Optimizing Laboratory Space: A 3D-Model Approach for the Redesign of Laboratory WH114 at University of Twente

Student: Ali Hama

Faculty of Engineering Technology (ET)

Supervisor: Floriana Anselmucci

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Abstract

This Bachelor Thesis present an approach to optimizing laboratory spaces through the redesign of the WH114 laboratory at the University of Twente using 3D modelling techniques. The aim of the study is to address the issues and spatial constraints currently affecting the laboratory. By utilizing a system engineering-based approach and a BIM based 3D modelling approach, this research identifies key design challenges and proposes solutions to enhance the laboratory layout, workflow, and overall efficiency. The results of this research demonstrate improvements in spatial design and user experience which offers practical insights for future laboratory redesign projects. This research contributes to the broader field of space optimization in educational and research facilities, highlighting the value of 3D modelling as a tool for effective spatial planning.

Contents

1. Introduction ... 4
1.1. Background and Context ... 4
1.2. Problem Statement ... 4
1.3. Research Objective ... 5
1.4. Elaboration on Research Objective ... 5
1.5. Research Questions ... 5
1.6. Relevance and Importance of the Research ... 5
2. Literature Review ... 7
3. Methodology ... 10
3.1. Preparation/Situation Analysis ... 10
3.1.1 Boundary Conditions ... 10
3.1.2 Stakeholder Analysis ... 11
3.1.3. SWOT Analysis ... 13
3.1.4. Data Collection Strategies ... 14
3.2. Data Collection ... 16
3.2.1. Interviews ... 17
3.3. Analysis ... 17
3.4. Integration ... 18
3.5. Model Development ... 21
3.5.1. Modelling ... 21
3.5.2 MCDA Process ... 31
3.6. Validation ... 32
4. Results ... 34
5. Discussion ... 37
6. Conclusion ... 41
7. Bibliography ... 42
8. Appendices ... 44
Appendix 1 – Requirement Allocation Sheet ... 44
Appendix 2 – 3D Images of Current Status and Alternative Designs ... 46
Current Status ... 46
Alternative 1 ... 47
Alternative 2 ... 49
Alternative 3 ... 52
Appendix 3 – MCDA Weighting Calculation ... 54
Appendix 4 – Cost Estimations for Each Alternative ... 55

1. Introduction

1.1. Background and Context

The WH114 Laboratory in the Horst building at the University of Twente has been primarily used for research and experimentation related to concrete design and material testing. It is an important laboratory space for researchers as well as students as experiments are carried out by both groups there. Additionally, the space is used for teaching several bachelor and master courses.

To accommodate the needs of both concrete and geotechnical research activities, the University has decided to redesign the laboratory. The main objective of this redesign is to restructure the laboratory into two distinct, functionally optimized areas with one area being dedicated to concrete design and production, and the other area to geotechnical analysis.

It is crucial to dedicate separate areas to concrete design and geotechnical analysis. There are various reasons for this. First, it allows for the optimization of space and resources related to the specific needs of each discipline. For example, concrete design requires large machinery such as mixers which are usually not needed for geotechnical analysis. By separating the areas concerning their disciplines, interference is minimized which allows researchers to access specialized equipment without compromise. Additionally, dedicated spaces facilitate focused research environments.

The current configuration of the WH114 laboratory presents several challenges and limitations. For instance, space optimization is a considerable challenge. The existing layout does not efficiently optimize the space. This is a crucial point of improvement.

Functional integration is another challenge and limitation. The integration of diverse equipment and machinery for both concrete design and geotechnical analysis can pose challenges in ensuring spatial optimization. Without adequate functional integration, there can be interference between the two activities which can affect the quality and reliability of research outcomes.

1.2. Problem Statement

Currently, the redesign of the WH114 laboratory presents a challenge which aims to efficiently divide the space into two specialized areas. One is dedicated to concrete design and production and the other is dedicated to geotechnical analysis. The task involves maintaining the existing infrastructure while accommodating new spatial requirements for various machines and equipment. The overarching goal is to develop a comprehensive 3D model of the space which optimizes the functionality, accessibility, and efficiency of both research activities. This goal requires innovative spatial design and systems engineering (SE) to ensure that the integration of the new spatial requirements is properly implemented while enhancing the overall effectiveness of the laboratory and the facilitation of future research.

1.3. Research Objective

The primary objective is to develop a comprehensive 3D redesign model for Laboratory WH114, aimed at optimizing spatial layout and functional integration to enhance efficiency and effectiveness in both concrete design and geotechnical analysis activities.

1.4. Elaboration on Research Objective

Specifically, the research aims to:

- Assess the existing infrastructure and spatial layout of the laboratory, including water pipes, electrical sockets, and equipment placement.
- Identify the specific spatial requirements and functional needs of equipment for both concrete design and geotechnical analysis.
- Utilize advanced 3D modelling techniques to create a detailed redesign plan that optimizes functionality, accessibility, and efficiency for both research areas.
- Incorporate feedback from stakeholders and potential end-users to ensure the practicality and effectiveness of the proposed redesign.
- Provide recommendations for additional equipment or modifications to enhance the laboratory's capabilities and future research potential.
- Assess the preliminary cost of the new equipment/infrastructure that will be implemented in the redesign.

By achieving these objectives, this research aims to contribute significantly to the improvement of Laboratory WH114, facilitating enhanced research capabilities and advancing knowledge in concrete technology and geotechnical engineering.

1.5. Research Questions

- How can the spatial layout of Laboratory WH114 be optimized to maximize efficiency and accessibility for both concrete design and production, as well as geotechnical analysis and testing?
  - What are the specific spatial requirements for each activity involved in concrete design and geotechnical analysis, and how do they differ?
  - How can feedback from researchers and stakeholders involved in concrete design and geotechnical analysis inform the iterative refinement of the spatial layout to better meet their needs and preferences?
  - How can 3D modelling be utilized to aid with spatial design?

1.6. Relevance and Importance of the Research

The relevance and importance of this research lies in the potential to address critical challenges present in the laboratory and provide solutions to enhance the efficiency and effectiveness of laboratories conducting concrete design and geotechnical analysis research.

With the aid of 3D modelling and BIM, the aim is to propose an optimal solution for the design of the dual usage of the lab.

This thesis addresses the need for an optimized spatial layout and functional integration in laboratories. Laboratories setups often lack efficient organization which can lead to congestion, inefficiencies, and safety hazards. Again, with the use of a 3D model, this research will provide insights into how spatial resources can be utilized, which ensures smoother workflow and enhanced accessibility. Additionally, it improves safety in the laboratory. These insights are relevant to researchers and students but also to administrators responsible for overseeing the laboratory.

Another point of relevance and importance is the interdisciplinary nature of this research. It bridges the gap between concrete design and geotechnical analysis. These two fields often share common laboratory infrastructures, but they do have distinct spatial requirements and research methodologies that differ. By integrating these diverse requirements into a cohesive redesign, this research can offer insight into how different research activities can essentially coexist within the same laboratory environment. These kinds of insights are quite relevant to educational institutions, research organisations and engineering firms.

Ultimately, the conducted research promises to deliver valuable insights, recommendations, and guidelines for the optimization of laboratory design and spatial organization. By addressing a real-world problem and providing an innovative solution, the research can potentially impact the efficiency and safety of laboratory environments by conducting concrete design and geotechnical experiments and research. Therefore, the research is worth pursuing as it aligns with broader goals of enhancing research infrastructure, improving interdisciplinary collaboration, and driving innovation in research and education.

2. Literature Review

There are several types of literature that would be crucial to the project. For example, literature that focuses on principles and practises of laboratory design and spatial organization of the said laboratory. Studies about optimizing laboratory layouts, equipment placement and safety protocols would also be useful for this purpose. Some relevant examples are laboratory design guidelines from other institutions.

These types of literature are relevant to this thesis project as they allow for informed decision-making which is possible due to a clear understanding of the principles of lab design, spatial design, and equipment placement in a lab. Additionally, similar types of literature that detail the optimisation of lab layouts and spatial organization processes offer valuable insights into enhancing the efficiency and functionality of lab spaces. By reviewing these types of literature, strategies to achieve improved efficiencies and functionality within a lab can be identified.

The importance of taking guidelines into consideration is to ensure compliance with industry standards, regulatory requirements and to ensure that the best practises are utilised. By adhering to established guidelines, risks can be mitigated, safety is promoted, and the overall effectiveness of the lab environment should be improved. Additionally, guidelines help maintain consistency in quality across distinct phases of the project. By following standardized recommendations, uniformity in quality can be achieved in certain design choices which minimizes variability in quality compared to most laboratory design.

The study by Santoso et al. (2022) provides a comprehensive framework for developing the design of a building materials laboratory specifically designed for Teacher Education Institutes. This study can inform and support the redesign project by utilizing the insights and methodologies from the study. For example, the study presents its results in a systematic and structured manner which served as a model for this redesign project. The study used clear and readable diagrams and layout plans to illustrate the proposed lab design. Similar visual aids were used in this thesis project to help convey the spatial information effectively. Additionally, the visual aids complement textual descriptions which make the results more accessible and understandable.

The study also included evaluation feedback from potential users of the lab which helps ensure that the design meets user expectations. A similar notion was implemented in this thesis project in chapter 3.6 by gathering feedback to validate design choices and to make any necessary adjustments.

