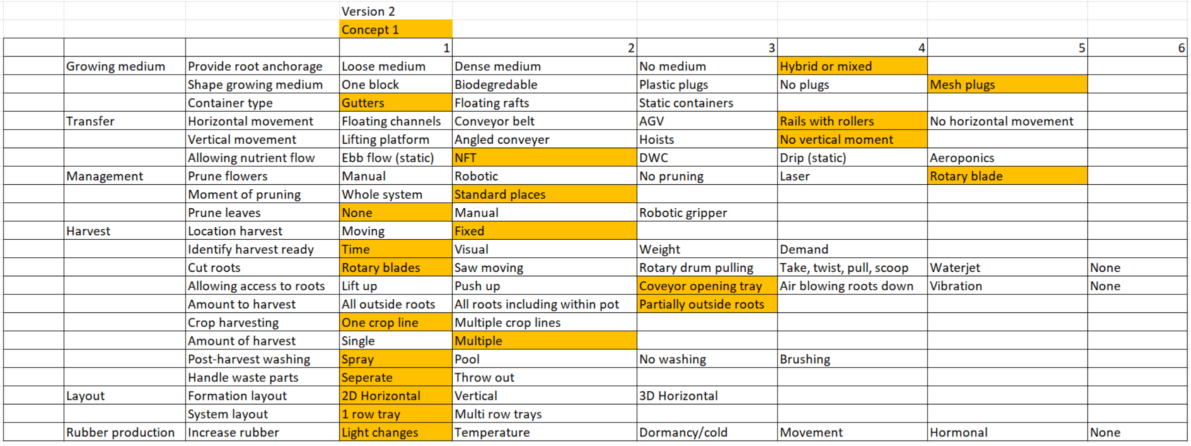


Fig. 4: Concept 1 Sketch



			Version 2					
			Concept 1					
			1	2	3	4	5	6
	Growing medium	Provide root anchorage	Loose medium	Dense medium	No medium	Hybrid or mixed		
		Shape growing medium	One block	Biodegredable	Plastic plugs	No plugs	Mesh plugs	
		Container type	Gutters	Floating rafts	Static containers			
	Transfer	Horizontal movement	Floating channels	Conveyor belt	AGV	Rails with rollers	No horizontal movement	
		Vertical movement	Lifting platform	Angled conveyer	Hoists	No vertical moment		
		Allowing nutrient flow	Ebb flow (static)	NFT	DWC	Drip (static)	Aeroponics	
	Management	Prune flowers	Manual	Robotic	No pruning	Laser	Rotary blade	
		Moment of pruning	Whole system	Standard places				
		Prune leaves	None	Manual	Robotic gripper			
	Harvest	Location harvest	Moving	Fixed				
		Identify harvest ready	Time	Visual	Weight	Demand		
		Cut roots	Rotary blades	Saw moving	Rotary drum pulling	Take, twist, pull, scoop	Waterjet	None
		Allowing access to roots	Lift up	Push up	Coveyor opening tray	Air blowing roots down	Vibration	None
		Amount to harvest	All outside roots	All roots including within pot	Partially outside roots			
		Crop harvesting	One crop line	Multiple crop lines				
		Amount of harvest	Single	Multiple				
		Post-harvest washing	Spray	Pool	No washing	Brushing		
		Handle waste parts	Seperate	Throw out				
	Layout	Formation layout	2D Horizontal	Vertical	3D Horizontal			
		System layout	1 row tray	Multi row trays				
	Rubber production	Increase rubber	Light changes	Temperature	Dormancy/cold	Movement	Hormonal	None

Fig. 5: Morphological Chart Concept 1

B

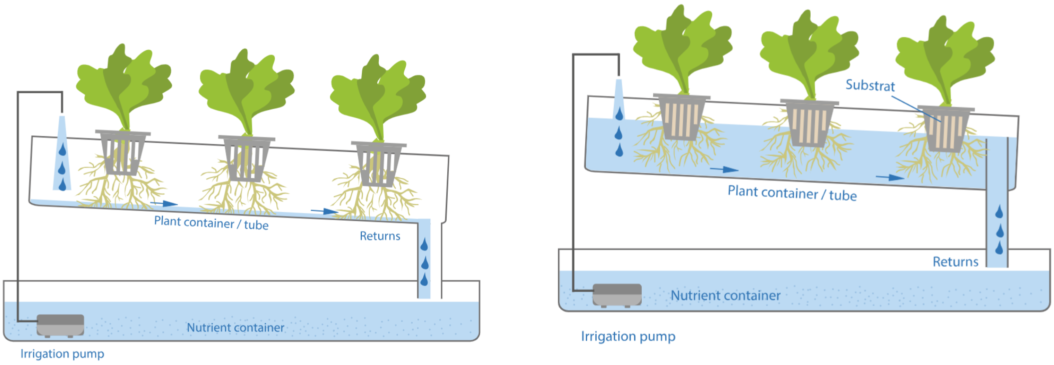
Hydroponic systems

Hydroponic System Typologies Illustrated

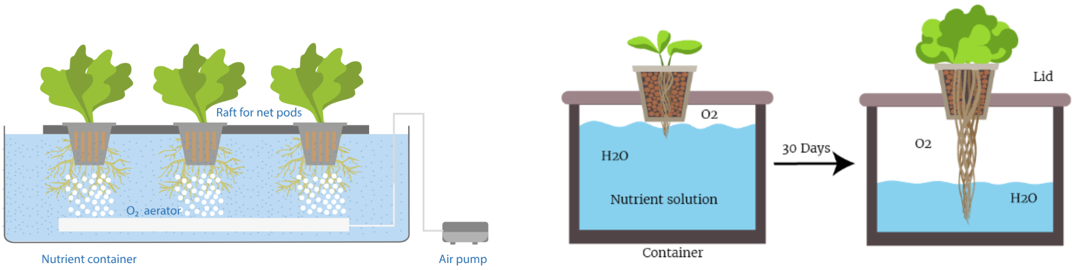
Visualization of hydroponic system typologies in Figure B.1, corresponding to the provided list in subsection 3.2.1.

List with picture and corresponding reference:

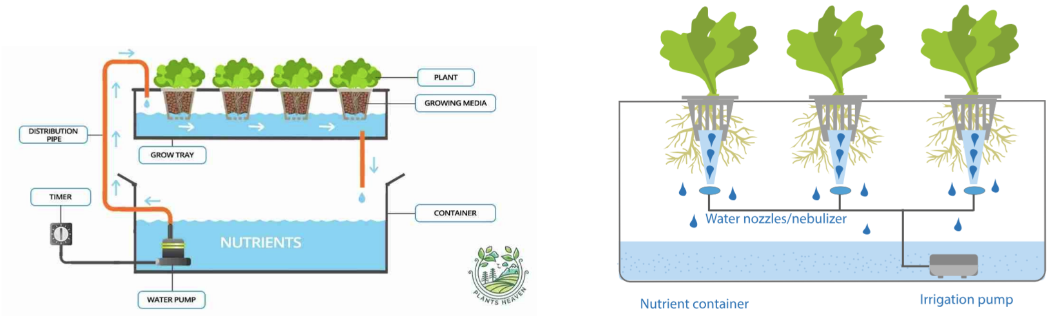
- Nutrient film technique (NFT): a (Staff, 2025)
- Deep flow technique (DFT): b (Staff, 2025)
- Deep water culture (DWC): c (Staff, 2025)
- Kratky Method: d (Staff, 2024)
- Ebb and Flow/Ebb and Flood (EF): e (Staff, 2023)
- Aeroponics: f (Staff, 2025)
- Aerohydroponics: g (Eldridge et al., 2020)
- Drip/Pass-Through Systems: h (Staff, 2025)
- Wick system: i (Staff, 2025)
- Aquaponics: j (Staff, 2025)



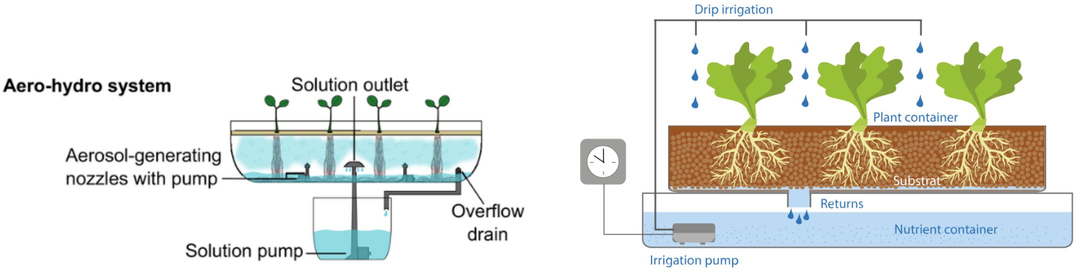
(a) NFT **(b)** DFT



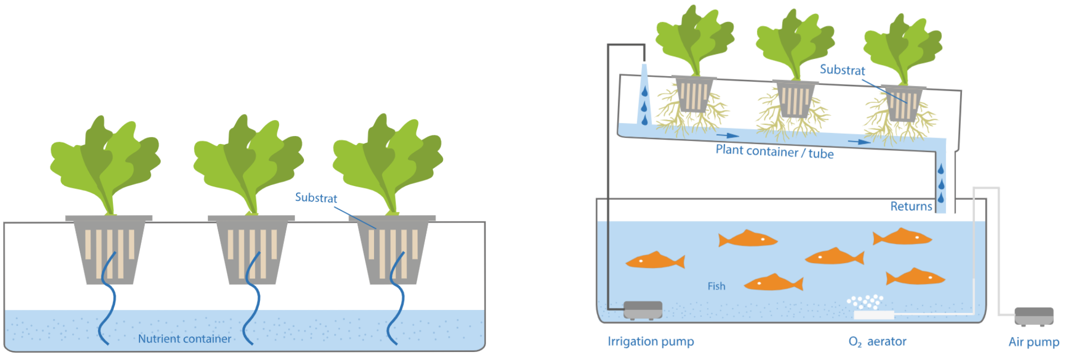
(c) DWC **(d)** Kratky



(e) EF **(f)** Aeroponics



(g) Aerohydroponics **(h)** Drip/pass



(i) Wick **(j)** Aquaponics

Figure B.1: Overview of Hydroponic Systems

C

Existing Methodologies Explained

Pahl & Beitz

The schematic overview of Pahl & Beitz is illustrated in both Figure C.1 and Figure C.2.

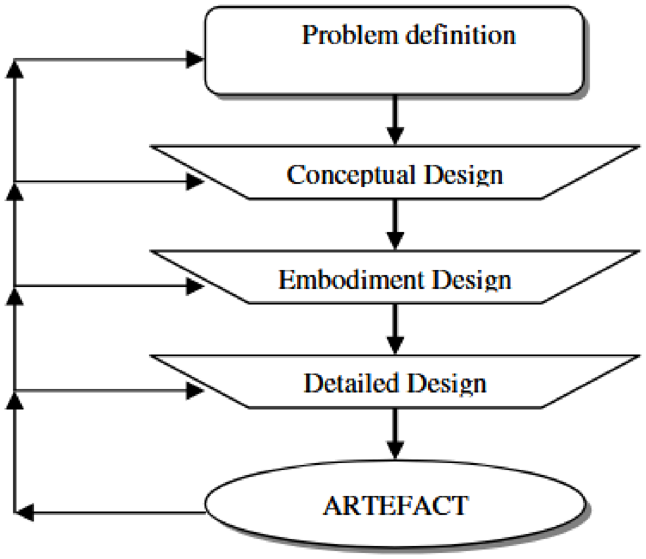


Figure C.1: Design phases of Pahl & Beitz from (Drăghici & Banciu, 2004)

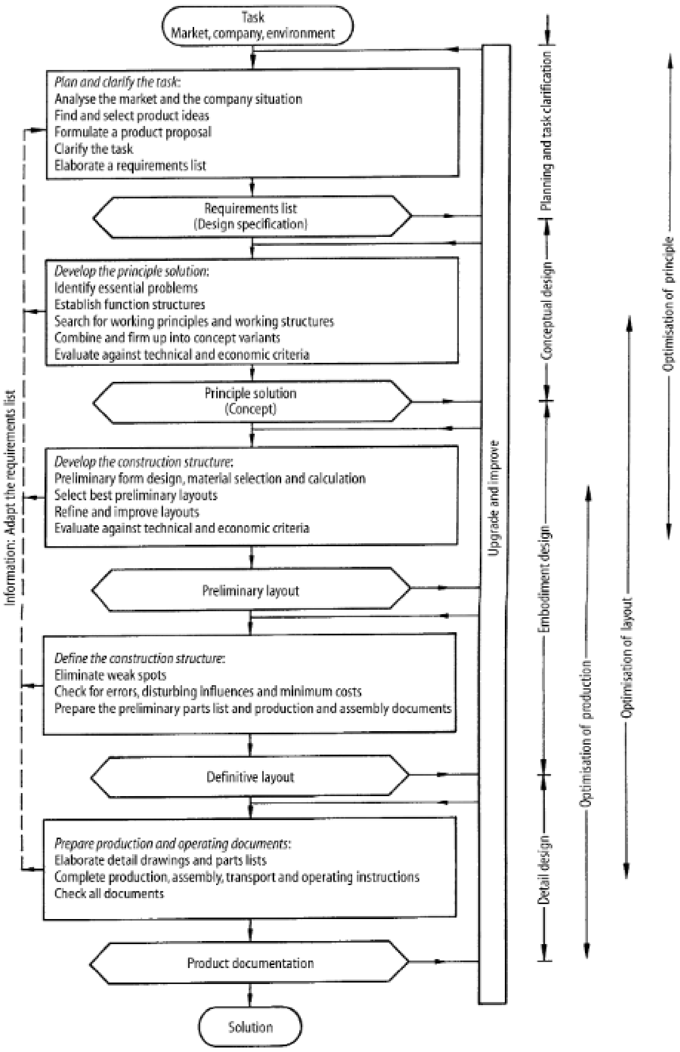


Figure C.2: Design Process (Pahl et al., 2007)

Roozenburg & Eekels

The schematic representation is illustrated in Figure C.3.

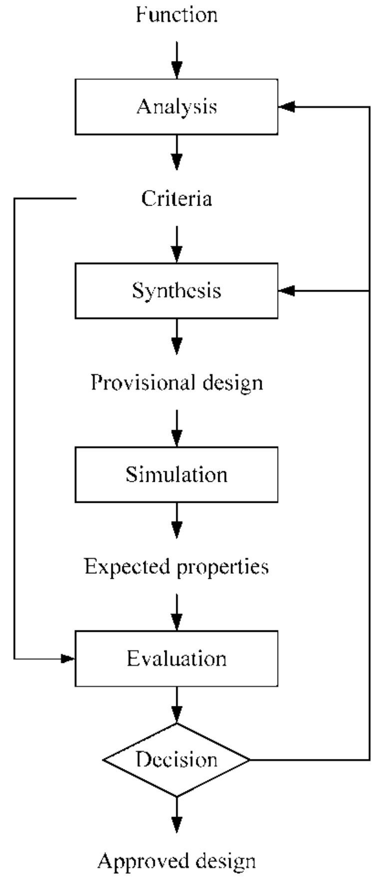


Figure C.3: Schematic representation of design cycle (Redelinghuys & Bahill, 2006)

DFMA

Figure C.4 illustrates the DFMA process.