A document by Columbia University (2023) showcases guidelines for the design of a laboratory. As this institution is based in the USA, it should be noted that the national standards and regulations will differ a lot. The same argument can be applied to Stanford University (2023). However, the guidelines presented served as a reference point for this project as they are guidelines from reputable universities. Using their guidelines helped with identifying gaps and areas for improvement such as equipment placement and safety protocols.

Additionally, to bring innovations and improvements to the laboratory, studies, and research on emerging technologies in laboratories might be useful. These can be concepts such as modular construction, and smart infrastructure integrations. Implementations such as these can aid functionality within a lab, efficiency, and sustainability of laboratory facilities. An article by Backlund et al. (2022) discusses the implementation and benefits of smart laboratory settings. It improves safety, comfort, lab productivity, etc. The redesign project used this study as a point of reference for the implementation of smart technologies. An example of this is the implementation of upgraded desktop computers and software for geotechnical experiments. Connected Lab Equipment allows for remote monitoring and control which in turn allows for real-time status updates and possibly control from a different location. Another example of smart and modular technology is the implementation of a mobile fume cupboard. Sensors and automation in this fume cupboard allow for the adjustment of airflow based on real-time data which enhances safety and energy efficiency. The mobility of the fume cupboard offers exceptional practicality and value for money, which are aspects that this document emphasized as well.

This document also discusses the challenges such as managing ventilation requirements and communication between stakeholders which is also relevant for this project. As the Backlund study is a pilot project, inspirations can be drawn from it.

Other literature such as Zontek et al. (2021) discussed safety practices in university laboratories. Although various kinds of labs were described and used in this research, it still helped highlight the importance of considering proper ventilation and protective equipment in laboratory spaces. By implementing similar ventilation systems, dust from concrete or geotechnical experiments can be controlled more adequately which ensures a safer environment for students and researchers.

Additionally, it mentioned that the design of laboratories should accommodate emerging hazards and promote safety by using modular design and remote workstations. The knowledge from this research was beneficial for this project as it did mention how laboratory spaces could be improved in specific regards. Modular design elements were implemented within the design to allow for easy reconfiguration of the space.

An important reference point from Zontek et al. (2021) study was the suggestion that computer workstations should be isolated and protected from their environment which may be exposed to harmful "emissions". This aspect was carefully thought about as the exposure of computers to the dusty environment is a real problem in the current laboratory setup.

Research by Sigmann (2022) discusses the renovation of laboratories and emphasizes the importance of planning and adapting to changing needs in laboratory spaces. A key point of the case study carried out in this research is the importance of balancing equipment and space requirements. Overall, it highlights important takeaways such as the importance of proactive planning and safety and functionality. As this research project will deal with many similar issues and themes, this research and its results are particularly important to consider during the research process.

Another important concept is systems engineering and stakeholders. Literature that provides insight into understanding the needs, preferences and perspectives of users and stakeholders throughout the design process is needed. This can include papers that dissect engineering design processes. An example of this is in a book by Haberfellner et al. (2019a), more specifically in its Systems Design chapter where it describes how to implement and design a Systems Engineering process model. This literature provides a framework for the methodology and procedure of this thesis project. Other aspects such as the Systems Thinking chapter (Haberfellner et al., 2019b) will be considered and implemented in this thesis project. This is because Systems Thinking promotes holistic thinking among other aspects of project processes. It will be beneficial as it allows for the understanding of interdependencies, holistic solutions and adaptability and resilience during the research and work process. The design of the research methodology is based off of the system engineering processes described in these works.

For the regulatory and standard literature, ISO 17025 (NEN, 2018), IEC 61010 (NEN, 2010) and NEN-EN 12845:2015+NEN 1073:2018 (NEN, 2018b) were considered.

ISO 17025 (NEN, 2018) is an international standard that specifies general requirements for the competence and consistent operation of laboratories. It concerns a wide range of testing and calibration performed by laboratories and is used by said laboratories to develop their quality management systems. The key aspect of this standard includes technical requirements, management requirements and the need for continuous improvement. Compliance with this standard ensures that the WH114 laboratory operates consistently and with valid results. This standard is important to maintain the credibility and reliability of the laboratory's outputs. This research has demonstrated adequate compliance with this regulation by detailing the steps taken to ensure accurate and reliable testing. Many of these are present in the requirement allocation sheet provided in the appendix 1. The standard also mentions internal measures such as management reviews, such measures were not considered in this research as it is not withing the research scope.

IEC 61010 (NEN, 2010) is an international standard that sets safety requirements for electrical equipment within laboratory environments. To ensure safety in the WH114 laboratory, it was important to ensure compliance with this standard. This research outlined safety protocols and procedures implemented in the laboratory that would ensure compliance with this standard.

NEN-EN 12845:2015+NEN 1073:2018 (NEN, 2018b) specified the requirements for automatic sprinkler systems to ensure their function during a fire. Fire safety is an important aspect of any space in the university. The WH114 laboratory was already equipped with a sprinkler system that adheres to this standard. The focus in this research was to ensure that any changes made do not affect the functionality of these sprinkler systems.

By synthesizing these various kinds of literature, a theoretical foundation for the project can be established by informing the research objectives, methodologies, and design considerations. Ultimately, it provides a comprehensive understanding of the key concepts that are relevant to the thesis project. These key concepts are the principles of lab design, interdisciplinary collaboration, systems engineering and stakeholders and regulatory compliance.

3. Methodology

The research process for the research conducted can be described in six stages. The preparation/Situation Analysis, Data Collection, Analysis, Integration, Model Development, Validation.

3.1. Preparation/Situation Analysis

To properly conduct the research, several aspects of the methodology/process had to be prepared before the start of the research process, as well as a situation analysis to fully grasp the scope and goals of the redesign. A situation analysis in a systems engineering process involves a comprehensive assessment of the current state of a system or project. In this case it would be the current state of the WH114 laboratory. To do this, the boundary conditions of the research were first clearly defined. This is further elaborated on in 3.1.2. Afterwards, a stakeholder analysis was carried out in order to identify the relevant stakeholders and their influence on the research. Additionally, a current model of the situation was prepared in order to fully conduct the situation analysis. Using observations within the lab and an analysis of the modelled situation, a SWOT analysis was conducted to figure out the strengths, weakness, opportunities, and threats of the current layout of the lab. Lastly, data collection strategies were developed.

3.1.1 Boundary Conditions

The research's goals and objectives were described in the introduction and the boundary conditions will follow up on those aspects to delineate the exact boundaries and objectives of the research. These boundary conditions are established and delineated to ensure that the research remains focused and feasible without overstepping defined limits.

Physical Boundaries

The research project is confined to the existing WH114 laboratory at the University of Twente. Adjacent rooms, hallways, and other facilities are excluded. Existing structural walls, support beams and other fixed installations must remain intact and unchanged.

Additionally, the focus of the project is on a macroscopic scale of the laboratory layout and equipment. This means that the arrangement of sizeable items and important tools/equipment are assessed while excluding smaller tools and objects that do not affect the operations in the laboratory considerably, from consideration.

Functional Boundaries

All current and planned geotechnical and concrete testing equipment must be accommodated in the redesigned space. Research equipment not related to the overall project scope is excluded. For example, this excludes a large box of sand which at the time of this research is temporarily present in the laboratory for research purposes.

Regulatory Boundaries

All modifications to the laboratory must adhere to relevant regulatory and safety requirements. The research project cannot implement changes that would violate these requirements.

Budgetary Boundaries

The redesign does not have a specific budget limit, but it must remain economically feasible. Redesigns that have excessive costs would not be feasible as the university would not approve of them. Therefore, it is important to keep costs low for the designs. This includes costs for new equipment, infrastructure upgrades and other unforeseen expenses.

Additionally, the reuse of equipment is encouraged to stay within the budget, however, it should not compromise the functionality and safety of the laboratory.

Technical Boundaries

Existing infrastructure like air ventilation systems, electrical systems and plumbing must be utilized as much as possible. This is to avoid extensive renovations. If there are new installations, they should integrate seamlessly with current systems.

Furthermore, any new technological equipment introduced to the laboratory must be compatible with the existing technological infrastructure.

3.1.2 Stakeholder Analysis

A fundamental aspect of the preparation and systems engineering process employed in this research is the stakeholder analysis. This helps identify the stakeholders relevant to the research's process and outcomes. It is a necessary and fundamental step as it helps understand the interests, expectations and needs of various stakeholders involved with the laboratory. Additionally, it aids effective project management, risk mitigation and overall alignment with objectives and requirements for the laboratory. This ultimately leads to the satisfaction of all relevant stakeholders.

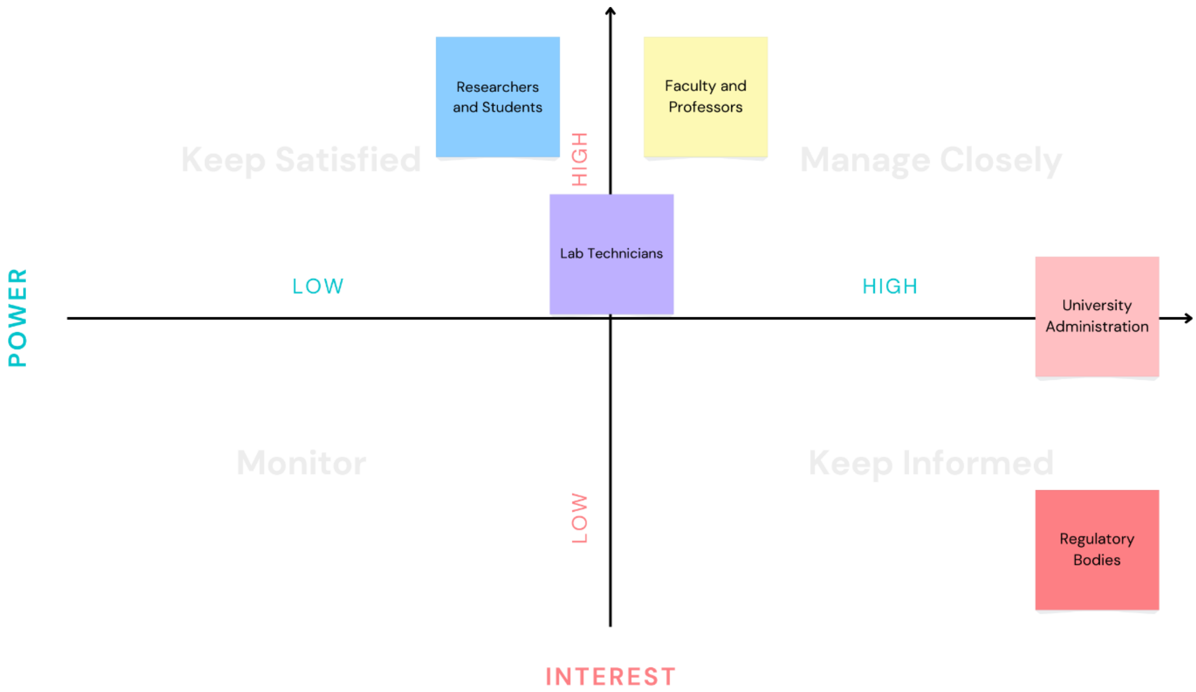
The first step was to identify the stakeholders and list them. These stakeholders are then categorized into high-low influence and high-low power stakeholders. This was done by utilizing a stakeholder table which gives a clear overview of the stakeholders.

List of Stakeholders

- Researchers and Students: These are the primary users of the laboratory. They primarily consist of researchers and students conducting geotechnical and concrete experiments.
- Lab Technicians: Lab Technicians are important to consider since they are responsible for the technical setups, maintenance, and operation of lab equipment.
- Faculty and Professors: They oversee the research activities, provide guidance, and ensure that academic standards are met.
- University Administration: Provides the funding, and resources for the laboratory.
- Regulatory Bodies: Regulatory bodies are relevant as they want the lab space to comply with relevant laws, standards, and regulations.

Figure 1

Stakeholder Power-Interest Matrix



The reasoning behind the setup of the power-interest grid shown in figure 1 is explained as follows.

Researchers and Students: Their power is low, and their interest is high. This is because they are primary users of the lab with a high interest in its functionality and setup. They use the laboratory for experiments and studies; therefore, their work is greatly affected by the laboratory's setup and condition. However, they do not have much influence over any management or resource decisions within the laboratory.

Lab Technicians: They have medium power and a high interest. This is because they are responsible for the technical setup and maintenance, making them highly invested in this area. They can have a say in how the laboratory should be maintained and run, therefore they are considered to have medium decision-making powers.

Faculty and Professors: They have a high interest and high power. They need the laboratory to function properly for research and teaching purposes. This would ensure academic standards and successful research outcomes. As a result, they would have a high interest in the project's outcomes. Additionally, they can influence the laboratory's changes as they oversee research activities and consequently have substantial authority within the laboratory.

University Administration: They have a medium interest in the project's outcomes and high power. While the university provides funding and resources, their actual involvement in the laboratory's daily operations is limited. Their main area of interest is the efficient use of budgets/resources and overall adherence to the university policies. As a result, their interest is considered to be medium as they would not care much about the design of the laboratory as long as it stays within budget and allows for effective research to be conducted. However, their control over budget and resources does make them important stakeholders to consider as they have high power because of this.

Regulatory Bodies: Their interest is low as their only area of interest is limited to ensuring that the laboratory meets safety and regulatory requirements. However, they do have high power as they have the authority to enforce compliance with laws and regulations. Therefore, it is important to consider the regulatory aspects of the project to ensure that regulatory bodies keep informed about the situation and are satisfied.

3.1.3. SWOT Analysis

A SWOT analysis is performed to assess categorical factors in the lab that could affect the redesign. It aids in forming a thorough understanding of the laboratory. Additionally, it helps with the strategic planning of the spatial design aspects of the redesign as well as the planning of solutions and overall decision-making. In this case, the purpose of this SWOT analysis is to aid the understanding of the laboratory's current layout and situation by identifying strengths and weaknesses in this space.

To perform the SWOT analysis, issues and objectives are identified. In the case of this redesign project, the SWOT analysis is related to the current state of the laboratory as an understanding of this will aid the further steps needed to achieve the research objective. Keeping this in mind, the SWOT analysis was carried out by using a matrix showcasing the strengths, weaknesses, opportunities and threats of the current state of the laboratory. The results are shown in Table 1.

Table 1

SWOT Analysis

Strengths:	**Weaknesses:**
• **Diverse Equipment:** The laboratory is equipped with various essential tools and machines required for conducting a wide range of geotechnical and concrete experiments. • **Dedicated Workspaces:** There are established areas for different types of research which allows for organized workflows. • **Skilled Personnel:** The researchers in the laboratory are experienced and familiar with the laboratory. Their knowledge could prove useful in order to identify any points of improvement and any suggestion for said improvements.	• **Disorganisation and Underutilised Space:** The layout of the laboratory is in a cramped condition due to the inefficient use of space. For example, many items lay around on the floor when they could simply be stored in any of the storage racks. • **Obstructed Access:** Equipment and Furniture obstructs access to electricity plugs and doors. • **Safety and Health Concerns:** There is a high dust exposure to sensitive equipment but also to people. This might cause health issues for those affected by dust allergies. • **Unused Equipment:** Equipment such as the bending test machine and the boot storage rack are not being used enough in the laboratory to justify their presence within it. The presence of such unused equipment means that a lot of space is taken up unnecessarily. The red oven in the back of the concrete section is also unused.

Opportunities:	Threats:
• **Implementation of Smart Technologies:** Introducing technologies such as IoT sensors, digital data logging can enhance efficiency and safety in the lab. • **Reorganisation for Improved Workflow:** By reallocating and organizing the laboratory space better, the laboratory's functionality can be significantly improved. • **Enhanced Safety Measures:** Establishing clear instructions, better dust protection measures and adequate storage systems can improve the overall safety of the lab space. • **Additional Resources and Equipment:** The upgrading of some equipment can address some inefficiencies and support more experiments.	• **Funding Limitations:** Budget constraints by the university might limit the ability to implement the ideal upgrades and improvements. • **Competition for Lab Space:** Sharing the lab space with different research groups leads to a conflict of interests and competition for lab space. • **Regulatory Compliance:** Failure to comply with relevant regulations and requirements could result in penalties and restrictions.

3.1.4. Data Collection Strategies

The last step was to develop methods to collect qualitative and quantitative data. The qualitative data collection was carried out using semi-structured interviews. The purpose of these interviews was to gather several types of information. These include the following:

- *Specific Requirements*: Through the use of interviews, the specific requirements and preferences of stakeholders related to the lab layout, equipment and workflow challenges are identified.

- *Functional Needs*: The functional needs of researchers for both concrete and geotechnical research are identified which ensures the redesign meets their operational needs.

- *Spatial Layout*: The interviews also gather insights into the stakeholders' vision for a better layout of the laboratory.

- *Equipment Preferences*: Stakeholder preferences for equipment placement, usage replacements and/or any additional tools required are identified.

- *Workflow Challenges*: Explore any existing workflow challenges within the laboratory that stakeholders have encountered.

- *Feedback and Suggestions*: Stakeholders are encouraged to provide feedback, suggestions, and ideas for improving the laboratory design.

Using these information categories, the following interview questions were formulated:

- Can you describe your role and responsibilities within the laboratory?

- What are the main activities or tasks you perform in the laboratory on a regular basis?
- How would you describe the current layout and design of the laboratory space?
- Are there any specific challenges or inefficiencies you encounter in the current laboratory setup?
- What equipment or tools do you use frequently in your work?
- Are there any specific requirements that you believe are essential for the laboratory to function more effectively?
- Can you provide any suggestions or ideas for improving the design and functionality of the laboratory?
- In your opinion, what are the most critical aspects that need to be considered in the redesign of the laboratory?
- Are there any specific equipment placements or workflow improvements you would like to see in the redesigned space?
- What are your future needs or expectations regarding equipment upgrades or additional tools in the laboratory?
- Have you encountered any workflow challenges or bottlenecks in the current lab setup? If so, could you elaborate on them?

The quantitative data collection is carried out by including measurable surveys together with the interviews. An example of how this could be done is by using the Likert scale (Bhandari, 2020). The purpose of this is to support the information gathered in the interviews by using the Likert Scale to add numerical scales to the information gathered. This will make following steps like requirement formulation and alternative design generation much simpler as a lot of the objectives and requirements will already have importance weightings associated with them. The types of questions asked during these surveys consist of the following topics:

- *Satisfaction Levels*: Measure stakeholder satisfaction levels with the current lab layout and overall functionality using a Likert scale ranging from “1” to “5”.
- *Importance of Spatial Requirements*: Assess the importance of specific spatial requirements.
- *Preference for Equipment Placement*: Determine stakeholder preferences for equipment and tools within the laboratory space.
- *Workflow Efficiency*: Measure stakeholder perceptions of workflow efficiency in the current lab layout and their expectations for improvement of specific workflow aspects.