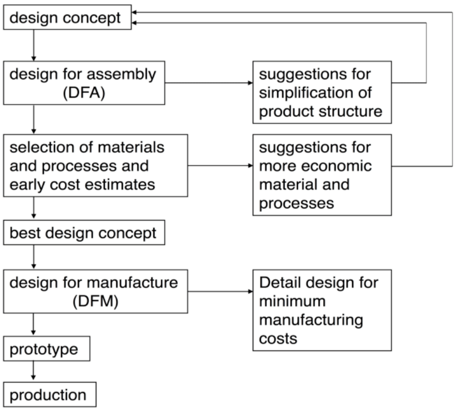
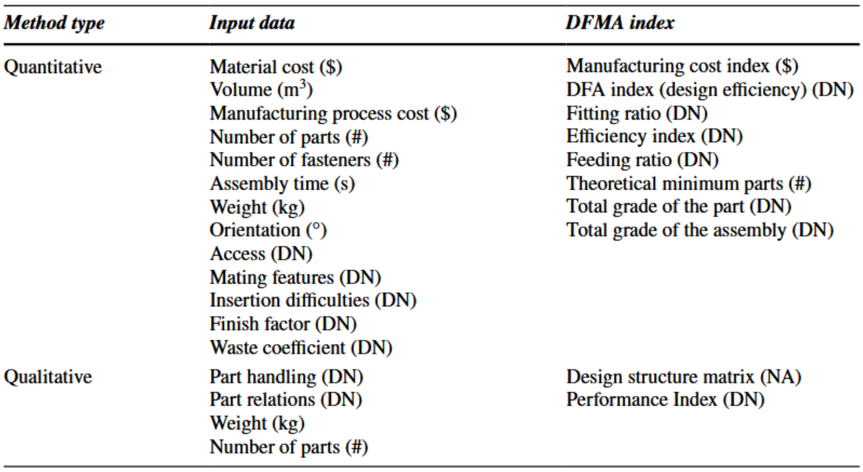


Figure C.4: Schematic overview of DFMA process (Madrid, n.d.)

Table Figure C.5 reports the main types of information required to perform DFMA analysis, in relation to quantitative and qualitative methods.



Method type	*Input data*	*DFMA index*
Quantitative	Material cost ($) Volume ($m^3$) Manufacturing process cost ($) Number of parts (#) Number of fasteners (#) Assembly time (s) Weight (kg) Orientation (°) Access (DN) Mating features (DN) Insertion difficulties (DN) Finish factor (DN) Waste coefficient (DN)	Manufacturing cost index ($) DFA index (design efficiency) (DN) Fitting ratio (DN) Efficiency index (DN) Feeding ratio (DN) Theoretical minimum parts (#) Total grade of the part (DN) Total grade of the assembly (DN)
Qualitative	Part handling (DN) Part relations (DN) Weight (kg) Number of parts (#)	Design structure matrix (NA) Performance Index (DN)

Figure C.5: Inputs and outputs of qualitative and quantitative methods of DMFA (Formentini et al., 2022)

(DN — dimensionless; [#] — quantity; NA — not available)
Compact list of principles of DFMA combined from Formentini et al. (2022) and Naiju (2021):

1. Simplify design
2. Reduce components
3. Simplify montage, and montage time
4. Reduce costs
5. Eliminate montage actions
6. Minimize connections
7. Standardize components
8. Standardize montage actions
9. Reduce orientation changes product
10. Reduce process steps
11. Optimize modularity
12. Include ergonomics
13. Select materials with geometry in mind
14. Simplify tolerances

Axiomatic design

The schematic overview of AD is illustrated in Figure C.6.

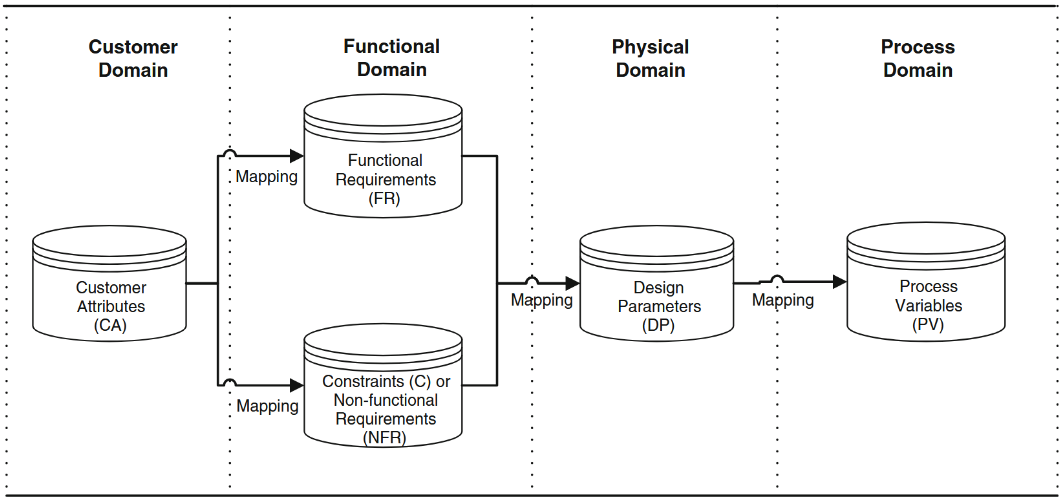


Figure C.6: Axiomatic Design structure (Adams, 2015)

TRIZ

The structure of TRIZ is illustrated in Figure C.7.

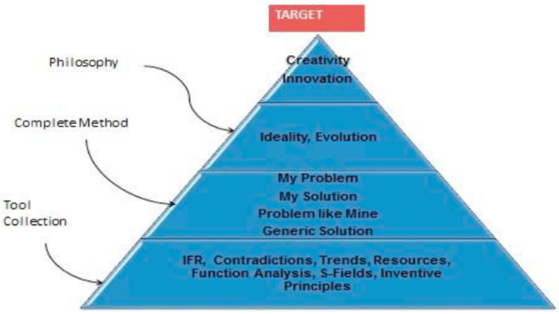


Figure C.7: TRIZ structure (Ekmekci & Nebati, 2019)

The following 40 principles of TRIZ, based on Ekmekci and Nebati (2019):

1. Segmentation
2. Extraction / Separation / Removal / Segregation
3. Local Quality
4. Asymmetry
5. Combining, Integration, Margin
6. Universality, Multi-functional
7. Nesting
8. Counter weight, Levitation, Anti-Weight
9. Preliminary anti-action, Prior counteraction
10. Prior action
11. Cushion in advance, compensate before
12. Equipotentiality, remove stress
13. Inversion, the other way around
14. Spheroidicity, Curvilinearity
15. Dynamicity, Optimization
16. Partial or excessive action

17. Another Dimension
18. Mechanical vibration/oscillation
19. Periodic action
20. Continuity of a useful action
21. Rushing through / Skipping
22. Convert harm into benefit, ”Blessing in disguise”, Make lemonade from lemon
23. Feedback
24. Mediator, intermediary
25. Self-service, self-organization
26. Copying
27. Cheap, disposable/short-living objects
28. Mechanics Substitution
29. Pneumatics or hydraulics / Liquids
30. Flexible membranes or thin film
31. Use of porous materials
32. Changing color or optical properties
33. Homogeneity
34. Rejection and regeneration, Discarding and recovering
35. Parameter changes
36. Phase transformation / transition
37. Thermal expansion
38. Use strong oxidizers, enriched atmospheres, accelerated oxidation
39. Inert environment or atmosphere
40. Composite materials

The tools of TRIZ, based on (Ekmekci & Nebati, 2019):

1. IFR
2. Contradictions
3. Trends
4. Resources
5. Function analysis
6. S-Fields
7. Inventive Principles
8. 40 principles

Rationale for Pugh Matrix Scores

Table Table C.1 provides detailed justification for the comparative scores assigned in the Pugh matrix (Table 4.1). Each score is supported by evidence from the primary literature, reflecting how well each methodology aligns with the six evaluation criteria defined in subsection 4.1.1. The evaluation focuses on structural, procedural, and contextual suitability for hydroponic system design.

Table C.1: Detailed Rationale for Pugh Matrix Scores of Design Methodologies

Criterion	**Explanation and supporting evidence**	**Score**
Pahl & Beitz		

(continued) Detailed Rationale for Pugh Matrix Scores of Design Methodologies

Criterion	Explanation and supporting evidence	Score
Flexibility	Follows a clear but partly iterative process with planning, conceptual, embodiment, and detailed design stages. Although feedback loops exist, its structured phases make it less adaptable to sudden system changes.	1
Decision-support	Offers strong guidance for design choices through tools such as function structures, morphological charts, and evaluation matrices.	2
Design from start	Well suited for developing completely new systems using functional breakdown and systematic concept generation.	2
Adaption of reference processes	Can reference existing designs, but mainly focuses on creating new concepts rather than improving old ones.	1
Implementation speed	The thorough phase-based workflow can slow early implementation, though efficiency improves with experience.	0
Process efficiency	Clear structure and documentation reduce errors and duplication, leading to efficient design execution.	2
Roozenburg & Eekels		
Flexibility	The Basic Design Cycle encourages ongoing iteration between analysis, idea generation, testing, and evaluation, allowing high adaptability to different situations.	2
Decision-support	Relies more on the designer’s reasoning than fixed tools but still provides moderate guidance through its structured cycle.	1
Design from start	Intended for both new and improved designs, supporting early concept creation and exploration.	2
Adaption of reference processes	Can reuse existing ideas through iteration, though this is not its main purpose.	1
Implementation speed	The cycle allows quick initial results, even if repeated evaluations extend total time.	1
Process efficiency	Encourages reflection and refinement, but the iterative nature can temporarily slow progress.	0
DFMA		
Flexibility	Focused on manufacturability and cost reduction, offering limited flexibility for new biological or environmental challenges.	-1
Decision-support	Provides clear decision tools for evaluating part count, assembly time, and cost.	1
Design from start	Primarily used to refine existing products rather than to guide new conceptual designs.	-1
Adaption of reference processes	Very effective for improving or simplifying existing systems and processes.	2
Implementation speed	Straightforward tools and checklists make it quick to apply in practice.	1
Process efficiency	Reduces waste and duplication through part simplification and assembly optimization.	2
Axiomatic Design		
Flexibility	Uses structured decomposition that allows some adaptability but is limited by its rigid hierarchy.	1
Decision-support	The Independence and Information Axioms provide strong logic for evaluating design decisions.	2
Design from start	Supports the development of new systems by defining functions and matching them to design parameters.	1

(continued) Detailed Rationale for Pugh Matrix Scores of Design Methodologies

Criterion	Explanation and supporting evidence	Score
Adaption of reference processes	Can be applied to existing systems, though adaptation is not its main focus.	2
Implementation speed	Requires detailed mapping between functions and design parameters, which can be time-consuming.	-1
Process efficiency	Logical structure helps reduce rework and ambiguity, promoting consistent results.	1
TRIZ		
Flexibility	Highly adaptable through the use of contradiction analysis and inventive principles that encourage creative thinking.	2
Decision-support	Offers systematic tools for solving conflicts and identifying innovative solutions.	1
Design from start	Promotes the creation of new ideas by redefining problems and applying known solution patterns.	1
Adaption of reference processes	Builds on a large library of existing solutions and examples, making it strong for adapting proven ideas.	2
Implementation speed	Can take time to apply effectively since contradictions and inventive steps must be clearly defined.	0
Process efficiency	Encourages structured innovation and avoids redundant problem-solving, though the learning curve can slow early use.	1

D

Functional Requirement Addition

The following list connects the FRs to the stakeholders.

F1 (M) The system must support all essential crop phases. Cultivator.
F2 (M) The system must maintain crop-specific root-zone parameters. Cultivator.
F3 (M) The system must ensure operational resilience. Cultivator, system development.
F4 (M) The system must comply with machine safety and regulations. Government, local communities.
F5 (S) The system should recycle the resources [1, 4]. Investor, government, suppliers.
F6 (S) The system should implement integrated preventive measures against algae, pests, and pathogens. Cultivator, government.
F7 (S) Plant-specific maintenance should be available. Cultivator, research institutions.
F8 (S) The system should ensure the quality of the crop. Investor, cultivator, customers.
F9 (C) The design could support modularity to accommodate different crops within the same system. Investor, cultivator, system development.
F10 (C) The system could collect crop residues or by-products for potential value addition. Investor.
NF1 (S) The quality of the product should stay within [X] amount of %. Investor, cultivator.
NF2 (S) The system should achieve [X] % operational time. A specific amount of time is dependent on the machine or component in the system. System development, investor.
NF3 (S) The structural systems shall have a design service life of [X] years under continuous operational loads and environmental conditions. Per component, this differs between 10–20 years. Investor, system development.
NF4 (S) The machines should be able to process [X] plants/day to ensure throughput of the system. Cultivator.

E

Case study additional

Side Products

Rubber is the main objective in TKS, of both this literature review and other researchers. In addition to rubber, other valuable products can be extracted from the Russian dandelion. As noted by Salehi et al. (2022) and Van Beilen and Poirier (2007), the economic viability of Russian dandelions also depends on valuable side products. This section summarizes key findings.

One important by-product is inulin, which can be extracted from the roots. According to Ramirez-Cadavid et al. (2017), inulin is widely used in the food and pharmaceutical industries. TKS roots can contain up to 40% of inulin in DRW (Seilkhan, 2024; Van Beilen & Poirier, 2007). Additionally, proteins, acids, and other sugars in the roots can be used to make ethanol and other chemicals. Ramirez-Cadavid et al. (2017) suggests a biorefinery model to extract these components, as shown in Figure E.1. Similar process diagrams have been proposed by Salehi et al. (2022) and Van Beilen and Poirier (2007).

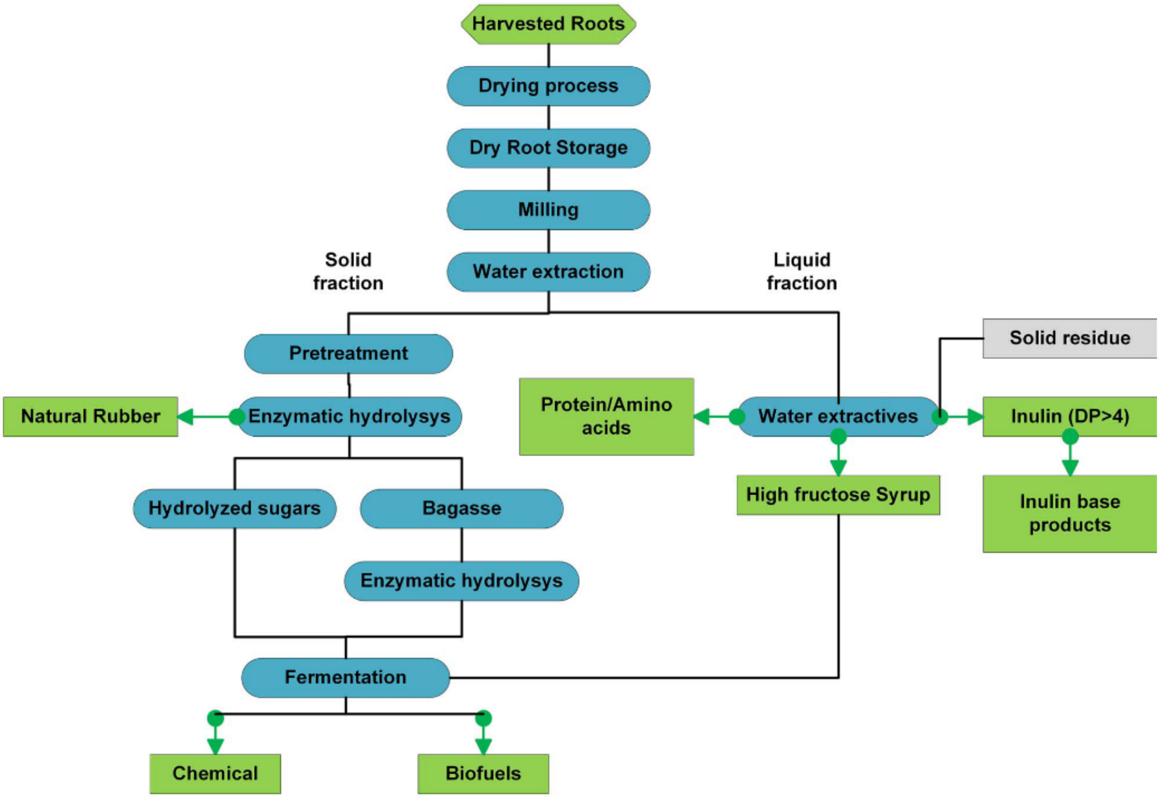


Figure E.1: Proposed Process Diagram for a Taraxacum Kok-saghyz Root Biorefinery (Ramirez-Cadavid et al., 2017)

Aside from the roots, other biomass, like the leaves of TKS can also be used. They contain moisture, fiber, vitamins, minerals, carbohydrates, and small amounts of rubber (Krotkov, 1945; Seilkhan, 2024). Some studies suggest they could be processed in a biorefinery or even used as food, as they are similar to arugula (Seilkhan, 2024). Another option, suggested by Van Beilen and Poirier (2007), is to use the non-root parts of the plant for biogas production. Leaves could also be used for animal feed, fertilizers, or compost.