- *Future Needs Assessment*: Measure stakeholders' needs for equipment upgrades or additional tools.

Using these topics and criteria, the following survey questions were formulated:

- How satisfied are you with the current layout and functionality of the laboratory space?
    - 1 (Not Satisfied) to 5 (Very Satisfied)
- On a scale of 1 to 5, how important do you consider specific spatial requirements such as workspace size, storage areas, and equipment placement in the laboratory?
    - 1 (Not Important) to 5 (Extremely Important)
- How would you rate the efficiency of workflow in the current lab layout?
    - 1 (Very Inefficient) to 5 (Very Efficient)
- How safe do you perceive the current spatial layout of the laboratory to be?
    - 1 (Unsafe) to 5 (Very Safe)
- How satisfied are you with the equipment placement within the laboratory space?
    - 1 (Not Satisfied) to 5 (Very Satisfied)
- On a scale of 1 to 5, how important is it for you to have easy access to equipment and tools in the laboratory?
    - 1 (Not Important) to 5 (Extremely Important)
- How likely are you to recommend additional equipment or upgrades in the lab?
    - 1 (Very Unlikely) to 5 (Very Likely)

3.2. Data Collection

This phase consisted of carrying out the data collection. This data collection was conducted using the aforementioned developed strategies. The data collection consisted of on one interviews with stakeholders. The surveys would be done immediately after the interviews.

Through these one-on-one interviews with stakeholders, key insights into specific requirements, preferences and challenges related to the laboratory were gathered. Additionally, the short surveys were conducted after the interviews to gather quantitative data related to the current laboratory setup. Personal observations were also an important data collection strategy. With observations, the current workflow and dynamics within the laboratory could be identified. The identification of these aspects allowed areas of improvement and potential bottlenecks to be highlighted during the analysis.

3.2.1. Interviews

The interviews were conducted in a semi-structured format with specific. There was a structured framework in place which was established in 3.1.4, however, the interview allowed for open-ended responses which enabled interviewees to elaborate on their answers and provide detailed feedback.

The surveys were conducted verbally rather than digitally or on paper. This was done so that participants could also clarify and elaborate on their answers. Additionally, verbal surveys were more time efficient as they were done immediately after the interview questions. This made it easier to arrange meetings with the participants as it ensured that the interview/survey would not take a long time.

3.3. Analysis

With the quantitative and qualitative data gathered in the previous phase, different methods were utilised to analyse the gathered data sets. Qualitative data from the interviews were analysed using a thematic analysis. The data obtained from the interviews was thoroughly analysed for recurring themes, patterns and noteworthy discoveries related to the laboratory's design and functionality. The acquired data was categorized and summarized in two tables for a better overview of the situation. This is shown in appendix 5.

The results from this analysis ultimately led to insights into priorities, requirements and suggestions related to the laboratory redesign. These were worked on in the integration phase. The findings of this analysis are summarized below.

The stakeholders emphasized the need for an improved layout and better organization in the laboratory. Suggestions were gathered from these stakeholders on how to achieve this. These provided insights into necessary requirements. Important aspects such as accessibility and sufficient workspace were highlighted. Stakeholders also expressed their preferences for better workflows. As different stakeholders were interviewed, there was a varied range of preferences regarding equipment placements and upgrades. These were all taken into account in later phases. The general consensus agreed on the need for more organized and accessible storage solutions. It was noted that some of the key challenges with current workflow are overcrowding, inefficient equipment placements and inadequate storage. Some suggestions also included better ventilations systems and better dust control measures throughout the laboratory.

The quantitative data gathered from the surveys was analysed using descriptive statistics. Although it is unconventional to gather quantitative data and use descriptive statistics for a project of this kind, the purpose of this was to provide numerical summaries of the preferences and responses of the stakeholders. Similarly, to the thematic analysis, it provided insights into the priorities and requirements of the stakeholders but more specifically, it provided a clear and numerical understanding of the preferences and opinions of the stakeholders. This is especially useful when assigning weightings during the MCDA process which took place in the model development phase. The descriptive statistic results are shown below and elaborated on.

Table 2

Descriptive statistics gathered from surveys.

	Average	Mode	Median	STDev
Current Layout and	3.36	3	3.5	0.99
Importance of Worksp	4.5	5	5	1.22
Importance of Storage	4.5	5	5	1.22
Importance of Equipm	3.83	5	5	1.83
Workflow Efficienc	3	2	3	0.89
Safety of Current Layout	3.93	5	4	1.1
Equipment Placeme	3	4	4	1.41
Easy Access to	4.33	5	5	0.82

The descriptive statistics gathered from students and faculty reveal valuable insights. On average, satisfaction with the current layout and functionality is at a medium level. Workspace size and storage areas are important topics according to the participants. Participants generally perceive workflow efficiency and safety positively. The satisfaction with equipment placement shows some variance however, it has a mean of 3 and a standard deviation of 1.41 which indicates diverse opinions among the participants. Easy access to equipment is also noted as a key factor in the redesign as it has a high mean and a relatively low standard deviation which indicates most participants feel similar about this issue. These statistics provide a numerical understanding of user perspectives which helps guide efforts to improve the lab space according to their needs.

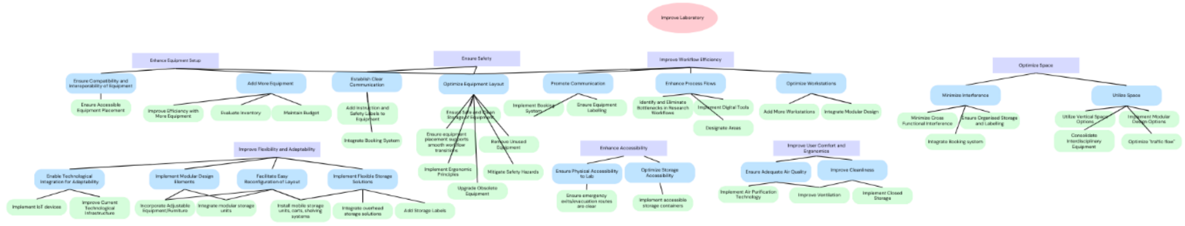
Finally, regulations, standards, and guidelines relevant to the research were analysed to identify requirements and other points of interest. The findings of this were reported in the literature review.

3.4. Integration

This phase concludes the analysis by integrating the findings from the analysis. These include recurring patterns in stakeholder preferences, requirements and needs, priorities, standards, and regulations among other crucial points. Using these findings, an objective tree was created which aided the creation of requirements afterwards. The objective tree is shown below in figure 2.

Figure 2

Objective Tree



The hierarchical structure of the objective tree allows for an insight into the key areas that need to be addressed to meet the project's objectives. The green levels represent detailed objectives. These detailed objectives were further translated into specific requirements that must be fulfilled. Using a systematic approach like this ensured that the requirements were aligned with the project's objectives and the stakeholders' goals.

With the stakeholders, their objectives and their interests having been identified, the requirements were collected in a requirements allocation sheet (RAS). Personal ideas and innovations were also considered during the formulation of objectives and requirements. This was ultimately a result of the observations noted during the data collection phase. The RAS is present in appendix 1.

To adequately formulate the requirements, the objective tree had been thoroughly understood. The objective tree's objectives were largely translated into requirements by thoroughly analysing it and cross-referencing it with knowledge from literature. requirements within the RAS were split into various categories. This was done to make it easier to monitor the status of various requirements and improves the ability to track project requirements.

These categories are shown below.

1. **Functional Requirements:**
    - Equipment functionality: Specify the functions and capabilities required for laboratory equipment to support research activities.
    - Workflow optimization: Define requirements for efficient and effective workflow processes within the lab space.
    - Safety features: Outline safety requirements for equipment, materials, and overall lab operations.
    - Environmental controls: Specify requirements for temperature, humidity, ventilation, and other environmental factors critical for lab operations.
2. **Space Requirements:**
    - Layout and organization: Define spatial requirements for workstations, storage areas, equipment placement, and traffic flow within the lab.
    - Flexibility and adaptability: Specify requirements for modular or flexible lab configurations to accommodate changing research needs.

- Accessibility: Ensure that the lab design meets accessibility standards for users with disabilities.

3. **Regulatory and Compliance Requirements:**
    - Health and safety regulations: Address compliance with relevant health and safety regulations and standards for laboratory facilities.
    - Environmental regulations: Consider requirements related to waste management, hazardous materials handling, and environmental sustainability.
    - Building codes: Ensure that the lab redesign complies with local building codes and regulations.
4. **User Requirements:**
    - Researcher needs: Capture requirements related to the specific research activities and workflows of lab users.
    - Stakeholder preferences: Consider input from stakeholders such as researchers, technicians, students, and faculty members regarding their preferences for the lab redesign.
5. **Technological Requirements:**
    - Integration with BIM software: Specify requirements for integrating Building Information Modelling (BIM) software like Revit for precise modelling of lab infrastructure.
    - Equipment compatibility: Ensure that the lab design accommodates the integration of existing and new equipment seamlessly.
    - Equipment that is generally required in the laboratory to conduct experiments.
6. **Operational Requirements:**
    - Maintenance and upkeep: Define requirements for easy maintenance, cleaning, and upkeep of lab equipment and infrastructure.
    - Energy efficiency: Include requirements for energy-efficient lighting, Heating, ventilation, and air conditioning (HVAC) systems, and equipment to reduce operational costs.
7. **Budget and Resource Constraints:**
    - Cost considerations: Specify budget constraints and cost-effective design solutions to ensure economic viability.
    - Resource availability: Consider limitations in terms of time, budget, and availability of equipment or materials for the redesign project.