Choosing the right extraction method is important to get the most value from these side products. Depending on the demand, the side products can be determined. By not choosing the correct extraction methods, inulin and proteins could be lost during the processing steps (Ramirez-Cadavid et al., 2017). It is also important that the extraction does not negatively impact the properties or quality of the NR (Ramirez-Cadavid et al., 2017). Multiple extraction and processing steps are tested (Ramirez-Cadavid et al., 2017) but as mentioned by Salehi et al. (2022), there are extraction methods with environmental and safety concerns. Next to this, cost should be included in the decision for the extraction method (Salehi et al., 2022). This is supported by the advice of Ramirez-Cadavid et al. (2017) to create a techno-economic analysis for feasibility.

The literature study on this crop showed numerous factors that influence the rubber yield from the crops. Next to this, most studies focused their experiments on open-field cultivation.

Latex to Rubber

NR is made of extracting latex. For the Hevea brasiliensis tree, the latex is collected by tapping the tree. The process differs, but in general, the latex is mixed with ammonia so it is stable for transport. After this, acids are added to extract the rubber. This step is called coagulation. After this water is pressed out and allowed to dry. Finally, in combination with sulfur, it is heated, which is called vulcanization. Here, the cross-links are made. This gives the properties of elasticity, strength and durability. This is the moment the material is rubber.

Other processing and shaping methods of rubber include:

- Casting
- Spraying and dipping
- Electrospinning

The choice of processing method depends on the desired shape and mechanical properties of the final rubber product. The adjustments of the rubber properties can be done through chemical, mechanical, or thermal processing.

Functional requirements

The additional functional requirements adjusted to the case study are given as:

F11 (W) The equipment won't provide physical support to the crop [1]. **For the dandelion, this is not needed.**

F12 (M) The system **must** enable non-destructive harvesting of the roots to protect for root rot due to extreme damage.

F13 (C) The system **could** allow recirculating the crops.

F14 (S) The system **should** implement risk measures for recirculated water and substrates to mitigate problems.

F15(C) The system **could** include rubber-inducing measures.

Identified research questions

The research and design questions related to this crop are:

- **1.1. Root Morphology and Function:**
  - What is the influence of root morphology (e.g., taproot presence) on rubber biosynthesis and final yield?
  - What specific root system architecture is needed for optimal rubber production?
- **1.2. Root Trimming and Regrowth:**
  - How quickly do the roots grow?
  - How quickly do the roots contain rubber?
  - How much of the root system can be cut at one time without killing the plant?
  - How often can roots be trimmed over the plant's lifespan?
  - What is the precise impact of root cutting on the plant's life cycle and its rubber synthesis capability?

  - Does a strategy of frequent cutting result in better plant survival and yield compared to drastic, single-event harvesting?
  - Will the plant eventually die after a certain number of harvesting cycles, even with conservative cutting?
  - How significantly does root trimming ”stun” or stress the crop, and how does this impact growth cycles?
  - Do re-grown roots after trimming contain rubber, and if so, is the content and quality comparable to the original roots?
  - Do the crops need stress to produce rubber?
  - How will the crop interact the rubber content with a stress-free CEA system?
- **1.3. Root System Optimization:**
  - How can the root system be optimized specifically for rubber yield?
  - Can you prioritize root growth over shoot growth, and does this directly translate to better rubber production?
  - What growing conditions create the highest rubber yield per volume of plant material?
- **2.1. System Configuration:**
  - How does the target root morphology translate into choices for:
    - Hydroponic system type?
    - Growing medium or substrate?
    - Nutrient solution composition?
    - Pots material?
    - Size and depth of equipment?
  - How does substrate density affect root development and rubber yield?
  - What is the optimal container size to accommodate root structures (like taproots) without limiting growth?
- **2.2. System Longevity and Practicality:**
  - How long can the substrate and hydroponic system remain viable if the plant is harvested multiple times?
  - What are the risks and solutions for practical issues like roots growing out of the pot or pots breaking under root pressure?
  - Is using ”pots that grow with the roots and crop” (as with orchids) a feasible solution?
  - How does water quality change over long cycles, and what impact does this have?
  - Can you implement a system with multiple, separate water parts to mitigate risks like disease?
  - How can IPM be applied?
- **2.3. Harvesting Access:**
  - What is the best method to access and cut the roots within the chosen system design?
  - How does the method of harvesting taproots affect the remaining root structure, system design, and overall long-term yield?
  - How will the crop affect the machine maintenance and operations?
- **3.1. Triggering and Prioritizing Synthesis:**
  - How can you prioritize or enhance the rubber synthesis metabolism?
  - Can known rubber-increasing practices from field cultivation be successfully applied in a controlled environment system?
  - Does repeated root trimming create a stress response that increases rubber content?
- **3.2. Environmental Stressors:**
  - Which environmental stressors (e.g., cold, nutrient stress, light spectrum) can enhance latex production, and under what specific conditions?
  - How do dormancy cycles and seasonal temperature variations affect rubber content in hydroponic versus field-grown plants?

- **3.3. Rubber Quality and Extractability:**
  - Does the rubber quality change under different growing or harvesting conditions?
  - Is there a difference in rubber extractability between fresh roots and decayed or rotten roots?
  - Do rotten roots still contain usable rubber?
- **4.1. Shoot-Root Balance and Debris:**
  - When root cutting reduces the plant's nutrient uptake, causing shoot die-back, how should the resulting dying leaves and debris be handled to prevent mold?
  - Is manual removal required, or can the process be automated?
  - From a cost-benefit perspective, is intervening less (cutting fewer roots) ultimately rewarded by lower maintenance costs?
- **4.2. Flowering Control:**
  - Should flowering be delayed, encouraged, or removed?
  - Does flowering, as a secondary metabolism, trigger additional rubber synthesis?
  - How can flowering be controlled through environmental factors like light color/spectrum or induced stress?
  - Given that flowering is asynchronous, how can flower removal be timed or automated to manage debris and mold risk?
- **5.1 Propagation and Plant Lifecycle**
  - Can dandelions grow pups (new plants from its base) in a cultivated setting, allowing for vegetative propagation?
    - *Preliminary insight: Tests suggest it is possible.*
  - How do plant age and size influence rubber content?
- **6.1. Predictive Modeling:**
  - Can a reliable model or calculation be created to predict the rubber yield resulting from changes to agronomic factors?
  - *Preliminary insight: This may not be possible; testing in multiple scenarios appears necessary.*
- **6.2. System Automation:**
  - What is the feasible level of automation for this cultivation and harvesting system?
- **6.3. Economic Viability:**
  - What are the break-even points for the different design solutions?

Experiments and Research Horizon

This section outlines the proposed experiments and defines the overall research horizon. Each test builds on the previous one to improve understanding of crop behavior, optimize cultivation conditions, and guide system development.

Test 3 – S-Curve After Cutting

Purpose: This test examines the regrowth capacity of *TKS* after cutting and investigates whether a new S-curve is established post-harvest. It also evaluates how cutting frequency, intensity, and plant age affect growth and rubber yield.

Approach: Following Test 2, plants will be cut and regrown under constant environmental conditions. Additional age groups may be included. The main variables are cutting frequency, cutting intensity, and plant age.

Data analysis: Data will be processed using the same nonlinear regression method applied in Test 2, focusing on regrowth dynamics after cutting.

Expected outcome: Comprehensive growth datasets and fitted post-cutting S-curves describing regrowth behavior.

Test 4 – Rubber Content Change

Purpose: This experiment aims to identify cultivation and design factors that increase rubber yield and provide input for large-scale system optimization.

Approach: A factorial ANOVA experiment will be conducted to analyze environmental, design, and stress-related factors influencing rubber yield.

Independent variables:

- **Environmental:** Nutrient level, light intensity and spectrum, CO_2 concentration
- **Design:** Substrate type, pot size and material
- **Stress:** Light schedule, root-zone temperature shifts, cutting stress, induced dormancy, mechanical or hormonal treatments, and plant age

Dependent variables:

- Root biomass yield
- Rubber content
- Root structure and morphology

Data analysis: ANOVA will be used to determine which factors have the greatest influence on rubber yield.

Expected outcome: Quantified datasets linking growth conditions to rubber content and root development, with corresponding fitted models.

Test 5 – Root Rot and System Effects

Purpose: This test investigates the risk of root rot following repeated cutting and its effects on plant health, rubber yield, and system performance. Latex leakage behavior will also be examined.

Approach: Plants from Test 3 will be assessed for signs of root rot and latex leakage. Control groups without cutting will serve as reference. Both visual and physical inspections will be carried out to identify symptoms.

Data analysis: The influence of cutting regime, root rot incidence, and latex leakage on rubber yield will be evaluated.

Expected outcome: Guidelines for handling practices and system design to minimize root rot and improve long-term plant health.

Mechanical Testing

A series of mechanical tests will complement the biological experiments:

- Test 1: Blade performance during root cutting
- Test 2: Crop stickiness and root adherence to blades
- Test 3: Post-harvest refinery performance
- Test 4: Valorization assays for side products (inulin and proteins)

Decision Threshold

Feasibility will guide continuation decisions based on experimental and economic data. The following thresholds will define when scaling or redesign is justified:

- Empirical mean DRW% $< 5\%$ — stop scaling (insufficient biomass)
- Survival after two harvests $< 30\%$ — reject multi-harvest concept
- Persistent growth stagnation after cutting — terminate multi-harvest trials

Economic thresholds:

- Rubber yield below Hevea per m^2 — reconsider project continuation
- Significant drop in market rubber price — pause optimization
- Rising rubber price — prioritize short-term production, add optimization later

All results will feed back into the model, incorporating uncertainty (standard deviation), mortality, losses, and potential side revenues. A summary table will link each *assumption* to its corresponding *experiment* and the resulting *updated model parameter* for full traceability.

Research Horizon

The research is structured along three time horizons:

- **Short term (0–12 months):** Assess uncertainty and feasibility.
- **Medium term (12–24 months):** Explore optimization potential.
- **Long term (2–10 years):** Integrate system design and scale towards commercial application.

The immediate focus will be on Tests 1–3, addressing rubber content and regrowth behavior. Longer-term objectives include crop breeding, process optimization, greenhouse integration, and establishing a pilot refinery for market introduction.

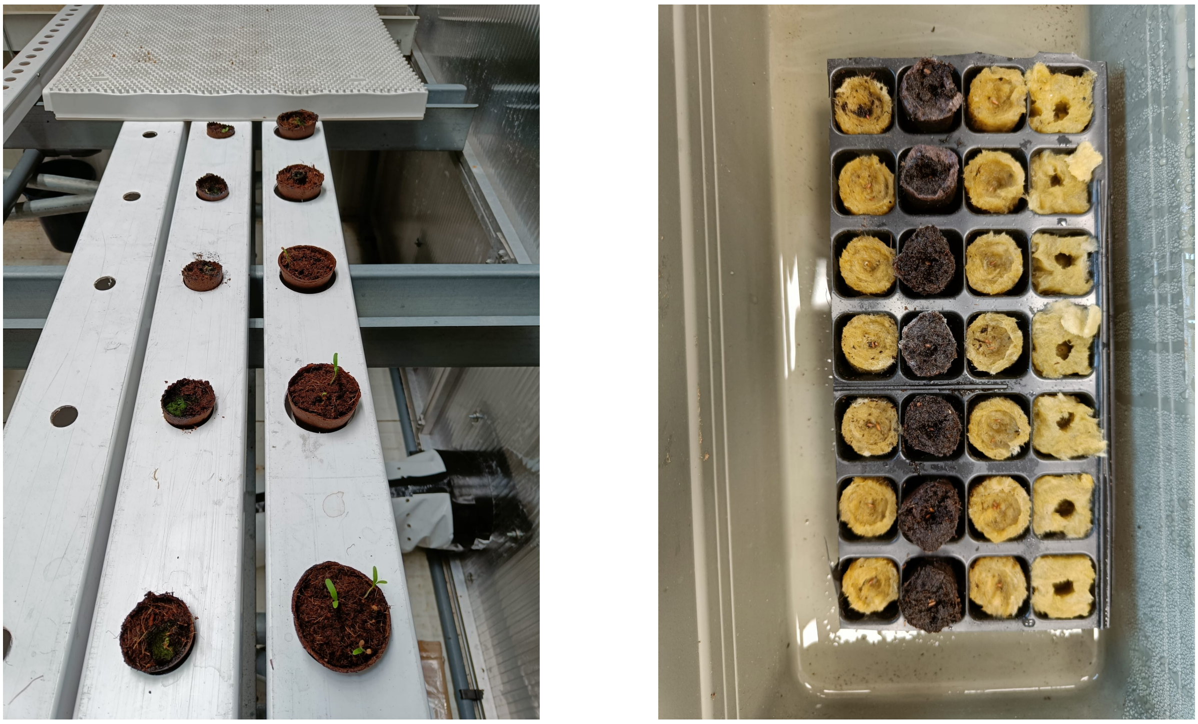
Each experimental block will follow a structured cycle of preparation, cultivation, data collection, analysis, and model integration, ensuring a consistent and iterative research process.

F

Experiment addition

The used system is illustrated in Figure F.1. The logbook of alive plants is given in Figure F.2. The interference during the cultivation is elaborated in Figure F.

Pictures system



(a) Setup Crops

(b) Germination Dome

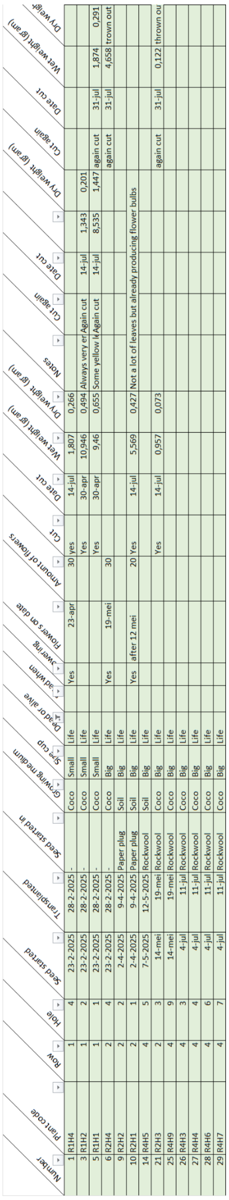
(c) Climate Chamber Access

(d) Flexible Tubes

Figure F.1: Climate Chamber

Cultivation and interference

To allow the crops to grow without influence from the testing as minimal impact was tried to happen. However, certain steps needed to be taken to get the results or protect the system.