The creation of the RAS allows for the development of a redesign that meets all the necessary needs and requirements.

3.5. Model Development

To ensure that the best possible model is created and selected, several alternative designs were modelled. This was done using a multi-criteria decision analysis (MCDA) process. The importance of the alternatives lies in the fact that they promote creative thinking and the exploration of unique designs that may consist of different solutions. Thus, the alternatives were modelled in detail to ensure that a proper overview of each alternative was possible.

The modelling of the alternatives itself was performed using Revit and BIM principles. The usage of BIM allows for precise modelling of laboratory infrastructures and layouts. Software such as Revit provided the necessary tools to undergo this BIM process and effectively create a 3D model of the alternative designs. However, Revit does not have the tools for the modelling of equipment and furniture, it only facilitates the assembly of the whole design by incorporating all the equipment and furniture together in one model. Therefore, to model detailed equipment and furniture, Autodesk Fusion 360 was used.

An issue that arose during the model development is the simplification of some model aspects. Some aspects had to be simplified in order to manage software limitations, reduce complexity, and ensure efficient processing and rendering. When it comes to software limitations, Revit presented a significant amount of them. Revit works with a “family” system which are models and data that represent building components. These components are particularly useful due to the data that accompanies each model. Using these families, an efficient and realistic BIM model can be created. The issue that presented itself during this research was the fact that the family system was complex to use as well as the fact that many items in the lab did not have detailed information about them. Revit families from the internet often included additional costs as well as specific use licenses that prevented their implementation in this project. Therefore, these could often not be used. As a result, the models had to be created manually using Fusion 360. The issue with this was that the models were less detailed and did not have the accompanying data. Therefore, a fully functional BIM process was not possible. However, as this research had a larger focus on spatial design, the aforementioned limitations proved to be acceptable.

Some of the 3D modelled equipment were reused from the model created by Vahdatikhaki et al. (2023). This was done with permission from the researcher. The reused items include the concrete mixer as well as the scale.

3.5.1. Modelling

The first step was to model the current model. This was performed in earlier stages in order to utilize the current model to aid the creation of objectives and requirements. Additionally, it served as a baseplate for the redesign models that would be created afterwards.

To create a replica of the current layout of the laboratory, the room dimensions had to be computed. This had to be done manually by using a tape measurer as the exact dimensions were not known. The use of a tape measurer allows for accurate measurements regarding smaller areas or specific objects; however, the measurements are still prone to human error. This means that most measurements have an uncertainty of ±7.2 cm.

When these measurements were taken, the walls, flooring and infrastructure in the lab were modelled. This created an empty lab space which was used as the baseplate for all the models. The equipment and furniture were modelled into this baseplate and were finished. The 2D and 3D overviews of the models can be found in the figures below.

Some common implementations that all the alternative redesigns included are the following. All the designs had to ensure that no items are elevated higher than 2 meters. This was to ensure the proper functioning of the sprinkler system. All the storage solutions should have labels as well. This was not modelled in as it would be considerably time-consuming, but it is included in the RAS. A sanding dust table and a fume chamber were included in all the redesigns as well. These are implementations that were highly desired by the researchers. Therefore, it was important to include these in all the redesigns.

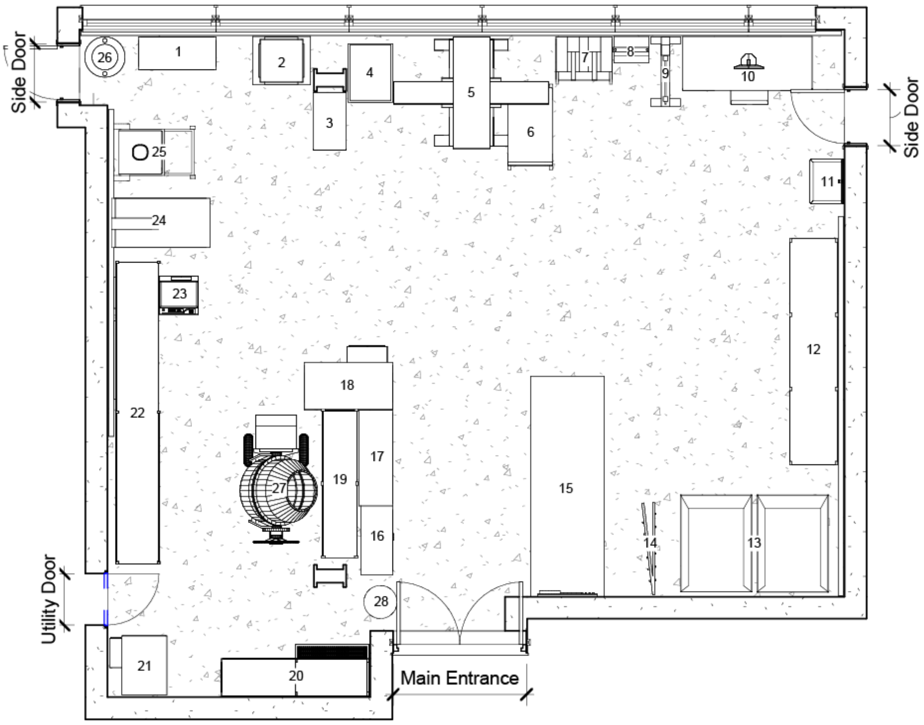
During the modelling phase, most of the newer equipment and items were gathered from kaiserkraft.nl. The reason for this is that this provider displays sustainability performances of all their items. This is particularly useful when trying to implement sustainable practices in the design as it allows for quick overviews of the sustainability of a certain item. The sustainability performance is measured using 5 categories: circular economy, climate protection, biodiversity, economic responsibility, and innovation (Kaiserkraft, 2024). These criteria are ranked and an overall score of the item is determined. This study used this information to select the best possible items available. The sustainability performance scores are from 1 to 5.9, with 3 being considered sustainable. Therefore, most of the new items implemented in the redesign models had to have a score of 3 or higher.

An important note is that the bending test machine in the middle of the lab was previously explained to be unused in the lab. It takes up a lot of space. However, due to the fact that the university has no other place to store this machine, it has to remain in place. It would also cost a lot to move equipment of that size.

3.5.1.1 Current Status Model

Figure 3

2D Overview of The Current Status of the Lab



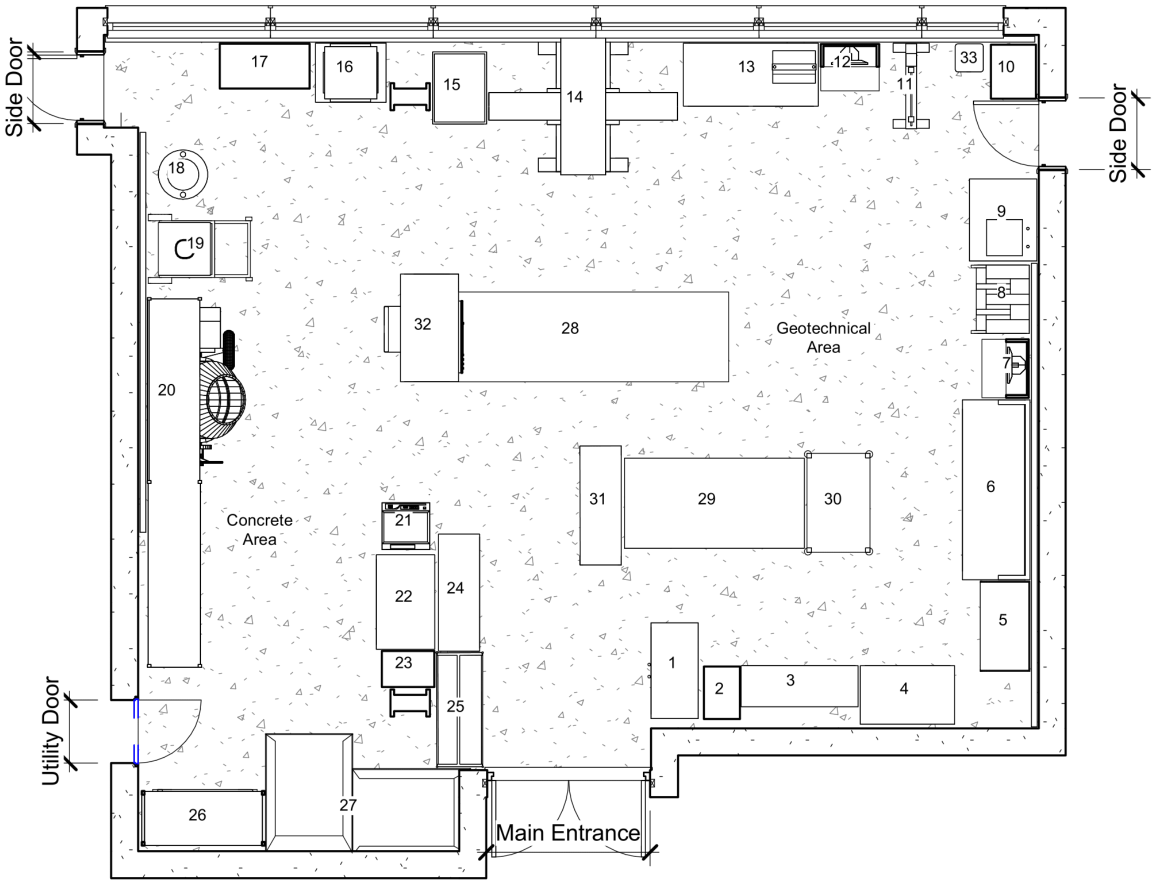
1. Shelf for Sieve Equipment
2. Compression Strength Testing Machine
3. Drawer Unit
4. Computer Bending Test Machine
5. Bending Test Machine
6. Trolley (Under Bending Test Machine)
7. Oedometer
8. Load Frame (Triaxial)
9. Direct Shear Test
10. Desk with Desktop Computer
11. Sink
12. Geotechnical Shelf
13. Curing Tanks
14. Tool Holder
15. Workbench with Vacuum Device
16. Cabinet
17. Cabinet
18. Workbench
19. Small Concrete Shelf
20. Boot Shelf
21. Red Oven
22. Large Shelf with Oven
23. Scale
24. Masonry Saw
25. Dust Collector
26. Sieve Shaker Machine
27. Concrete Mixer
28. Coat Hanger

The 2D overview of the current status of the lab is shown above. The 3D model is shown in appendix 2.

3.5.1.2 Alternative Model 1

Figure 4

2D Overview of Alternative Model 1



1. Oven
2. Small Cabinet Unit
3. Cabinet
4. Material Storage Cabinet
5. Sanding Dust Table
6. Workbench
7. Computer Workstation
8. Oedometer
9. New Sink
10. File Cabinet
11. Direct Shear Test
12. Computer Workstation
13. Workbench with Load Frame (Triaxial)
14. Bending Test Machine
15. Bending Test Machine Computer
16. Compression Strength Testing Machine
17. Cabinet
18. Sieve Shaker Machine
19. Dust Collector
20. Shelf with Concrete Mixer under it
21. Scale
22. Material Storage Cabinet
23. Small Cabinet Unit
24. Cabinet
25. Coat Rack + Boot Storage
26. Shelf with Trolley under it
27. Curing Tanks
28. Large Workbench
29. Workbench
30. Fume Chamber
31. Mobile Toolbox
32. Workbench
33. Air Purifier

The 2D overview of the alternative 1 redesign is shown above. The 3D model is shown in appendix 2. The design philosophy behind this alternative redesign model was to maximize the utilization of free space and workflow throughout the laboratory. Several key actions were taken to achieve this. These are explained as follows.

The implementation of a workbench with a vertical tool rack helps in the organization of tools and smaller equipment in a vertical position. This helps with freeing up horizontal space on the workbench itself and provides more space for certain items, so they do not end up cluttering the workbenches or floors. Additionally, most open storage shelves were removed. These were mostly replaced with lockable cabinets. This helps with the organization and efficiency of the lab as it provides a designated place for storing items and it also reduces clutter which helps maintain a clean and efficient laboratory.

The necessity for closed cabinets was considered due to safety concerns. Closed cabinets help meet regulatory requirements for storing chemicals and other potential hazards. It ensures that only authorized people can use the equipment needed which aids in maintaining a safe environment. Vertical space storage solutions were implemented through the use of cupboards. This ensures that the floor space remains uncluttered, and the vertical space is utilized effectively.

The placement of equipment was planned in positions that prevent the need to make long transitions between each piece of equipment. For example, the three geotechnical tests can be run in parallel with the layout in this alternative redesign. A major change is the removal of the boot rack in the concrete section of the laboratory. The interviews with stakeholders revealed that this took up a lot of space and was not necessary in the lab. It was replaced with a mobile coat + boot rack which takes up less space and can have its position reconfigured due to its mobility. The curing tanks were placed in the freed-up space. This is what allowed for the major reconfiguration of the geotechnical area.

The workbenches were setup horizontally. The idea behind this is to optimize workflow. By placing the workbenches horizontally in the middle of the lab, equal access from all sides is provided. This reduces the distance needed to travel between workstations. Additionally, the central layout of this redesign creates clear pathways around the laboratory which helps facilitate smooth travel throughout the laboratory.

Additionally, this design aspect ensures that the lab does not become too crowded in one certain area by distributing most of the equipment across the space while maintaining the capabilities for smooth workflow. In case more space is required or there is a need for a slight reconfiguration of the laboratory, items 31, 29 and 30 are all mobile which means they can be moved around the lab for various reasons. As a result, this layout supports flexibility in how the laboratory space is used.

Another design choice was to move the oven to a more central position. The purpose of this was to improve workflow and provide quick access to the oven. The central positioning of the oven allows for both researchers engaged in both areas of research to access the oven more conveniently. One concern that may arise from this changed position is the heat management from the oven. As it is located quite close to the main entrance, it might be inconvenient to have the oven situated there as a hot oven might present some safety concerns. For instance, the main entrance could be crowded during experiments involving several students or researchers. Having the oven turned on around a crowd of people might result in discomfort and safety concerns.

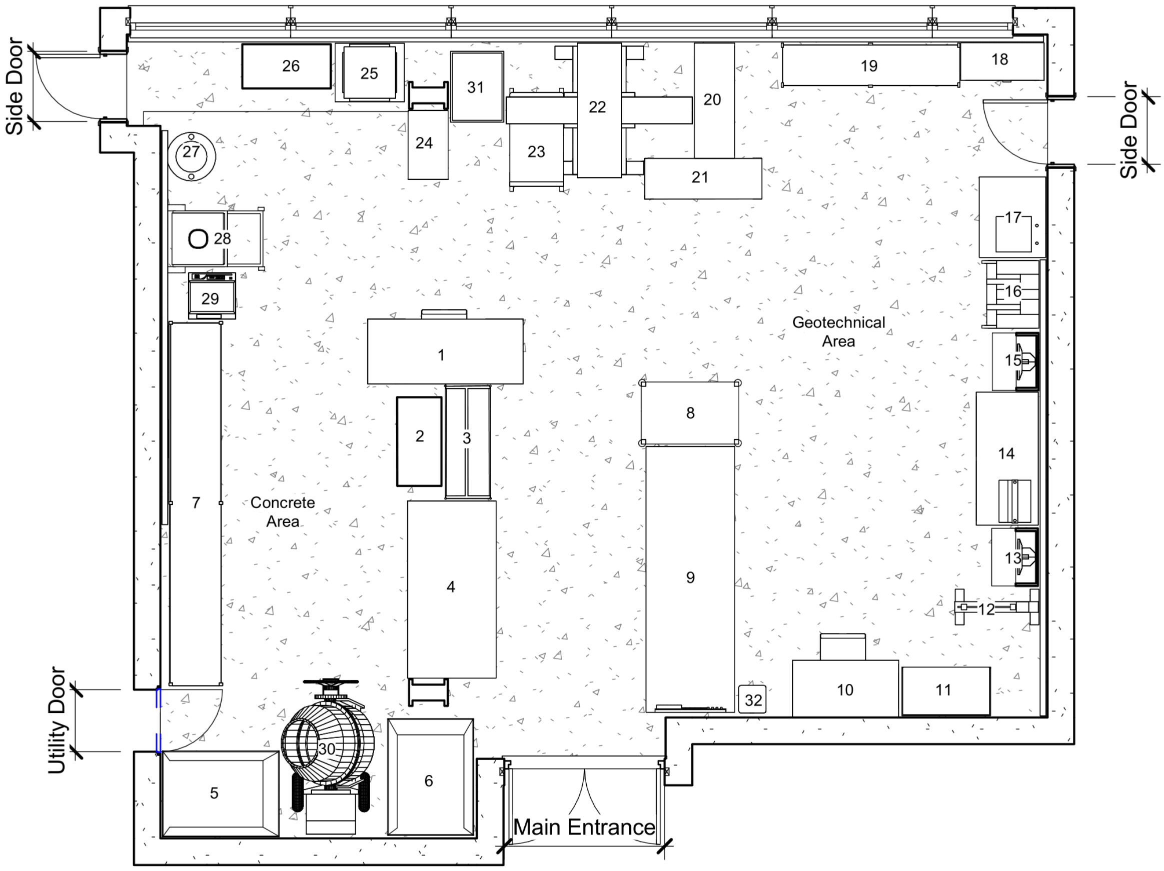
For the management of dust and overall air quality in the laboratory, dust collection table inserts are implemented into two of the workbenches (6 & 28). The reason for the exclusion of the mobile workbench for this table insert is the fact that there might be issues with the accessibility of power outlets when the workbench is moved to other locations. Additional measures to prevent dust build up are the inclusion of a sanding dust table and an air purifier. The sanding dust table is a specialized workstation specifically designed to capture dust and other debris during experiments and operations that can generate a lot of sand and debris. The air purifier ensures that contaminants are removed from the indoor laboratory air to improve air quality. It removes particulate matter using HEPA filter technology which can trap particles with a high degree of efficiency. The particular model used in the design also has smart monitoring technology which allows for functionalities such as light recognition and the reduction of the ventilation and power usage when the lights are out. As such, this contributes to the overall air quality in the laboratory and the specific product also is sustainable.

Ultimately, the preliminary costs of implementing this design were estimated at € 34,428.95. The calculations as well as the list of the new items can be found in appendix 4. This is the most the most expensive model out of the three.