Number	Plant code	Row	Hole	Seed started	Transplanted	Seed started in	Growing medium	Size cup	Dead or alive	ad when	owering	Flowers on date	Amount of flowers	Cut	Date cut	Wet weight (gram)	Dry weight (gram)	Notes	Cut again	Date cut		Dry weight (gram)	Cut again	Date cut	Wet weight (gram)	Dry weigh
1	R1H4	1	4	23-2-2025	28-2-2025	-	Coco	Small	Life		Yes	23-apr	30	yes	14-jul	1,807	0,266									
3	R1H2	1	2	23-2-2025	28-2-2025	-	Coco	Small	Life					Yes	30-apr	10,946	0,494	Always very er	Again cut	14-jul	1,343	0,201				
5	R1H1	1	1	23-2-2025	28-2-2025	-	Coco	Small	Life					Yes	30-apr	9,46	0,655	Some yellow l	Again cut	14-jul	8,535	1,447	again cut	31-jul	1,874	0,291
6	R2H4	2	4	23-2-2025	28-2-2025	-	Coco	Big	Life		Yes	19-mei	30										again cut	31-jul	4,658	trown out
9	R2H2	2	2	2-4-2025	9-4-2025	Paper plug	Soil	Big	Life																	
10	R2H1	2	1	2-4-2025	9-4-2025	Paper plug	Soil	Big	Life		Yes	after 12 mei	20	Yes	14-jul	5,569	0,427	Not a lot of leaves but already producing flower bulbs								
14	R4H5	4	5	7-5-2025	12-5-2025	Rockwool	Soil	Big	Life																	
21	R2H3	2	3	14-mei	19-mei	Rockwool	Coco	Big	Life					Yes	14-jul	0,957	0,073						again cut	31-jul	0,122	thrown ou
25	R4H9	4	9	14-mei	19-mei	Rockwool	Coco	Big	Life																	
26	R4H3	4	3	4-jul	11-jul	Rockwool	Coco	Big	Life																	
27	R4H4	4	4	4-jul	11-jul	Rockwool	Coco	Big	Life																	
28	R4H6	4	6	4-jul	11-jul	Rockwool	Coco	Big	Life																	
29	R4H7	4	7	4-jul	11-jul	Rockwool	Coco	Big	Life																	

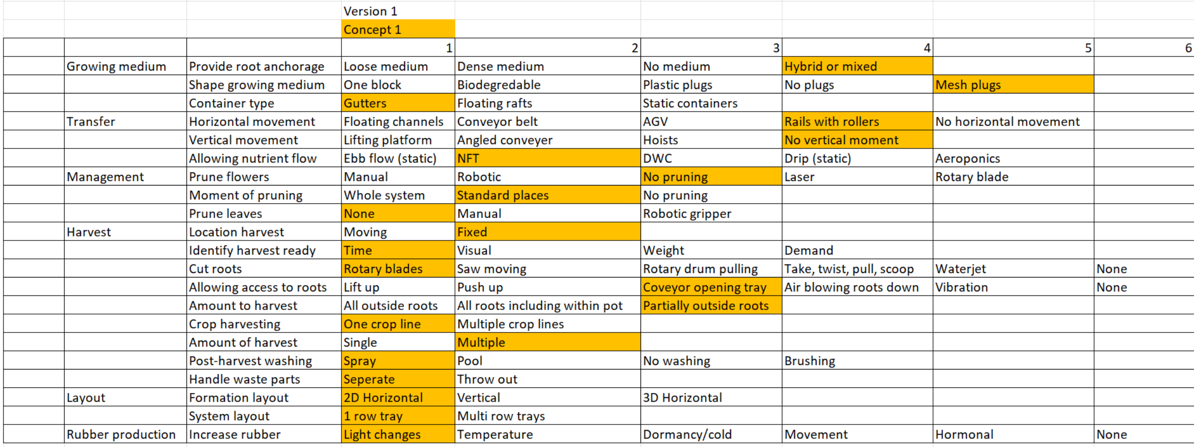
Figure F.2: Logbook Alive Plants

- Crops were checked at least two times a week. Here, the system's parameters (EC, pH, water level) were checked. If necessary, these were adjusted.
- Crop R1H1 was often taken out of the system to check on the root growth. This crop also showed the most torn of roots as it grew too big to keep removing.
- After letting test 3 results happen, the flowers were cut in order to prevent mold.
- The brown leaves were cut to prevent mold.
- New seeds were sown multiple times, as new knowledge about the cultivation could improve the survival rate.
- Basil, lettuce, and spinach were grown simultaneously in the climate chamber to improve humidity and knowledge. They were harvested to prevent overcrowding the NFT channels

G

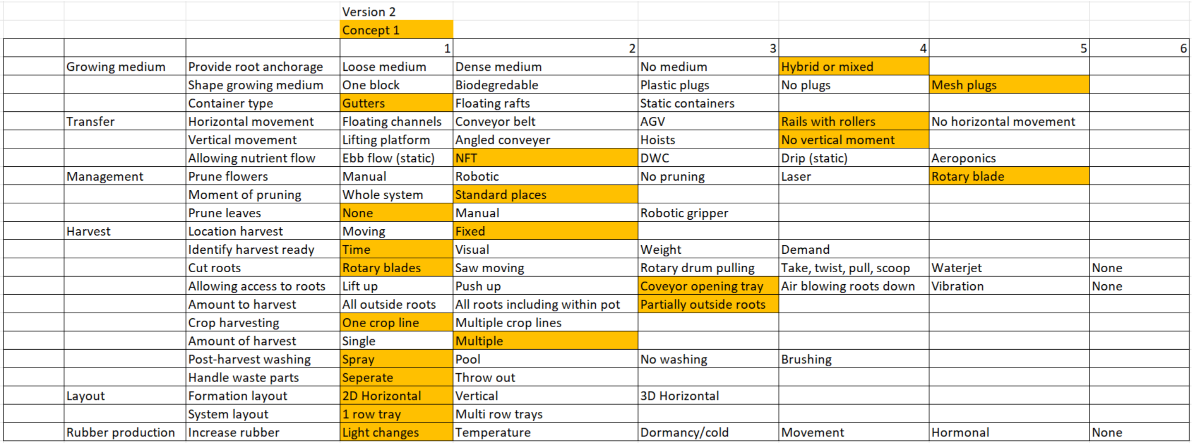
Concepts case study

Visual representations concepts 1, 2 and 3



			Version 1					
			Concept 1					
			1	2	3	4	5	6
	Growing medium	Provide root anchorage	Loose medium	Dense medium	No medium	Hybrid or mixed		
		Shape growing medium	One block	Biodegradable	Plastic plugs	No plugs	Mesh plugs	
		Container type	Gutters	Floating rafts	Static containers			
	Transfer	Horizontal movement	Floating channels	Conveyor belt	AGV	Rails with rollers	No horizontal movement	
		Vertical movement	Lifting platform	Angled conveyer	Hoists	No vertical moment		
		Allowing nutrient flow	Ebb flow (static)	NFT	DWC	Drip (static)	Aeroponics	
	Management	Prune flowers	Manual	Robotic	No pruning	Laser	Rotary blade	
		Moment of pruning	Whole system	Standard places	No pruning			
		Prune leaves	None	Manual	Robotic gripper			
	Harvest	Location harvest	Moving	Fixed				
		Identify harvest ready	Time	Visual	Weight	Demand		
		Cut roots	Rotary blades	Saw moving	Rotary drum pulling	Take, twist, pull, scoop	Waterjet	None
		Allowing access to roots	Lift up	Push up	Coveyor opening tray	Air blowing roots down	Vibration	None
		Amount to harvest	All outside roots	All roots including within pot	Partially outside roots			
		Crop harvesting	One crop line	Multiple crop lines				
		Amount of harvest	Single	Multiple				
		Post-harvest washing	Spray	Pool	No washing	Brushing		
		Handle waste parts	Seperate	Throw out				
	Layout	Formation layout	2D Horizontal	Vertical	3D Horizontal			
		System layout	1 row tray	Multi row trays				
	Rubber production	Increase rubber	Light changes	Temperature	Dormancy/cold	Movement	Hormonal	None

Figure G.1: Concept 1

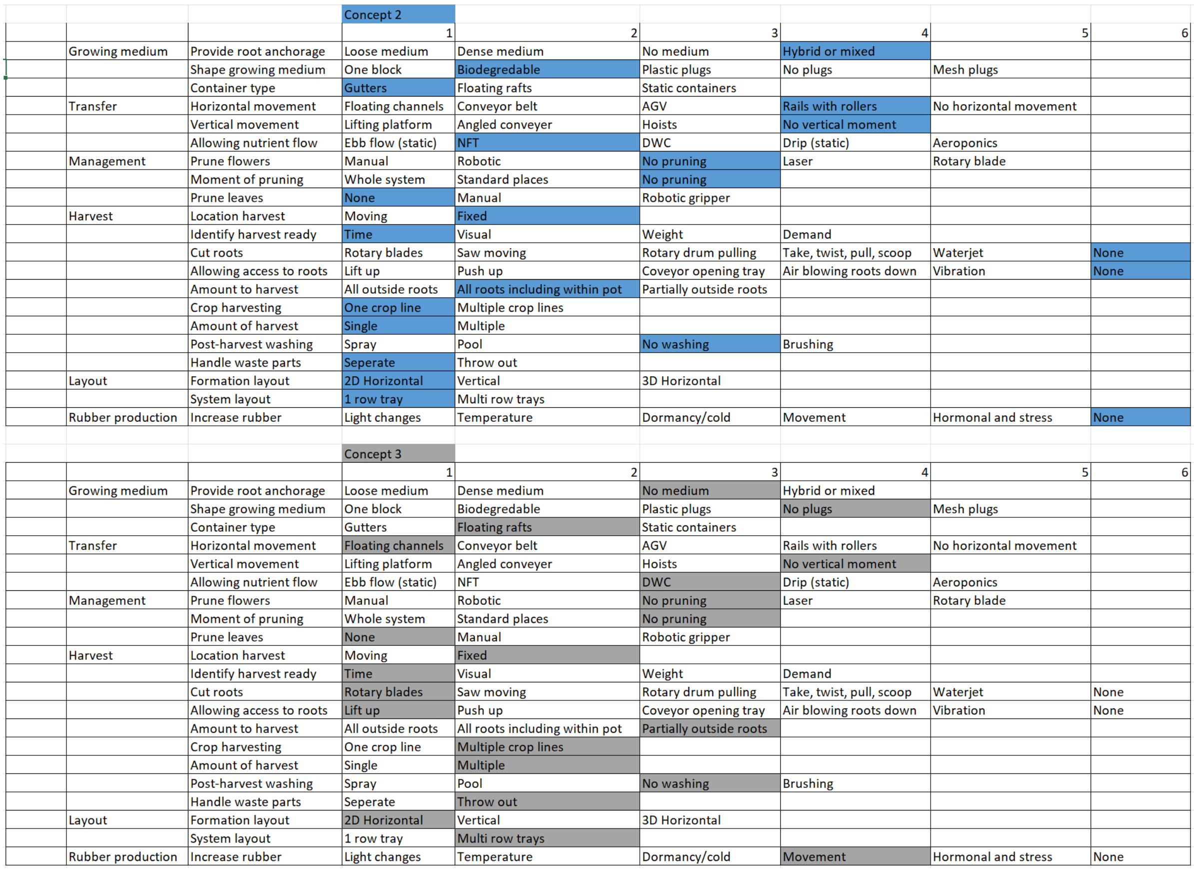


			Version 2					
			Concept 1					
			1	2	3	4	5	6
	Growing medium	Provide root anchorage	Loose medium	Dense medium	No medium	Hybrid or mixed		
		Shape growing medium	One block	Biodegradable	Plastic plugs	No plugs	Mesh plugs	
		Container type	Gutters	Floating rafts	Static containers			
	Transfer	Horizontal movement	Floating channels	Conveyor belt	AGV	Rails with rollers	No horizontal movement	
		Vertical movement	Lifting platform	Angled conveyer	Hoists	No vertical moment		
		Allowing nutrient flow	Ebb flow (static)	NFT	DWC	Drip (static)	Aeroponics	
	Management	Prune flowers	Manual	Robotic	No pruning	Laser	Rotary blade	
		Moment of pruning	Whole system	Standard places				
		Prune leaves	None	Manual	Robotic gripper			
	Harvest	Location harvest	Moving	Fixed				
		Identify harvest ready	Time	Visual	Weight	Demand		
		Cut roots	Rotary blades	Saw moving	Rotary drum pulling	Take, twist, pull, scoop	Waterjet	None
		Allowing access to roots	Lift up	Push up	Coveyor opening tray	Air blowing roots down	Vibration	None
		Amount to harvest	All outside roots	All roots including within pot	Partially outside roots			
		Crop harvesting	One crop line	Multiple crop lines				
		Amount of harvest	Single	Multiple				
		Post-harvest washing	Spray	Pool	No washing	Brushing		
		Handle waste parts	Seperate	Throw out				
	Layout	Formation layout	2D Horizontal	Vertical	3D Horizontal			
		System layout	1 row tray	Multi row trays				
	Rubber production	Increase rubber	Light changes	Temperature	Dormancy/cold	Movement	Hormonal	None

Figure G.2: Concept 1 Revised

Other concepts

Table G.1 shows the full comparison of all the concepts.



			Concept 2					
			1	2	3	4	5	6
	Growing medium	Provide root anchorage	Loose medium	Dense medium	No medium	[✓ Hybrid or mixed]		
		Shape growing medium	One block	[✓ Biodegredable]	Plastic plugs	No plugs	Mesh plugs	
		Container type	[✓ Gutters]	Floating rafts	Static containers			
	Transfer	Horizontal movement	Floating channels	Conveyor belt	AGV	[✓ Rails with rollers]	No horizontal movement	
		Vertical movement	Lifting platform	Angled conveyer	Hoists	[✓ No vertical moment]		
		Allowing nutrient flow	Ebb flow (static)	[✓ NFT]	DWC	Drip (static)	Aeroponics	
	Management	Prune flowers	Manual	Robotic	[✓ No pruning]	Laser	Rotary blade	
		Moment of pruning	Whole system	Standard places	[✓ No pruning]			
		Prune leaves	[✓ None]	Manual	Robotic gripper			
	Harvest	Location harvest	Moving	[✓ Fixed]				
		Identify harvest ready	[✓ Time]	Visual	Weight	Demand		
		Cut roots	Rotary blades	Saw moving	Rotary drum pulling	Take, twist, pull, scoop	Waterjet	[✓ None]
		Allowing access to roots	Lift up	Push up	Coveyor opening tray	Air blowing roots down	Vibration	[✓ None]
		Amount to harvest	All outside roots	[✓ All roots including within pot]	Partially outside roots			
		Crop harvesting	[✓ One crop line]	Multiple crop lines				
		Amount of harvest	[✓ Single]	Multiple				
		Post-harvest washing	Spray	Pool	[✓ No washing]	Brushing		
		Handle waste parts	[✓ Seperate]	Throw out				
	Layout	Formation layout	[✓ 2D Horizontal]	Vertical	3D Horizontal			
		System layout	[✓ 1 row tray]	Multi row trays				
	Rubber production	Increase rubber	Light changes	Temperature	Dormancy/cold	Movement	Hormonal and stress	[✓ None]

			Concept 3					
			1	2	3	4	5	6
	Growing medium	Provide root anchorage	Loose medium	Dense medium	[✓ No medium]	Hybrid or mixed		
		Shape growing medium	One block	Biodegredable	Plastic plugs	[✓ No plugs]	Mesh plugs	
		Container type	Gutters	[✓ Floating rafts]	Static containers			
	Transfer	Horizontal movement	[✓ Floating channels]	Conveyor belt	AGV	Rails with rollers	No horizontal movement	
		Vertical movement	Lifting platform	Angled conveyer	Hoists	[✓ No vertical moment]		
		Allowing nutrient flow	Ebb flow (static)	NFT	[✓ DWC]	Drip (static)	Aeroponics	
	Management	Prune flowers	Manual	Robotic	[✓ No pruning]	Laser	Rotary blade	
		Moment of pruning	Whole system	Standard places	[✓ No pruning]			
		Prune leaves	[✓ None]	Manual	Robotic gripper			
	Harvest	Location harvest	Moving	[✓ Fixed]				
		Identify harvest ready	[✓ Time]	Visual	Weight	Demand		
		Cut roots	[✓ Rotary blades]	Saw moving	Rotary drum pulling	Take, twist, pull, scoop	Waterjet	None
		Allowing access to roots	[✓ Lift up]	Push up	Coveyor opening tray	Air blowing roots down	Vibration	None
		Amount to harvest	All outside roots	All roots including within pot	[✓ Partially outside roots]			
		Crop harvesting	One crop line	[✓ Multiple crop lines]				
		Amount of harvest	Single	[✓ Multiple]				
		Post-harvest washing	Spray	Pool	[✓ No washing]	Brushing		
		Handle waste parts	Seperate	[✓ Throw out]				
	Layout	Formation layout	[✓ 2D Horizontal]	Vertical	3D Horizontal			
		System layout	1 row tray	[✓ Multi row trays]				
	Rubber production	Increase rubber	Light changes	Temperature	Dormancy/cold	[✓ Movement]	Hormonal and stress	None

Figure G.3: Concept 2 and 3

Concept 4: ebb and flow

This concept adapts the Ebb and Flow hydroponic principle, which operates on a table-based system or the ground rather than gullies. For this concept the key feature is the use of a submerged, mobile crate or roaster that supports the plants and their substrate. This system is designed for a multiple, batch-harvest cycle where the entire root mat is harvested.