3.5.1.2 Alternative Model 2

Figure 5

2D Overview of Alternative Model 2



1. Desk
2. Cabinet
3. Coat Rack + Boot Storage
4. Workbench
5. Curing Tank
6. Curing Tank
7. Shelf with Oven under it
8. Fume Chamber
9. Workbench
10. Workbench
11. Sanding Dust Table
12. Direct Shear Test
13. Computer Workstation
14. Workbench with Load Frame (triaxial)
15. Computer Workstation
16. Oedometer
17. New Sink
18. Cabinet
19. Shelf
20. Cabinet
21. Mobile Toolbox
22. Bending Test Machine
23. Trolley
24. Drawer Unit
25. Compression Strength Testing Machine
26. Cabinet
27. Sieve Shaker Machine
28. Dust Collector
29. Weighing Scale
30. Concrete Mixer
31. Bending Test Machine Computer
32. Air Purifier

The 2D overview of the alternative 2 redesign is shown above. The 3D model is shown in appendix 2. The design philosophy behind this redesign model was to be as sustainable as possible by reusing as many old items and equipment as possible. Additionally, in this alternative, the zoning for specific research activities is clearer compared to alternative 1.

As mentioned, the main idea of this redesign was to create a low-cost and sustainable design that still achieves all its goals. This approach to the redesign will minimize waste, reduce the environmental impact of a massive redesign, and maximise the lifecycle of the laboratory layout and its items.

The key elements of the redesign are described as follows:

The reuse of existing equipment and furniture allows for cost-friendly solutions. For example, the workbenches and desks. The large workbench (9) stays where it is in the current status of the lab. As the workbench is still functional and does not present any issues, it was not deemed necessary to change the position of this workbench. Additionally, as it is a heavy, large, immobile piece of furniture in the lab, it would be quite costly to remove it and store it somewhere in the university.

Current shelves and cabinets are reorganized and reincorporated into design. The shelf in the concrete section remained in place as it provided an effective way of storing aggregates. Many of the other open shelves were removed or moved to distinct positions in the laboratory. The reuse of all these storage solutions provides adequate storage within the lab without the need for new purchases. This keeps the redesign sustainable and keeps the costs low. Similarly, all functional lab equipment such as ovens and testing machines are kept and incorporated into the new design.

Some new shelves were incorporated into the design to ensure the availability of safe and secure storage. This is necessary for, for example, chemicals which need to be organised and stored in safe locations, instead of all around the laboratory. Additionally, cleaning equipment is stored vertically using a clamp system. This ensures that floor space is not taken up. Similarly, industrial-grade cupboards are implemented in order to utilize the free vertical space for storage purposes.

The zoning division was not significantly changed from the original layout. If this redesign stuck too closely to the original design, it would encounter similar concerns and problems again. To avoid this, measures to optimize workflow, space utilization, flexibility and safety considerations were implemented.

An innovative design choice was to consider the bending test machine as a static part of the laboratory infrastructure. This was done due to the fact that this machine is not used. However, the removal of this machine would be too costly due to the machine's large size and the lack of storage space for it within the university. Therefore, keeping the machine is the best option. In figure 5 it can be clearly seen how storage units and the trolley are placed around the bending test machine. Machinery and equipment were not placed around the bending test machine as the electrical outlets would not be accessible from there.

The positioning of the oven in this design remained the same. The idea behind this is that the design cannot efficiently accommodate a central oven position without posing safety risks. It remains located in the concrete area which decreases workflow efficiency for the geotechnical researchers. However, the oven is not used over a long period, and it does not need to be attended to when using it. Therefore, according to this redesign's design philosophy, the positioning of the oven is justified by the fact that it will not affect workflow efficiency significantly due to the aforementioned reasons.

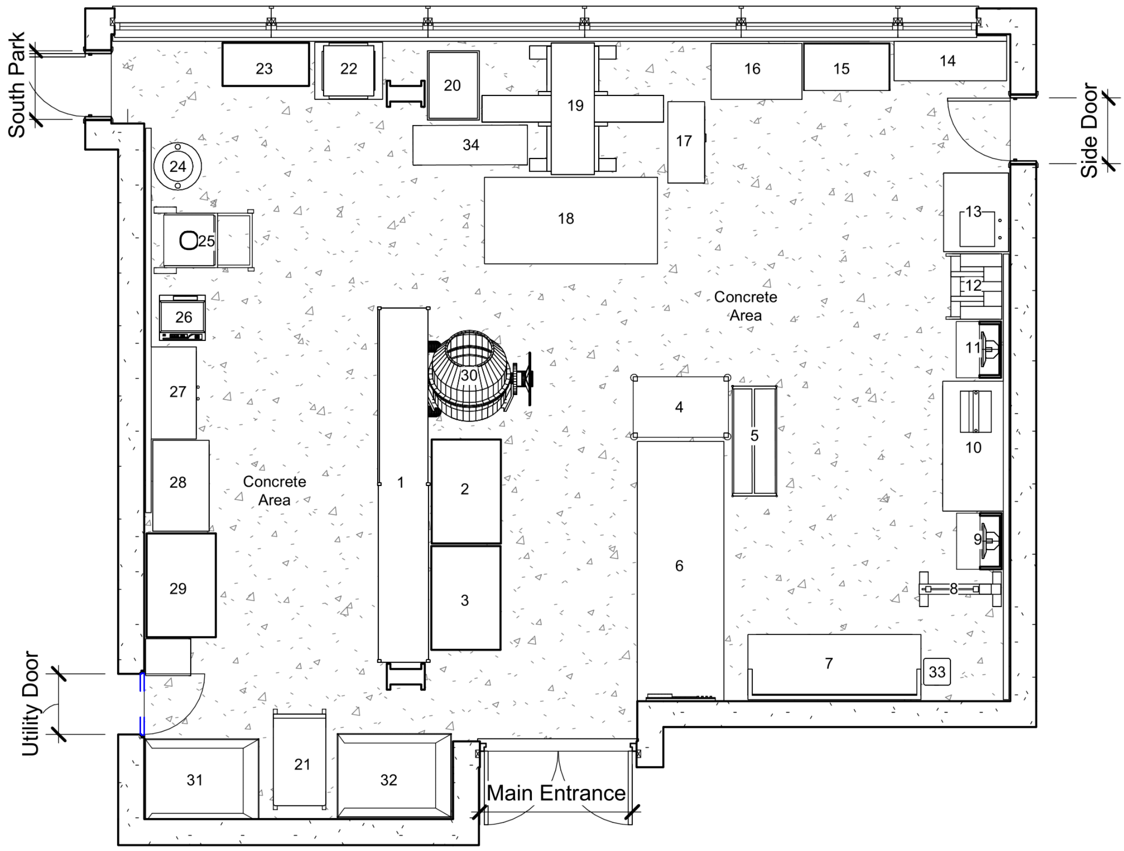
This redesign provides a mobile workbench in the concrete area. This provides an adaptable workspace in that area as the space can be quickly freed up if necessary. Additionally, by placing the mobile workbench in the concrete area, researchers have access to a workspace while reducing the time spent moving between different areas of the lab.

For the management of dust and overall air quality in the laboratory, a dust collection table insert is implemented into the fixed workbench (9). Similarly to alternative 1, an air purifier is also included for the same reason.

Ultimately, the preliminary costs of implementing this design were estimated at € 26,889.9. The calculations as well as the list of the new items can be found in appendix 4. This is the lowest-cost model out of the three.

Figure 6

2D Overview of Alternative Model 3



1. Shelf
2. XL Cabinet
3. XL Cabinet

17. Cabinet
18. Workbench
19. Bending Test Machine

4. Fume Chamber
5. Coat Rack + Boot Storage
6. Workbench
7. Workbench
8. Direct Shear Test
9. Computer Workstation
10. Workbench with Load Frame (Triaxial)
11. Computer Workstation
12. Oedometer
13. New Sink
14. Cabinet
15. Sanding Dust Table
16. Material Storage Cabinet
20. Bending Test Machine Computer
21. Trolley
22. Compression Strength Testing Machine
23. Cabinet
24. Sieve Shaker Machine
25. Dust Collector
26. Weighing Scale
27. Oven
28. Material Storage Cabinet
29. XL Cabinet
30. Concrete Mixer
31. Curing Tank
32. Curing Tank
33. Air Purifier
34. Mobile Toolbox

The 2D overview of the alternative 3 redesign is shown above. The 3D model is shown in appendix 2.

The design philosophy behind the third alternative redesign model was to use the space innovatively, including the removal of unused equipment and optimizing the placement of important equipment. It aims to optimize the workflow of research by ensuring that there are smooth transitions between equipment during research activities. The key activities conducted in this design are described below.

A key focus of this redesign was to declutter the laboratory. By moving or removing all outdated and unused equipment, valuable floor space is freed up. This creates a more open and organized lab space which improves workflow as it becomes easier to move around. Additionally, the free space allows for more strategic placements of equipment and items.

Equipment is placed strategically to minimize the distance needed to travel between different workstations. An example of this is the shelf in the concrete area. It was moved from the wall to a more central position. This allows the concrete mixer to have a dedicated spot as well as the mobility to move it around. Cabinets were placed against the shelf itself in order to prevent items from falling out from the other side. This aids the safety of the lab. Another example is the placement of the three geotechnical tests. The oedometer is placed right next to the water supply which allows it to be used in parallel with the other two tests.

Similar to alternative 2, the oven remains located in the concrete area. This is due to the same reason as alternative 2. Placing it in a central position in this redesign would pose safety risks.

There are several workbenches including the sanding table located in the geotechnical area. There is a mobile workbench placed in the middle of the lab which is primarily meant for the concrete section. The mobility of this workbench allows for flexibility in the usage of the lab space and usage of the table. However, this workbench is still in a slightly inconvenient position for the concrete area, regardless of it being mobile. The lack of convenient and accessible workspace for the concrete area presents issues in workflow efficiency. This is not the case for the geotechnical area where it is improved on significantly.