Plants are cultivated in a static manner. They are started in small pots. They are then transplanted and put into pots that are placed on the crates. During growth cycles, the nutrient solution periodically floods the table from channels below, submerging the root zone, and then drains away, ensuring oxygenation. The roots grow through the crate's perforations, eventually forming a dense, interconnected mat beneath it.

The harvest principle is based on lifting this entire crate. The harvest can be done based on demand. The crate is mechanically raised from the table. This action pulls the entire plant batch upwards, presenting the uniform root mat that has grown below the crate and above the table. This will be cut. A stationary, horizontal blade or saw assembly then cuts the roots cleanly at the base of the crate. A spray system can clean the crate of debris before it is lowered back into the table to begin a new cycle. The harvested material falls onto a conveyor or chute for collection. The harvest machine travels through the system.

Concept 5: low tech

This concept is inspired by traditional soil agriculture for root vegetables like beets, translated into a controlled environment. It utilizes a drip irrigation system where plants are grown in a bulk, inert, and washable granular medium contained within large troughs or blocks. It is designed exclusively for a single, bulk-harvest cycle where the entire plant is removed. The crops grow in a horizontal layer in the ground but not in soil.

Plants are started directly in the bulk medium, which is irrigated via a drip line network. The roots develop freely within the loose medium, forming individual root balls rather than a continuous mat, as seen in liquid systems. The harvest principle is mechanical and bulk-oriented. A harvesting vehicle or mechanism moves along the trough. It

		Concept 4					
		1	2	3	4	5	6
Growing medium	Provide root anchorage	Loose medium	Dense medium	No medium	Hybrid or mixed		
	Shape growing medium	One block	Biodegredable	Plastic plugs	No plugs	Mesh plugs	
	Container type	Gutters	Floating rafts	Static containers			
Transfer	Horizontal movement	Floating channels	Conveyor belt	AGV	Rails with rollers	No horizontal movement	
	Vertical movement	Lifting platform	Angled conveyer	Hoists	No vertical moment		
	Allowing nutrient flow	Ebb flow (static)	NFT	DWC	Drip (static)	Aeroponics	
Management	Prune flowers	Manual	Robotic	No pruning	Laser	Rotary blade	
	Moment of pruning	Whole system	Standard places	No pruning			
	Prune leaves	None	Manual	Robotic gripper			
Harvest	Location harvest	Moving	Fixed				
	Identify harvest ready	Time	Visual	Weight	Demand		
	Cut roots	Rotary blades	Saw moving	Rotary drum pulling	Take, twist, pull, scoop	Waterjet	None
	Allowing access to roots	Lift up	Push up	Coveyor opening tray	Air blowing roots down	Vibration	None
	Amount to harvest	All outside roots	All roots including within pot	Partially outside roots			
	Crop harvesting	One crop line	Multiple crop lines				
	Amount of harvest	Single	Multiple				
	Post-harvest washing	Spray	Pool	No washing	Brushing		
	Handle waste parts	Seperate	Throw out				
Layout	Formation layout	2D Horizontal	Vertical	3D Horizontal			
	System layout	1 row tray	Multi row trays				
Rubber production	Increase rubber	Light changes	Temperature	Dormancy/cold	Movement	Hormonal	None

Figure G.4: Concept 4

employs a shovel or a plough. It is driven underneath the root zone to lift the entire contents of the plants out of the system. The lifted material is then transferred to a processing area where the granular medium is vigorously washed and screened away from the plant biomass (roots and shoots). The cleaned plant product is collected, and the medium is recycled back into the system for the next cycle.

This concept offers simplicity in growth but high complexity at harvest. It requires robust equipment for bulk material handling and an efficient washing and separation stage. The mechanical harvesting process is disruptive, making it unsuitable for multi-harvest strategies. Next to this, it is almost field cultivation with a roof. The machinery used would need to be able to drive in the greenhouse, and that is not optimal.

		Concept 5					
		1	2	3	4	5	6
Growing medium	Provide root anchorage	Loose medium	Dense medium	No medium	Hybrid or mixed		
	Shape growing medium	One block	Biodegredable	Plastic plugs	No plugs	Mesh plugs	
	Container type	Gutters	Floating rafts	Static containers			
Transfer	Horizontal movement	Floating channels	Conveyor belt	AGV	Rails with rollers	No horizontal movement	
	Vertical movement	Lifting platform	Angled conveyer	Hoists	No vertical moment		
	Allowing nutrient flow	Ebb flow (static)	NFT	DWC	Drip (static)	Aeroponics	
Management	Prune flowers	Manual	Robotic	No pruning	Laser	Rotary blade	
	Moment of pruning	Whole system	Standard places	No pruning			
	Prune leaves	None	Manual	Robotic gripper			
Harvest	Location harvest	Moving	Fixed				
	Identify harvest ready	Time	Visual	Weight	Demand		
	Cut roots	Rotary blades	Saw moving	Rotary drum pulling	Take, twist, pull, scoop	Waterjet	None
	Allowing access to roots	Lift up	Push up	Coveyor opening tray	Air blowing roots down	Vibration	None
	Amount to harvest	All outside roots	All roots including within pot	Partially outside roots			
	Crop harvesting	One crop line	Multiple crop lines				
	Amount of harvest	Single	Multiple				
	Post-harvest washing	Spray	Pool	No washing	Brushing		
	Handle waste parts	Seperate	Throw out				
Layout	Formation layout	2D Horizontal	Vertical	3D Horizontal			
	System layout	1 row tray	Multi row trays				
Rubber production	Increase rubber	Light changes	Temperature	Dormancy/cold	Movement	Hormonal	None

Figure G.5: Concept 5

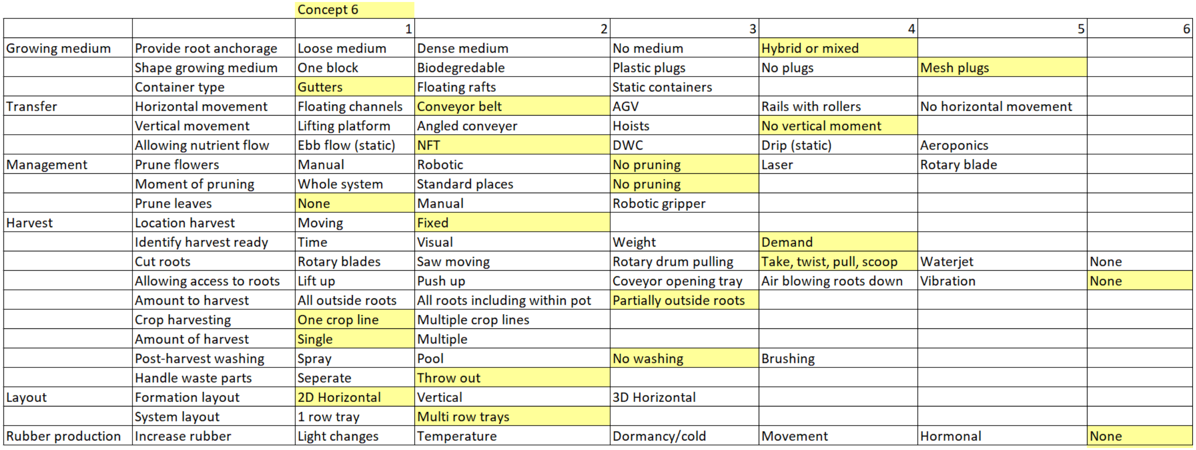
Concept 6: simplified nft

This concept is a variation of a standard NFT system, but with a significantly altered harvest mechanism integrated directly into the gully design. It is designed for a single harvest cycle, eliminating the need for complex external cutting assemblies by making the gully itself the harvesting tool.

Plants are cultivated in a conventional NFT setup, started in small plugs within net pots seated in rigid NFT gullies. A continuous flow of nutrient solution sustains growth. The gullies are designed with a unique feature: integrated, sharpened edges or recesses designed to act as cutting blades at a specific point.

The harvest principle is passive and triggered by plant removal. At harvest, the flow of nutrients is stopped, and the gully may be partially opened or accessed. Instead of an external blade, the action of lifting the plant and its plug from the gully forces the root mass against these integrated sharp edges. This severs the roots cleanly at a predetermined point, leaving the lower root mass behind in the gully. The harvested plant (shoot and top portion of roots) is then conveyed away. The gully is then flushed with water to evacuate the remaining root material and waste, which is collected separately, before the system is reset for the next cycle.

This concept minimizes moving parts in the harvester by embedding the function into the gully. However, it requires very precise and robust gully manufacturing. The effectiveness of the passive cutting action is highly dependent on root texture and density, posing a potential risk of incomplete cuts or clogging.



Concept 6

		1	2	3	4	5	6
Growing medium	Provide root anchorage	Loose medium	Dense medium	No medium	Hybrid or mixed		
	Shape growing medium	One block	Biodegredable	Plastic plugs	No plugs	Mesh plugs	
	Container type	Gutters	Floating rafts	Static containers			
Transfer	Horizontal movement	Floating channels	Conveyor belt	AGV	Rails with rollers	No horizontal movement	
	Vertical movement	Lifting platform	Angled conveyer	Hoists	No vertical moment		
	Allowing nutrient flow	Ebb flow (static)	NFT	DWC	Drip (static)	Aeroponics	
Management	Prune flowers	Manual	Robotic	No pruning	Laser	Rotary blade	
	Moment of pruning	Whole system	Standard places	No pruning			
	Prune leaves	None	Manual	Robotic gripper			
Harvest	Location harvest	Moving	Fixed				
	Identify harvest ready	Time	Visual	Weight	Demand		
	Cut roots	Rotary blades	Saw moving	Rotary drum pulling	Take, twist, pull, scoop	Waterjet	None
	Allowing access to roots	Lift up	Push up	Coveyor opening tray	Air blowing roots down	Vibration	None
	Amount to harvest	All outside roots	All roots including within pot	Partially outside roots			
	Crop harvesting	One crop line	Multiple crop lines				
	Amount of harvest	Single	Multiple				
	Post-harvest washing	Spray	Pool	No washing	Brushing		
	Handle waste parts	Seperate	Throw out				
Layout	Formation layout	2D Horizontal	Vertical	3D Horizontal			
	System layout	1 row tray	Multi row trays				
Rubber production	Increase rubber	Light changes	Temperature	Dormancy/cold	Movement	Hormonal	None

Figure G.6: Concept 6

Concept 7: 3D horizontal

This concept explores a spatial efficiency improvement on a standard NFT system by using a multi-layer, vertical farming approach. However, unlike the dynamically spaced mobile gullies in Concept 1, this system uses multiple fixed layers of NFT channels. It is designed for a single harvest cycle to mitigate the complexity of vertical access for multi-harvest operations.

The cultivation method is identical to a standard NFT system (Concept 2) but is replicated on 4-8 stacked vertical layers. Each tier has its own dedicated lighting, irrigation delivery, and drainage systems. Plants are started in plugs within net pots and transplanted into the gullies on each layer. The spacing between plants is dynamic to accommodate final plant size, potentially leading to better light utilization during the growth stages.

The harvest principle must accommodate the vertical stack. The rotary blades would be sufficient, but from multiple layers, the crops need to be transported vertically. The harvester would perform a similar function to other NFT concepts: potentially opening gullies and using mechanisms to present and cut the root mass. The complexity of automating harvesting across multiple tight layers is a significant challenge. Next to that, the energy cost would increase drastically.

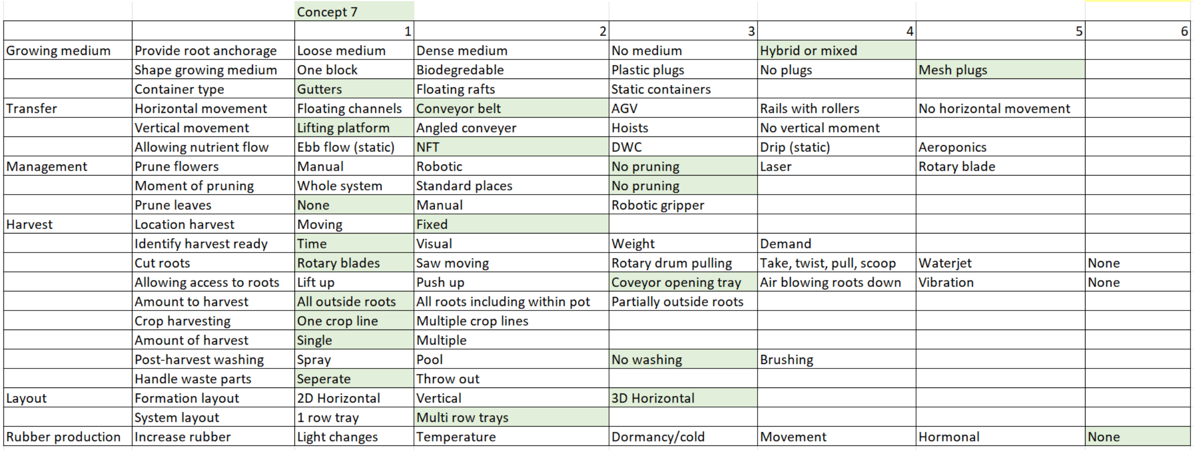
The primary advantage of this concept is the increase in growing area per footprint. The major limitations are the high capital cost for structure, lighting, and environmental control, and very high operational energy consumption. This makes the concept currently unfeasible from an economic standpoint for a cost-sensitive product like natural rubber.

Concept 8: V-shaped gutters

This concept modifies the substrate approach within an NFT framework. It replaces individual pots with a continuous, linear substrate block (rockwool or coir) that runs the length of the gully. This system is designed for a single harvest cycle, facilitating the removal of plants in a continuous row.

Plants are seeded directly into pre-formed holes in the long, sausage-like substrate block. The blocks are then placed into specially designed, likely V-shaped, NFT gullies that provide support and channel the nutrient flow. The roots develop within the block and eventually out into the gully, but the primary anchorage remains the continuous block.

The harvest principle leverages the continuous substrate. At maturity, the entire substrate block, now containing a full row of plants, is lifted from the gully as a single unit. The action of removal may be combined with a cutting mechanism that severs the roots that have extended outside the block. The continuous block with plants is then transported as a whole to a processing station where plants are separated from the substrate, or the entire block



		Concept 7					
		1	2	3	4	5	6
Growing medium	Provide root anchorage	Loose medium	Dense medium	No medium	Hybrid or mixed		
	Shape growing medium	One block	Biodegredable	Plastic plugs	No plugs	Mesh plugs	
	Container type	Gutters	Floating rafts	Static containers			
Transfer	Horizontal movement	Floating channels	Conveyor belt	AGV	Rails with rollers	No horizontal movement	
	Vertical movement	Lifting platform	Angled conveyer	Hoists	No vertical moment		
	Allowing nutrient flow	Ebb flow (static)	NFT	DWC	Drip (static)	Aeroponics	
Management	Prune flowers	Manual	Robotic	No pruning	Laser	Rotary blade	
	Moment of pruning	Whole system	Standard places	No pruning			
	Prune leaves	None	Manual	Robotic gripper			
Harvest	Location harvest	Moving	Fixed				
	Identify harvest ready	Time	Visual	Weight	Demand		
	Cut roots	Rotary blades	Saw moving	Rotary drum pulling	Take, twist, pull, scoop	Waterjet	None
	Allowing access to roots	Lift up	Push up	Coveyor opening tray	Air blowing roots down	Vibration	None
	Amount to harvest	All outside roots	All roots including within pot	Partially outside roots			
	Crop harvesting	One crop line	Multiple crop lines				
	Amount of harvest	Single	Multiple				
	Post-harvest washing	Spray	Pool	No washing	Brushing		
	Handle waste parts	Seperate	Throw out				
Layout	Formation layout	2D Horizontal	Vertical	3D Horizontal			
	System layout	1 row tray	Multi row trays				
Rubber production	Increase rubber	Light changes	Temperature	Dormancy/cold	Movement	Hormonal	None

Figure G.7: Concept 7

is processed. This concept simplifies plant handling and transplanting logistics. However, it offers no dynamic spacing adjustment, potentially wasting space early in the cycle.

		Concept 8					
		1	2	3	4	5	6
Growing medium	Provide root anchorage	Loose medium	Dense medium	No medium	Hybrid or mixed		
	Shape growing medium	One block	Biodegredable	Plastic plugs	No plugs	Mesh plugs	
	Container type	Gutters	Floating rafts	Static containers			
Transfer	Horizontal movement	Floating channels	Conveyor belt	AGV	Rails with rollers	No horizontal movement	
	Vertical movement	Lifting platform	Angled conveyer	Hoists	No vertical moment		
	Allowing nutrient flow	Ebb flow (static)	NFT	DWC	Drip (static)	Aeroponics	
Management	Prune flowers	Manual	Robotic	No pruning	Laser	Rotary blade	
	Moment of pruning	Whole system	Standard places	No pruning			
	Prune leaves	None	Manual	Robotic gripper			
Harvest	Location harvest	Moving	Fixed				
	Identify harvest ready	Time	Visual	Weight	Demand		
	Cut roots	Rotary blades	Saw moving	Rotary drum pulling	Take, twist, pull, scoop	Waterjet	None
	Allowing access to roots	Lift up	Push up	Coveyor opening tray	Air blowing roots down	Vibration	None
	Amount to harvest	All outside roots	All roots including within pot	Partially outside roots			
	Crop harvesting	One crop line	Multiple crop lines				
	Amount of harvest	Single	Multiple				
	Post-harvest washing	Spray	Pool	No washing	Brushing		
	Handle waste parts	Seperate	Throw out				
Layout	Formation layout	2D Horizontal	Vertical	3D Horizontal			
	System layout	1 row tray	Multi row trays				
Rubber production	Increase rubber	Light changes	Temperature	Dormancy/cold	Movement	Hormonal	None

Figure G.8: Concept 8

Certain choices

Some choices were not included. These were the vertical farming options and robotic harvesting. More expensive options and the system doesn't need that high accuracy, precision and costs.

Table G.1: Comparative Analysis of all Proposed Cultivation Concepts against Field Cultivation

	1	2	3	4	5	6	7	8	Field
Yield	High	High	Low	Medium	Low	High	Very High	High	Low
Energy usage	High	Medium	High	Medium	Low	Medium	Very High	Medium	Low
Water usage	Low	Low	High	Low	Low	Low	Low	Low	High
ROI	Medium	Medium	Low	Medium	Low	Medium	Low	Medium	Medium
System complexity	High	Medium	High	High	Low	Medium	Very High	Medium	Low
Automation potential	High	Medium	High	Medium	Low	Medium	High	Medium	Low

Note. Ratings are relative comparisons across proposed cultivation concepts and field cultivation.

H

Van der Hoeven and confidential papers

Van der Hoeven Horticultural Projects

This thesis was done with the guidance of the company: Van der Hoeven Horticultural Projects. They focus on tailor-made horticultural solutions while reducing the footprint in CO_2 and pesticides. They design, build, and operate the facilities while also investing in R&D. Their key values are: innovation, sustainability, commitment, entrepreneurship, and reliability. I would like to thank the company and my colleagues for this opportunity, their guidance, and their help.

Additional Information and Confidential Documents

To start this project, the company has provided additional documents. These are internal research reports and test results. These tests were done with in-house testing equipment. There are also unreleased documents from important researchers whose previous work is used in this literature review. These findings are included in the literature review as they bring industry-specific insights. There are also confidential reports. This is the source for the numbers for the calculation. These are sales reports, internal files, and statements. The reports included three cases for MGS system greenhouses, with their associated costs.

[redacted]

I

Calculation

Hevea Tree Comparison

This section translates the model outcomes into product-level terms and benchmarks them against conventional Hevea rubber production. The purpose is to illustrate what the greenhouse would actually produce and how this relates to industrial products.

As an illustrative case, the production of medical examination gloves is used, since they are manufactured from nearly 100% natural rubber latex, and cannot be made from synthetic rubber. Table I elaborates on the process of creating rubber from latex.

From Latex to Rubber (Method)

Natural latex typically contains 30–40% dry rubber content (Zhao et al., 2010). The conversion from latex to solid rubber is expressed as:

$$\text{DRC} = \frac{m_{\text{rubber}}}{m_{\text{latex}}} \times 100\%. \tag{I.1}$$

Accounting for processing losses during coagulation, drying, and shaping, the required rubber mass is:

$$m_{\text{rubber, required}} = \frac{m_{\text{final}}}{1 - \text{loss fraction}}. \tag{I.2}$$

The corresponding latex mass and volume are:

$$m_{\text{latex}} = \frac{m_{\text{rubber, required}}}{\text{DRC fraction}}, \quad V_{\text{latex}} = \frac{m_{\text{latex}}}{\rho_{\text{latex}}}. \tag{I.3}$$

Product-level Example (Medical Glove)

A standard glove weighs 10–15 g. With 10% production losses, this requires approximately:

- $m_{\text{rubber, required}} \approx 16.7$ g,
- $m_{\text{latex}} \approx 47.7$ g,
- $V_{\text{latex}} \approx 50$ mL.

Benchmark: Hevea Rubber

A mature *Hevea brasiliensis* tree produces 50–200 mL of latex per tap, harvested every two days for at least 20 years after a 6-year juvenile period (Alan N. Gent, 1998). At a planting density of 375 trees/ha, the average yield is $\sim$2,500 kg rubber/ha/year, equivalent to:

$$m_{\text{Hevea}} \approx 0.25 \text{ kg/m}^2\text{/year}. \tag{I.4}$$

A summary of the data is presented in Table I.1.

Benchmark: Russian Dandelion

From the calculation, it was found that the case with high performance contains:

$$m_{\text{H}} \approx 0.6857 \text{ kg/m}^2\text{/year} \tag{I.5}$$

And for the low-performance case:

$$m_{\text{L}} \approx 0.1290 \text{ kg/m}^2\text{/year} \tag{I.6}$$

Economic Comparison

Hevea has a long maturation period, but trees are productive for 20 years with regular harvesting. The Russian dandelion has a shorter growth cycle, potentially allowing faster turnover and crop rotation. However, the yield is currently higher for the low-case scenario of the Russian dandelion. The latex efficiency is not taken as a difference between the tree and the roots. However, it should be assumed that the roots have a lower extraction efficiency.

However, a clear economic comparison cannot be made, as the context and location of a Hevea plantation are very important. Additionally, it is already seen that the performance of the Russian dandelion is not positive. Furthermore, there is a big difference in yield between the two scenarios, so further research should be conducted to find more accurate data.

Table I.1: Parameters for Hevea Yield per Hectare

Parameter	Value	Source
Tapping frequency	Once every 2 days	(Alan N. Gent, 1998)
Rubber yield per tap	50 g dry rubber	(Alan N. Gent, 1998)
Tree density	375 trees/ha	(Alan N. Gent, 1998)
Annual yield per hectare	2,500 kg rubber	(Alan N. Gent, 1998)
Yield per m² per year	0.25 kg/m²	Calculated
Productive lifespan	20+ years	(Alan N. Gent, 1998)
Maturity age	5–6 years	(Alan N. Gent, 1998)

Latex and Rubber Gloves Example

Table I.2: Latex and Rubber Requirements for a 15 g Glove

Parameter	Value	Notes
Glove weight, m_{final}	15 g	Target final weight after processing
Processing loss fraction	0.10	10% typical loss during dipping/drying
Dry rubber content (DRC)	0.35	Fraction of solid rubber in latex
Density of latex, ρ_{latex}	0.95 g/mL	Typical for fresh Hevea latex
Rubber required, $m_{\text{rubber, required}}$	16.7 g	Accounts for 10% processing loss
Mass of latex required, m_{latex}	47.7 g	Calculated from DRC
Volume of latex required, V_{latex}	50.2 mL	Using density of latex

$$m_{\text{rubber, required}} = \frac{15\text{ g}}{1-0.1} \approx 16.7\text{ g} \tag{I.7}$$

$$m_{\text{latex}} = \frac{16.7\text{ g}}{0.35} \approx 47.7\text{ g} \tag{I.8}$$

$$V_{\text{latex}} = \frac{47.7\text{ g}}{0.95\text{ g/mL}} \approx 50.2\text{ mL} \tag{I.9}$$

Using the high-performance yield of Russian dandelion:

$$m_{\text{H}} = 0.6857\text{ kg/m²/year} = 685.7\text{ g/m²/year}.$$

The latex mass required for one glove is $m_{\text{latex}} \approx 47.7$ g. Therefore, the area of dandelions needed to produce a single glove in one year is:

$$A_{\text{glove}} = \frac{47.7\text{ g}}{685.7\text{ g/m²/year}} \approx 0.0695\text{ m²}.$$

For the low-performance case ($m_{\text{L}} = 0.1290$ kg/m²/year):

$$A_{\text{glove}} = \frac{47.7\text{ g}}{129\text{ g/m²/year}} \approx 0.37\text{ m²}.$$

To produce one medical glove annually, approximately 0.07–0.37 m² of Russian dandelion cultivation is needed, depending on the performance scenario.

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Code Calculation

Source Code: FinalVersionCode.py

```
"""
This code is made by Rhea Hugens. The basis and formula's are created based on the data from chapter: 7 Case study.
Models ChatGPT 5 and DeepSeek AI were used for assistence in developing and improving the code and visual representation.
"""



# CELL 1: Import libraries
import numpy as np
import matplotlib.pyplot as plt
import pandas as pd
from mpl_toolkits.mplot3d import Axes3D
from reportlab.lib.pagesizes import letter
from reportlab.pdfgen import canvas
from reportlab.lib.pagesizes import letter
from reportlab.pdfgen import canvas
from reportlab.lib.colors import Color, black, red, blue, green, purple, darkgreen
from reportlab.lib.styles import getSampleStyleSheet, ParagraphStyle
from reportlab.platypus import Paragraph, SimpleDocTemplate, Spacer
from reportlab.lib.units import inch
import re
def code_to_pdf_simple(input_file, output_file):
    c = canvas.Canvas(output_file, pagesize=letter)
    width, height = letter

    # Define colors
    background_color = Color(0.95, 0.95, 0.98)  # Light gray-blue background
    header_color = Color(0.2, 0.4, 0.6)  # Dark blue
    comment_color = Color(0, 0.5, 0)  # Dark green
    keyword_color = Color(0, 0, 0.8)  # Blue
    string_color = Color(0.8, 0, 0)  # Red
    function_color = Color(0.5, 0, 0.5)  # Purple

    # Draw background
    c.setFillColor(background_color)
    c.rect(0, 0, width, height, fill=1)

    # Draw header with background
    c.setFillColor(header_color)
    c.rect(0, height-60, width, 60, fill=1)
    c.setFillColor(white := Color(1, 1, 1))
    c.setFont("Helvetica-Bold", 16)
    c.drawString(40, height-40, f"Source Code: {input_file}")

    with open(input_file, "r") as f:
        text = f.readlines()

    python_keywords = {
        'def', 'class', 'return', 'if', 'else', 'elif', 'for', 'while',
        'import', 'from', 'as', 'in', 'is', 'and', 'or', 'not', 'try',
        'except', 'finally', 'with', 'pass', 'break', 'continue', 'lambda'
    }

    x, y = 40, height - 100
    line_height = 8

    for line_num, line in enumerate(text, 1):
        if y < 40:
            c.showPage()

            c.setFillColor(background_color)
            c.rect(0, 0, width, height, fill=1)
            y = height - 40


        c.setFillColor(Color(0.6, 0.6, 0.6))
        c.setFont("Courier", 7)
        c.drawString(x, y, f"{line_num:3d}")

        current_x = x + 30
        line = line.rstrip()

        if not line:
            # Empty line
            c.setFillColor(black)
            c.drawString(current_x, y, "")
            y -= line_height
            continue


        tokens = []
        i = 0
```

```
        while i < len(line):
            # Check for comments
            if line[i] == '#':
                tokens.append(('#comment', line[i:]))
                break

            # Check for strings
            elif line[i] in ('"', "'"):
                quote_char = line[i]
                j = i + 1
                while j < len(line):
                    if line[j] == quote_char and (j == i+1 or line[j-1] != '\\'):
                        break
                    j += 1
                tokens.append(('#string', line[i:j+1]))
                i = j + 1


            elif line[i].isalpha() or line[i] == '_':
                j = i
                while j < len(line) and (line[j].isalnum() or line[j] == '_'):
                    j += 1
                word = line[i:j]
                if word in python_keywords:
                    tokens.append(('#keyword', word))
                elif i > 0 and line[i-3:i] == 'def':  # Function names after def
                    tokens.append(('#function', word))
                else:
                    tokens.append(('#normal', word))
                i = j

            else:
                tokens.append(('#normal', line[i]))
                i += 1

        # Draw colored tokens
        for token_type, token_text in tokens:
            if token_type == '#comment':
                c.setFillColor(comment_color)
            elif token_type == '#keyword':
                c.setFillColor(keyword_color)
            elif token_type == '#string':
                c.setFillColor(string_color)
            elif token_type == '#function':
                c.setFillColor(function_color)
            else:
                c.setFillColor(black)

            c.setFont("Courier", 7)
            c.drawString(current_x, y, token_text)
            current_x += c.stringWidth(token_text, "Courier", 7)

        y -= line_height

    c.save()


code_to_pdf_simple("FinalVersionCode.py", "mycode_colored.pdf")

# CELL 2: Values for business case. Formulas correlate with the report.
def calculate_detailed_profit(growth_rate, rubber_price, cycle_days, num_harvests, planting_density, cost_level='option 2'):
    S0 = 10  # g, initial plant weight after germination
    Tyears = 25  # years, operational lifetime Literature
    Iplants = 5000  # plants/day, input plants , handling speed
    DRW_factor = 0.10  # 10% dry rubber weight Literature. Most optimal case
    Latex_factor = 0.1  # 10% latex part, literature
    time_germination = 4 # days
    time_first = 15  # days
    time_second = 41  # days
    area_margin = 1.05  # 5% additional space
    germination_pl_per_m2 = 160  # pl/m2
    first_stage_pl_per_m2 = 100  # pl/m2
    second_stage_pl_per_m2 = 80  # pl/m2
    harvest_pl_per_m2 = 40  # pl/m2 (final planting density)

    # Cost assumptions based on technology level
    if cost_level == 'option 1':
        Capex_per_m2 = 660# €/m2, cheap greenhouse
        Opex_fixed = 100        # €/m²/year, low operational cost
        # Slightly lower growth due to cheaper technology
        effective_growth_rate = growth_rate * 0.8
    elif cost_level == 'option 3':
        Capex_per_m2 = 1700  # €/m2, high-tech greenhouse
        Opex_fixed = 200        # €/m²/year, high operational cost
        # Better growth due to advanced technology
        effective_growth_rate = growth_rate * 1.3
    else:  # option 2
        Capex_per_m2 = 1200   # €/m2, standard greenhouse,
        Opex_fixed = 150        # €/m²/year, standard operational cost
        effective_growth_rate = growth_rate
```

```python

        Opex_variable = 0.10  # €/kg, variable cost per kg yield

        # FORMULA 7.2: Total Yield per Plant in WRW
        DaysCycle = time_germination+time_first+time_second + cycle_days * num_harvests  # days plant
        Yn = S0 + (effective_growth_rate * cycle_days * num_harvests)

        # Formula 7.3
        DYn = (Yn / DaysCycle)  # Daily yield roots per day g/plant/day

        # FORMULA 7.4: Actual Daily Yield (considering DRW)
        actual_daily_yield_per_plant = (DYn * DRW_factor * Latex_factor) / 1000  # kg rubber/plant/day
        # Spacing Germination
        germination_plants = time_germination * Iplants  # total plants in area
        germination_area = germination_plants / germination_pl_per_m2  # m2

        # Spacing First Stage
        first_stage_plants = time_first * Iplants  # total plants
        first_stage_area = first_stage_plants / first_stage_pl_per_m2  # m2

        # Spacing Second Stage
        second_stage_plants = time_second * Iplants  # total plants
        second_stage_area = second_stage_plants / second_stage_pl_per_m2  # m2

        # Formula 7.7  Spacing Harvest Stage - THIS VARIES WITH CYCLE DAYS AND HARVESTS
        harvest_plants = Iplants * cycle_days * num_harvests  # total plants in harvest stage
        # Formula 7.8
        harvest_area = harvest_plants / harvest_pl_per_m2  # m2

        # Formula 7.9
        # TOTAL AREA (sum of all stages)
        total_growing_area = (germination_area + first_stage_area +
                             second_stage_area + harvest_area)  # m2
        # Formula 7.10
        # Area margin for machinery/walkways
        total_area_with_margin = total_growing_area * area_margin  # m2

        # FORMULA 7.5: Daily Yield per m²
        daily_yield_per_m2 = actual_daily_yield_per_plant * harvest_pl_per_m2  # kg/m²/day

        # FORMULA 7.6: Annual Yield per m²
        annual_yield_per_m2 = daily_yield_per_m2 * 365  # kg/m²/year

        # FORMULA 7.11: Revenue per m²
        revenue_per_m2 = annual_yield_per_m2 * rubber_price  # €/m²/year

        # FORMULA 7.12: Total Revenue (NOTICE: only effective harvesting area used for revenue)
        total_revenue = revenue_per_m2 * harvest_area

        # FORMULA 7.13: Variable Cost per m²
        variable_cost_per_m2 = annual_yield_per_m2 * Opex_variable  # €/m²/year

        # FORMULA 7.14: Total Variable Cost
        total_variable_cost = variable_cost_per_m2 * harvest_area  # €/year

        # FORMULA 7.15: Fixed Cost per m²
        fixed_cost_per_m2 = Opex_fixed  # €/m²/year (already per area)
        # Formula 7.16
        total_fixed_cost = fixed_cost_per_m2 * total_area_with_margin  # €/year

        # FORMULA 7.17: Capex Cost per m² (annualized)
        capex_cost_per_m2 = Capex_per_m2 / Tyears  # €/m²/year

        # FORMULA 7.18: Total Annual Capex Cost
        total_capex_annual = capex_cost_per_m2 * total_area_with_margin  # €/year

        # FORMULA 7.19: Total Capex Investment (one-time)
        total_capex_investment = Capex_per_m2 * total_area_with_margin  # €

        # FORMULA 7.21: Profit per m²
        profit_per_m2 = (revenue_per_m2 - variable_cost_per_m2 -
                        fixed_cost_per_m2 - capex_cost_per_m2)  # €/m²/year

        # FORMULA 7.21: Total Annual Profit
        total_annual_profit = (total_revenue - total_variable_cost -  total_fixed_cost - total_capex_annual)  # €/year

        # Return all key metrics for analysis
        return {
           'profit_per_m2': profit_per_m2,
           'total_annual_profit': total_annual_profit,
           'total_area_m2': total_area_with_margin,
           'annual_yield_kg_m2': annual_yield_per_m2,
           'total_revenue': total_revenue,
           'total_costs': total_variable_cost + total_fixed_cost + total_capex_annual,
           'capex_per_m2': Capex_per_m2,
           'capex_total': total_capex_investment,
           'opex_fixed': Opex_fixed,
           'effective_growth_rate': effective_growth_rate,
           'cost_level': cost_level,
           'cycle_days': cycle_days,
```

```
       'num_harvests': num_harvests,
       'days_cycle': DaysCycle,
       'germination_area': germination_area,
       'first_stage_area': first_stage_area,
       'second_stage_area': second_stage_area,
       'harvest_area': harvest_area,
       'total_growing_area': total_growing_area,
       'capex_cost_per_m2_annual': capex_cost_per_m2
   }
# CELL 3: Enhanced sensitivity analysis with discrete values
def run_tradeoff_sensitivity_analysis():
    """Run analysis with cost-growth tradeoffs"""

    rubber_prices = np.linspace(1.65, 1.80, 5)
    growth_rates = np.linspace(2, 4, 5) #meerdere opties
    cycle_days_options = np.linspace(30, 90, 5)
    num_harvests_options = [1, 2, 3, 4, 5, 6]  # Reduced for clarity
    cost_levels = ['option 1', 'option 2', 'option 3']


    results = []

    for price in rubber_prices:
        for growth in growth_rates:
            for cycle_days in cycle_days_options:
                for num_harvests in num_harvests_options:
                    for cost_level in cost_levels:

                        result = calculate_detailed_profit(
                            growth_rate=growth,
                            rubber_price=price,
                            cycle_days=cycle_days,
                            num_harvests=num_harvests,
                            planting_density=40,
                            cost_level=cost_level
                        )

                        result.update({
                            'rubber_price': price,
                            'base_growth_rate': growth,
                            'cycle_days': cycle_days,
                            'num_harvests': num_harvests,
                            'cost_level': cost_level
                        })

                        results.append(result)

    return pd.DataFrame(results)

def create_enhanced_visualizations(results_df):
    """Create only the three requested visualizations"""

    # === PLOT 1: Yield vs Profit by Cost Level ===
    plt.figure(figsize=(10, 6))
    for cost_level in results_df['cost_level'].unique():
        subset = results_df[results_df['cost_level'] == cost_level]
        plt.scatter(
            subset['annual_yield_kg_m2'],
            subset['total_annual_profit'],
            alpha=0.6,
            label=cost_level,
            s=60,
            edgecolor='k',
            linewidth=0.3
        )

    plt.xlabel('Annual Yield (kg/m²)', fontsize=12)
    plt.ylabel('Total Annual Profit (€)', fontsize=12)
    plt.title('Yield vs Profit by Cost Level', fontsize=14, weight='bold')
    plt.legend(title="Cost Level")
    plt.grid(True, alpha=0.3)
    plt.tight_layout()
    plt.show()

    # === PLOT 2: Area Requirement vs Profit ===
    plt.figure(figsize=(10, 6))
    for cost_level in results_df["cost_level"].unique():
        subset = results_df[results_df["cost_level"] == cost_level]
        plt.scatter(subset["total_area_m2"], subset["total_annual_profit"],
                    alpha=0.5, label=cost_level, s=50)

    plt.xlabel("Total Area (m²)", fontsize=12)
    plt.ylabel("Annual Profit (€)", fontsize=12)
    plt.title("Tradeoff: Area Requirement vs Profit", fontsize=14, weight='bold')
    plt.legend(title="Cost Level")
    plt.grid(alpha=0.3)
    plt.tight_layout()
    plt.show()

    # === PLOT 3: 3D Rubber Price vs Area vs Profit ===
```

```
    fig = plt.figure(figsize=(12, 8))
    ax = fig.add_subplot(111, projection='3d')

# Select a broad sample for richer visualization
    sample_df = results_df[
        (results_df['cycle_days'].between(30, 90)) &
        (results_df['num_harvests'].between(2, 6))
        ].copy()

# Sort data for smoother color mapping
    sample_df = sample_df.sort_values(by="base_growth_rate")

# 3D scatter plot
    scatter = ax.scatter(
        sample_df['rubber_price'],
        sample_df['total_area_m2'],
        sample_df['total_annual_profit'],
        c=sample_df['base_growth_rate'],
        cmap='viridis',
    s=60,
    alpha=0.8,
    edgecolor='k',
    linewidth=0.3
)

# Labels and title with increased padding
    ax.set_xlabel('Rubber Price (€/kg)', labelpad=15)
    ax.set_ylabel('Total Area (m²)', labelpad=15)
    ax.set_zlabel('Annual Profit (€)', labelpad=1)  # Extra padding for z-axis
    ax.set_title('3D: Rubber Price vs Area vs Profit', fontsize=14, weight='bold', pad=10)

# Colorbar
    cbar = plt.colorbar(scatter, ax=ax, pad=0.1, shrink=0.7)
    cbar.set_label('Growth Rate (g/day)')

# Adjust view for better visualization
    ax.view_init(elev=20, azim=45)
    ax.grid(True, alpha=0.3)

plt.subplots_adjust(left=0.1, right=0.9, bottom=0.1, top=0.9)
plt.show()

# CELL 4: Run the analysis

print("Running enhanced sensitivity analysis with cost tradeoffs...")
tradeoff_df = run_tradeoff_sensitivity_analysis()

print("\nFirst 5 results with Capex per m²:")
print(tradeoff_df[['rubber_price', 'base_growth_rate', 'cost_level', 'capex_per_m2',
                  'total_annual_profit', 'profit_per_m2']].head())

print("\nCreating enhanced visualizations...")
create_enhanced_visualizations(tradeoff_df)

# CELL 6: Tradeoff analysis results
# FORMULA 7.22: ROI
# FORMULA 7.23: Payback period
print("\n" + "="*80)
print("COST-GROWTH TRADEOFF ANALYSIS (CAPEX PER M²)")
print("="*80)

# Analyze best strategy
best_by_cost_level = tradeoff_df.loc[tradeoff_df.groupby('cost_level')['total_annual_profit'].idxmax()]

print("\nBest scenario for each cost level:")
for i, (idx, row) in enumerate(best_by_cost_level.iterrows(), 1):
    # Calculate ROI
    roi_percentage = (row['total_annual_profit'] / row['capex_total']) * 100 if row['capex_total'] != 0 else float('inf')
    roi_years = row['capex_total'] / row['total_annual_profit'] if row['total_annual_profit'] != 0 else float('inf')

    print(f"\n{i}. {row['cost_level'].upper()} COST LEVEL:")
    print(f"   Profit: €{row['total_annual_profit']:,.0f}/year")
    print(f"   Profit per m²: €{row['profit_per_m2']:.2f}/m²/year")
    print(f"   Capex per m²: €{row['capex_per_m2']:,.0f}/m²")
    print(f"   Total Capex: €{row['capex_total']:,.0f}")
    print(f"   ROI: {roi_percentage:+.1f}%")  # + sign shows positive/negative
    print(f"   Payback Period: {roi_years:.1f} years")
    print(f"   Base Growth: {row['base_growth_rate']} g/day")
    print(f"   Cycle: {row['cycle_days']} days, Harvests: {row['num_harvests']}")
    print(f"   Area: {row['total_area_m2']:,.0f} m²")

# ROI analysis
print("\n" + "="*80)
print("RETURN ON INVESTMENT ANALYSIS (PER M²)")
print("="*80)

roi_analysis = tradeoff_df.groupby('cost_level').agg({
    'profit_per_m2': 'mean',
    'capex_per_m2': 'mean',
    'total_annual_profit': 'mean',
```

```
    'capex_total': 'mean'
}).round(0)

# ROI calculations based on per m² metrics
roi_analysis['ROI_years_per_m2'] = roi_analysis['capex_per_m2'] / roi_analysis['profit_per_m2']
roi_analysis['ROI_percentage_per_m2'] = (roi_analysis['profit_per_m2'] / roi_analysis['capex_per_m2']) * 100

print(roi_analysis[['profit_per_m2', 'capex_per_m2', 'ROI_years_per_m2', 'ROI_percentage_per_m2']])

print("\nKey insights with Capex per m²:")
capex_by_level = tradeoff_df.groupby('cost_level')['capex_per_m2'].mean()
print(f"• Option 1: €{capex_by_level['option 1']:.0f}/m² investment")
print(f"• Option 2: €{capex_by_level['option 2']:.0f}/m² investment")
print(f"• Option 3: €{capex_by_level['option 3']:.0f}/m² investment")


print("\n" + "="*80)
print("DETAILED ROI ANALYSIS FOR ALL SCENARIOS")
print("="*80)

# Calculate ROI for all scenarios
tradeoff_df['roi_percentage'] = (tradeoff_df['total_annual_profit'] / tradeoff_df['capex_total']) * 100
tradeoff_df['payback_years'] = tradeoff_df['capex_total'] / tradeoff_df['total_annual_profit']

# Replace infinite values with a large number for negative cases
tradeoff_df['roi_percentage'] = tradeoff_df['roi_percentage'].replace([float('inf'), -float('inf')], float('nan'))
tradeoff_df['payback_years'] = tradeoff_df['payback_years'].replace([float('inf'), -float('inf')], float('nan'))

# ROI statistics by cost level
roi_stats = tradeoff_df.groupby('cost_level').agg({
    'roi_percentage': ['mean', 'min', 'max', 'count'],
    'payback_years': ['mean', 'min', 'max'],
    'total_annual_profit': ['mean', 'min', 'max']
}).round(2)

print("\nROI Statistics by Cost Level:")
print("Formula: ROI = (Annual Profit / Total Capex) × 100%")
print("Payback Period = Total Capex / Annual Profit")
print("\n" + "-"*80)

for cost_level in roi_stats.index:
    stats = roi_stats.loc[cost_level]
    roi_mean = stats[('roi_percentage', 'mean')]
    roi_min = stats[('roi_percentage', 'min')]
    roi_max = stats[('roi_percentage', 'max')]
    payback_mean = stats[('payback_years', 'mean')]
    payback_min = stats[('payback_years', 'min')]
    payback_max = stats[('payback_years', 'max')]

    print(f"\n{cost_level.upper()}:")
    print(f"  ROI: {roi_mean:+.1f}% (Range: {roi_min:+.1f}% to {roi_max:+.1f}%)")
    print(f"  Payback: {payback_mean:.1f} years (Range: {payback_min:.1f} to {payback_max:.1f} years)")

    # Count positive vs negative ROI scenarios
    positive_roi = len(tradeoff_df[(tradeoff_df['cost_level'] == cost_level) & (tradeoff_df['roi_percentage'] > 0)])
    negative_roi = len(tradeoff_df[(tradeoff_df['cost_level'] == cost_level) & (tradeoff_df['roi_percentage'] < 0)])
    total_scenarios = stats[('roi_percentage', 'count')]

    print(f"  Positive ROI scenarios: {positive_roi}/{total_scenarios} ({positive_roi/total_scenarios*100:.1f}%)")
    print(f"  Negative ROI scenarios: {negative_roi}/{total_scenarios} ({negative_roi/total_scenarios*100:.1f}%)")

# Show worst-case scenarios (most negative ROI)
print("\n" + "="*80)
print("WORST-CASE SCENARIOS (MOST NEGATIVE ROI)")
print("="*80)

worst_scenarios = tradeoff_df.nsmallest(5, 'roi_percentage')[['cost_level', 'base_growth_rate', 'rubber_price', 'cycle_days', 'nu

for i, (idx, row) in enumerate(worst_scenarios.iterrows(), 1):
    print(f"\n{i}. {row['cost_level'].upper()} - ROI: {row['roi_percentage']:+.1f}%")
    print(f"   Growth: {row['base_growth_rate']} g/day, Price: €{row['rubber_price']}/kg")
    print(f"   Cycle: {row['cycle_days']} days, Harvests: {row['num_harvests']}")
    print(f"   Profit: €{row['total_annual_profit']:,.0f}, Capex: €{row['capex_total']:,.0f}")
    print(f"   Payback: {row['payback_years']:.1f} years")

# CELL 7: Tornado Plot for Sensitivity Analysis
def create_tornado_plot(results_df):
    """Create tornado plot to show sensitivity of profit to different parameters"""

    # Focus on the baseline scenario (Option 2, medium parameters)
    baseline = results_df[
        (results_df['cost_level'] == 'option 2') &
        (results_df['base_growth_rate'].between(2.5, 3.5)) &
        (results_df['rubber_price'].between(1.70, 1.75))
    ].copy()

    if len(baseline) == 0:
        baseline = results_df[results_df['cost_level'] == 'option 2'].copy()

    # Get baseline values
```

```
        baseline_profit = baseline['total_annual_profit'].median()

        # Calculate sensitivity for each parameter
        parameters = ['rubber_price', 'base_growth_rate', 'cycle_days', 'num_harvests']
        param_names = ['Rubber Price', 'Growth Rate', 'Cycle Days', 'Number of Harvests']

        sensitivities = []

        for param, name in zip(parameters, param_names):
            # Get min and max values and corresponding profits
            min_val = results_df[param].min()
            max_val = results_df[param].max()

            # Find scenarios with min and max values (keeping other parameters at baseline)
            min_scenario = results_df[results_df[param] == min_val]
            max_scenario = results_df[results_df[param] == max_val]

            if len(min_scenario) > 0 and len(max_scenario) > 0:
                min_profit = min_scenario['total_annual_profit'].median()
                max_profit = max_scenario['total_annual_profit'].median()

                sensitivities.append({
                    'parameter': name,
                    'min_impact': min_profit - baseline_profit,
                    'max_impact': max_profit - baseline_profit,
                    'min_value': min_val,
                    'max_value': max_val
                })

        # Sort by overall impact range
        sensitivities.sort(key=lambda x: abs(x['max_impact'] - x['min_impact']), reverse=True)

        # Create tornado plot
        fig, ax = plt.subplots(figsize=(10, 6))

        parameters = [s['parameter'] for s in sensitivities]
        min_impacts = [s['min_impact'] for s in sensitivities]
        max_impacts = [s['max_impact'] for s in sensitivities]

        y_pos = np.arange(len(parameters))

        # Plot negative impacts (left bars)
        ax.barh(y_pos, min_impacts, height=0.6, color='red', alpha=0.7, label='Negative Impact')

        # Plot positive impacts (right bars)
        ax.barh(y_pos, max_impacts, height=0.6, color='green', alpha=0.7, label='Positive Impact')

        # Add zero line
        ax.axvline(x=0, color='black', linestyle='-', alpha=0.8)

        # Customize plot
        ax.set_yticks(y_pos)
        ax.set_yticklabels(parameters)
        ax.set_xlabel('Impact on Annual Profit (€)', fontsize=12)
        ax.set_title('Tornado Plot: Sensitivity of Profit to Parameters', fontsize=14, weight='bold')
        ax.legend()
        ax.grid(True, alpha=0.3, axis='x')

        # Add value annotations
        for i, (min_imp, max_imp, sens) in enumerate(zip(min_impacts, max_impacts, sensitivities)):
            if min_imp < 0:
                ax.text(min_imp - max(abs(min_imp), abs(max_imp))*0.05, i,
                       f'{sens["min_value"]:.1f}',
                       ha='right', va='center', fontsize=9, color='darkred')
            if max_imp > 0:
                ax.text(max_imp + max(abs(min_imp), abs(max_imp))*0.05, i,
                       f'{sens["max_value"]:.1f}',
                       ha='left', va='center', fontsize=9, color='darkgreen')

        plt.tight_layout()
        plt.show()

        return sensitivities

    # CELL 8: Bar Diagram with Min/Max Ranges
    def create_variability_barchart(results_df):
        """Create bar chart showing average values with min/max ranges"""

        # Analyze by cost level
        cost_level_stats = results_df.groupby('cost_level').agg({
            'total_annual_profit': ['mean', 'min', 'max', 'std'],
            'profit_per_m2': ['mean', 'min', 'max'],
            'annual_yield_kg_m2': ['mean', 'min', 'max'],
            'capex_total': ['mean', 'min', 'max']
        }).round(0)

        # Flatten column names
        cost_level_stats.columns = ['_'.join(col).strip() for col in cost_level_stats.columns.values]

        # Create subplots
```

```
    fig, axes = plt.subplots(2, 2, figsize=(15, 10))
    fig.suptitle('Performance Metrics by Cost Level (with Variability Ranges)',
                fontsize=16, weight='bold', y=0.95)

    # Plot 1: Total Annual Profit
    cost_levels = cost_level_stats.index
    profit_means = cost_level_stats['total_annual_profit_mean']
    profit_mins = cost_level_stats['total_annual_profit_min']
    profit_maxs = cost_level_stats['total_annual_profit_max']

    bars1 = axes[0,0].bar(cost_levels, profit_means,
                         yerr=[profit_means - profit_mins, profit_maxs - profit_means],
                         capsize=5, alpha=0.7, color=['lightblue', 'lightgreen', 'lightcoral'])
    axes[0,0].set_title('Total Annual Profit')
    axes[0,0].set_ylabel('Profit (€)')
    axes[0,0].grid(True, alpha=0.3)

    # Add value labels on bars
    for bar, mean_val in zip(bars1, profit_means):
        height = bar.get_height()
        axes[0,0].text(bar.get_x() + bar.get_width()/2., height + 10000,
                       f'€{mean_val:,.0f}', ha='center', va='bottom', fontweight='bold')

    # Plot 2: Profit per m²
    profit_m2_means = cost_level_stats['profit_per_m2_mean']
    profit_m2_mins = cost_level_stats['profit_per_m2_min']
    profit_m2_maxs = cost_level_stats['profit_per_m2_max']

    bars2 = axes[0,1].bar(cost_levels, profit_m2_means,
                         yerr=[profit_m2_means - profit_m2_mins, profit_m2_maxs - profit_m2_means],
                         capsize=5, alpha=0.7, color=['lightblue', 'lightgreen', 'lightcoral'])
    axes[0,1].set_title('Profit per m²')
    axes[0,1].set_ylabel('Profit (€/m²)')
    axes[0,1].grid(True, alpha=0.3)

    for bar, mean_val in zip(bars2, profit_m2_means):
        height = bar.get_height()
        axes[0,1].text(bar.get_x() + bar.get_width()/2., height + 0.5,
                       f'€{mean_val:.2f}', ha='center', va='bottom', fontweight='bold')

    # Plot 3: Annual Yield
    yield_means = cost_level_stats['annual_yield_kg_m2_mean']
    yield_mins = cost_level_stats['annual_yield_kg_m2_min']
    yield_maxs = cost_level_stats['annual_yield_kg_m2_max']

    bars3 = axes[1,0].bar(cost_levels, yield_means,
                         yerr=[yield_means - yield_mins, yield_maxs - yield_means],
                         capsize=5, alpha=0.7, color=['lightblue', 'lightgreen', 'lightcoral'])
    axes[1,0].set_title('Annual Yield')
    axes[1,0].set_ylabel('Yield (kg/m²)')
    axes[1,0].grid(True, alpha=0.3)

    for bar, mean_val in zip(bars3, yield_means):
        height = bar.get_height()
        axes[1,0].text(bar.get_x() + bar.get_width()/2., height + 0.05,
                       f'{mean_val:.2f} kg', ha='center', va='bottom', fontweight='bold')

    # Plot 4: Capex Investment
    capex_means = cost_level_stats['capex_total_mean'] / 1000  # Convert to thousands
    capex_mins = cost_level_stats['capex_total_min'] / 1000
    capex_maxs = cost_level_stats['capex_total_max'] / 1000

    bars4 = axes[1,1].bar(cost_levels, capex_means,
                         yerr=[capex_means - capex_mins, capex_maxs - capex_means],
                         capsize=5, alpha=0.7, color=['lightblue', 'lightgreen', 'lightcoral'])
    axes[1,1].set_title('Total Capex Investment')
    axes[1,1].set_ylabel('Investment (thousands €)')
    axes[1,1].grid(True, alpha=0.3)

    for bar, mean_val in zip(bars4, capex_means):
        height = bar.get_height()
        axes[1,1].text(bar.get_x() + bar.get_width()/2., height + 5,
                       f'€{mean_val:,.0f}K', ha='center', va='bottom', fontweight='bold')

    plt.tight_layout()
    plt.show()

    return cost_level_stats

# CELL 9: Run the new analyses
print("\nCreating Tornado Plot for Sensitivity Analysis...")
sensitivities = create_tornado_plot(tradeoff_df)

print("\nCreating Variability Bar Charts...")
variability_stats = create_variability_barchart(tradeoff_df)

# CELL 10: Display sensitivity analysis results
print("\n" + "="*80)
print("SENSITIVITY ANALYSIS RESULTS")
print("="*80)
```

```python

print("\nMost Sensitive Parameters (by impact range):")
for i, sens in enumerate(sensitivities[:3], 1):
    impact_range = sens['max_impact'] - sens['min_impact']
    print(f"{i}. {sens['parameter']}: €{impact_range:,.0f} profit impact range")
    print(f"   Range: {sens['min_value']:.1f} to {sens['max_value']:.1f}")
    print(f"   Profit impact: €{sens['min_impact']:,.0f} to €{sens['max_impact']:,.0f}")

print("\n" + "="*80)
print("VARIABILITY ANALYSIS BY COST LEVEL")
print("="*80)

print("\nPerformance Ranges:")
for cost_level in variability_stats.index:
    stats = variability_stats.loc[cost_level]

    # Calculate ROI ranges
    roi_mean = (stats['total_annual_profit_mean'] / stats['capex_total_mean']) * 100
    roi_min = (stats['total_annual_profit_min'] / stats['capex_total_max']) * 100  # Worst case ROI
    roi_max = (stats['total_annual_profit_max'] / stats['capex_total_min']) * 100  # Best case ROI

    print(f"\n{cost_level.upper()}:")
    print(f"  Profit: €{stats['total_annual_profit_mean']:,.0f} (€{stats['total_annual_profit_min']:,.0f} - €{stats['total_annual
    print(f"  Profit/m²: €{stats['profit_per_m2_mean']:.2f} (€{stats['profit_per_m2_min']:.2f} - €{stats['profit_per_m2_max']:.2f
    print(f"  Yield: {stats['annual_yield_kg_m2_mean']:.2f} kg ({stats['annual_yield_kg_m2_min']:.2f} - {stats['annual_yield_kg_m
    print(f"  Capex: €{stats['capex_total_mean']:,.0f} (€{stats['capex_total_min']:,.0f} - €{stats['capex_total_max']:,.0f})")
    print(f"  ROI: {roi_mean:+.1f}% (Range: {roi_min:+.1f}% to {roi_max:+.1f}%)")

# ROI correlation analysis
print("\n" + "="*80)
print("ROI CORRELATION ANALYSIS")
print("="*80)

# Calculate correlation between parameters and ROI
correlation_analysis = tradeoff_df[['roi_percentage', 'base_growth_rate', 'rubber_price', 'cycle_days', 'num_harvests']].corr()['

print("\nCorrelation with ROI:")
for param, corr in correlation_analysis.items():
    param_name = {
        'base_growth_rate': 'Growth Rate',
        'rubber_price': 'Rubber Price',
        'cycle_days': 'Cycle Days',
        'num_harvests': 'Number of Harvests'
    }.get(param, param)

    print(f"  {param_name}: {corr:+.3f}")

# CELL 12: Print specific test cases for manual validation
print("\n" + "="*80)
print("SPECIFIC TEST CASES FOR MANUAL VALIDATION")
print("="*80)

# Test case 1: Low performance
print("\n--- TEST CASE 1: Low performance ---")
base_case = tradeoff_df[
    (tradeoff_df['rubber_price'] == 1.65) &
    (tradeoff_df['base_growth_rate'] == 2) &
    (tradeoff_df['cycle_days'] == 30) &
    (tradeoff_df['num_harvests'] == 2) &
    (tradeoff_df['cost_level'] == 'option 1')
].iloc[0]

# Calculate ROI for base case
base_roi = (base_case['total_annual_profit'] / base_case['capex_total']) * 100
base_payback = base_case['capex_total'] / base_case['total_annual_profit']

print(f"Parameters:")
print(f"  Rubber Price: €{base_case['rubber_price']}/kg")
print(f"  Growth Rate: {base_case['base_growth_rate']} g/day")
print(f"  Cost Level: {base_case['cost_level']}")
print(f"  Cycle Days: {base_case['cycle_days']} days")
print(f"  Number of Harvests: {base_case['num_harvests']}")
print(f"  Total Cycle Duration: {base_case['days_cycle']} days")

print(f"\nArea Breakdown:")
print(f"  Germination Area: {base_case['germination_area']:,.0f} m²")
print(f"  First Stage Area: {base_case['first_stage_area']:,.0f} m²")
print(f"  Second Stage Area: {base_case['second_stage_area']:,.0f} m²")
print(f"  Harvest Area: {base_case['harvest_area']:,.0f} m²")
print(f"  TOTAL AREA: {base_case['total_area_m2']:,.0f} m²")

print(f"\nFinancial Results:")
print(f"  Annual Yield: {base_case['annual_yield_kg_m2']:.4f} kg/m²")
print(f"  Total Revenue: €{base_case['total_revenue']:,.0f}")
print(f"  Total Costs: €{base_case['total_costs']:,.0f}")
print(f"  Annual Profit: €{base_case['total_annual_profit']:,.0f}")
print(f"  Total Capex: €{base_case['capex_total']:,.0f}")
print(f"  ROI: {base_roi:+.1f}%")
print(f"  Payback Period: {base_payback:.1f} years")

```

```python
# Test case 2: High-performance scenario
print("\n--- TEST CASE 2: HIGH-PERFORMANCE SCENARIO ---")
high_case = tradeoff_df[
    (tradeoff_df['rubber_price'] == 1.80) &
    (tradeoff_df['base_growth_rate'] == 4) &
    (tradeoff_df['cycle_days'] == 90) &
    (tradeoff_df['num_harvests'] == 6) &
    (tradeoff_df['cost_level'] == 'option 3')
].iloc[0]

# Calculate ROI for high case
high_roi = (high_case['total_annual_profit'] / high_case['capex_total']) * 100
high_payback = high_case['capex_total'] / high_case['total_annual_profit']

print(f"Parameters:")
print(f"  Rubber Price: €{high_case['rubber_price']}/kg")
print(f"  Growth Rate: {high_case['base_growth_rate']} g/day")
print(f"  Cost Level: {high_case['cost_level']}")
print(f"  Cycle Days: {high_case['cycle_days']} days")
print(f"  Number of Harvests: {high_case['num_harvests']}")
print(f"  Total Cycle Duration: {high_case['days_cycle']} days")

print(f"\nArea Breakdown:")
print(f"  Germination Area: {high_case['germination_area']:,.0f} m²")
print(f"  First Stage Area: {high_case['first_stage_area']:,.0f} m²")
print(f"  Second Stage Area: {high_case['second_stage_area']:,.0f} m²")
print(f"  Harvest Area: {high_case['harvest_area']:,.0f} m²")
print(f"  TOTAL AREA: {high_case['total_area_m2']:,.0f} m²")

print(f"\nFinancial Results:")
print(f"  Annual Yield: {high_case['annual_yield_kg_m2']:.4f} kg/m²")
print(f"  Total Revenue: €{high_case['total_revenue']:,.0f}")
print(f"  Total Costs: €{high_case['total_costs']:,.0f}")
print(f"  Annual Profit: €{high_case['total_annual_profit']:,.0f}")
print(f"  Total Capex: €{high_case['capex_total']:,.0f}")
print(f"  ROI: {high_roi:+.1f}%")
print(f"  Payback Period: {high_payback:.1f} years")
```