The organisation of storage in this redesign is a significant improvement over the original state of it. The workbench in the geotechnical area (7) includes a rack which allows for more vertical storage options. Additionally, similar to the other redesign, industrial cupboards are added to make use of free wall space. This approach to storage helps keep the floors free from clutter. Additionally, industrial-grade cabinets are used in order to ensure compliance with safety regulations and prevent accidents. For example, the concrete area often uses different chemicals during concrete mixing, these have to be stored in secure locations. These cabinets are also lockable which ensures that items do not suddenly go missing. Finally, when it comes to cleaning equipment, a vertical clamp system is used to keep brooms and other similar items in an organised position while not taking up floor space.

Ultimately, the preliminary costs of implementing this design were estimated at € 31,225.9. The calculations as well as the list of the new items can be found in appendix 4. This is a relatively high cost but not the highest.

3.5.2 MCDA Process

The first step is to score the alternative design based on the previously established criteria. These criteria were essentially created during the preparation phase and their weightings are the average survey's rankings of the interview participants. The criteria are elaborated on below and their weightings are shown below. The calculation of the weightings can be found in appendix 3.

1. **Layout and Functionality – 0.124**

This criterion measures how the layout supports the lab's activities. This includes ease of movement and useability of the redesigned lab space.

2. **Workspace Size – 0.166**

This criterion assesses whether the redesign provides adequate workspace size for conducting experiments. Ideal spatial usage should improve productivity and reduce crowding.

3. **Organisation of Storage Areas – 0.166**

This criterion evaluates the effectiveness of the storage capabilities of the redesign. Good storage solutions should maintain order, safety, and efficiency within the lab space.

4. **Equipment Placement – 0.141**

This criterion assesses the effectiveness of equipment placement in the redesign. Optimal equipment placement should reduce the need for excessive movement, minimize hazards and streamline workflow.

5. **Workflow Efficiency – 0.141**

This criterion assesses how the redesign supports efficient workflow. It considers the ease of transition between tasks, minimizing bottlenecks and maintaining a logical flow of activities.

6. **Safety – 0.111**

This criterion evaluates the safety improvements in the redesign. It considers mainly considers safe equipment placement and dust solutions.

7. **Cost – 0.148**

This criterion assesses the financial aspect of the redesign, focusing on the cost and efficient allocation of resources. It evaluates if the costs have a good value for money as the cost will have to be justified for the university.

The next step was to score the alternatives based on the previously established criteria. The scoring was done using a range of 1 to 5, with 1 being the worst and 5 being the highest possible score. The total scores are ultimately calculated by multiplying each criterion's score by its weight and summing up these results for each alternative.

Table 3
MCDA Analysis

Criteria	**Weight**	**Alternative 1**	**Alternative 2**	**Alternative 3**
Layout and Functionality	0.124	4	3	3
Workspace Size	0.166	4	5	3
Organisation of Storage Areas	0.166	3	5	4
Equipment Placement	0.141	4	3	5
Workflow Efficiency	0.141	5	4	4
Safety	0.111	3	4	5
Cost	0.148	3	5	3
Total Score	1	3.702	4.203	3.803

Based on the provided weight and scores, alternative 2 ends up with the highest total score. This means that alternative 2 which focuses on sustainable design and reusing as many old items as possible, is the best design according to the given criteria and weights. It performs particularly well in terms of workspace size, organization of storage areas and especially cost. However, this redesign does lack in other areas and lacks much innovation and new ideas.

3.6. Validation

The validation was carried out in different ways. Part of it was conducted during the model development when a final redesign model was not chosen yet. This was conducted by gathering stakeholder feedback on the three redesign models. By involving stakeholders in the validation of these models, it was ensured that the proposed solutions met the needs and requirements of the stakeholders. Additionally, by gathering the feedback of stakeholders such as researchers and faculty, the operational needs and feasibility of the design can be ensured. This is because of the fact that these stakeholders have an extensive knowledge about the issues and the setup of the laboratory.

Initially, during the model development phase. The curing tanks were placed in locations that would not have been feasible in reality. The reason for this was that there was no drainage in those areas. Therefore, this was an important point of improvement to ensure that the redesign option remain feasible. Additionally, a major point of improvement pointed out by the stakeholders was that the oedometer had to be connected to water somehow. In some of the redesigns, the oedometer was located in areas that would in theory have been workflow efficient. However, they were not close to the sink at all. This would lead to major issues in the operability of this equipment. To solve this problem, the oedometers were placed closer to the sink in all three redesigns.

Other examples of laboratories were used to evaluate the design's performance against already existing lab spaces with similar functions. For this research, the laboratory design created by Santoso et al. (2022) was used. Not only was the selected redesign validated but also the redesign process. By validating both aspects of the research conducted in this report, the viability of both are supported. It is important to note that due to the different purposes, requirements, and space dimensions. The laboratory in Santoso's study has two floors and is considerably spacious compared to the space in this research. Therefore, validation is mainly focused on the design implementations, ideas and outcomes.

The process presented in this report follows a systematic approach that integrates stakeholder feedback, creates useful visual aids both 3D and 2D. The phases that this research used were stated in chapter 3's introduction. This approach is relatively in line with the process used in the Santoso study which involves Analysis, Design, Development, Implementation and Evaluation phases to ensure that the best possible design is created. By adopting a similar structured methodology, the redesign process ensured that functionality and user satisfaction is achieved, similar to the outcomes achieved in the Santoso study.

When it comes to the designs themselves, the chosen redesign in this research (alternative 2) had an emphasis on sustainable design and efficiency space utilization. This was achieved with equipment placements that would improve workflow efficiency and modular equipment and items. The laboratory can be reconfigured to accommodate different user needs and free up space if necessary. Similarly, the Santoso design was designed to optimize space through the consideration of dimensions of equipment and equipment placements. Both designs have a focus on maximizing space efficiency and ensuring accessibility for its users. The similarity in the design implementations supports the feasibility and viability of the alternative 2 design as the outcomes of the Santoso study were successful with their implementations.

The alternative 2 redesign can be characterised by its user-centric design approach as it heavily involved the feedback from stakeholders to ensure that the laboratory meets the needs of its stakeholders. Similarly, the Santoso study included surveys and Focus Group Discussions (FGD) to collect data on the stakeholders' needs and requirements. Both the designs demonstrate a thorough understanding of the stakeholders' needs and requirements.

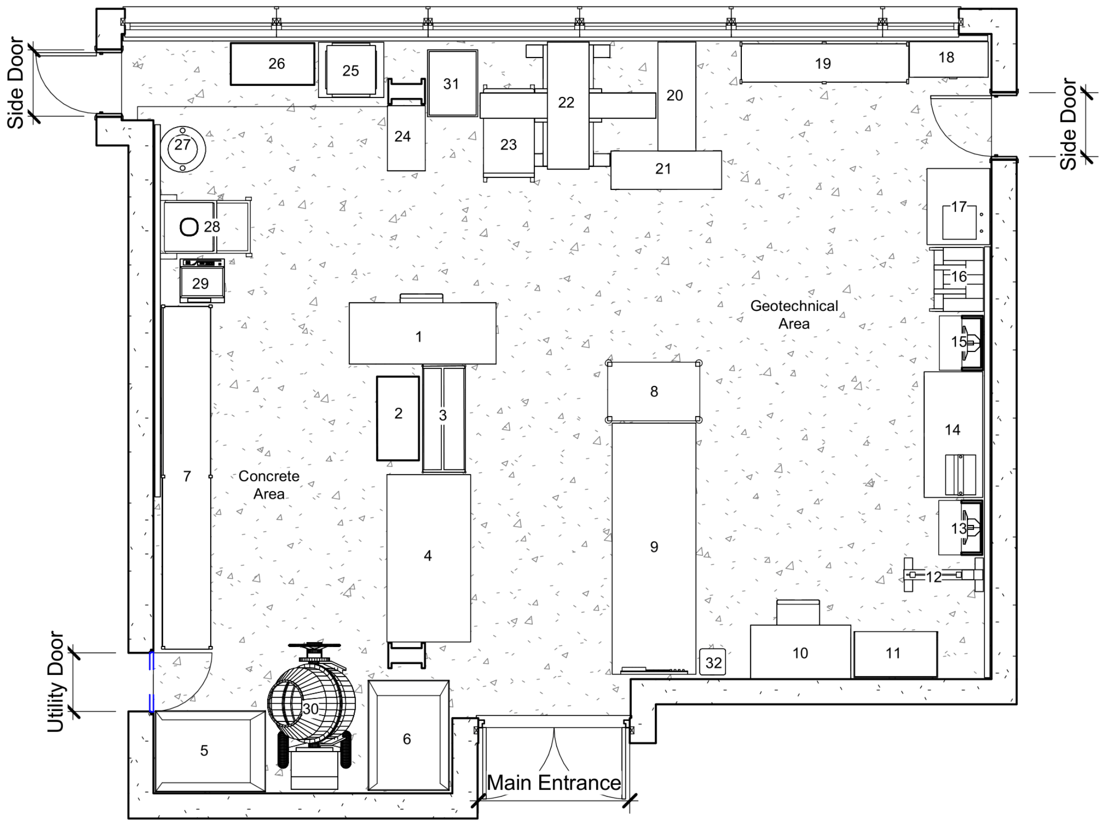
Overall, the alternative 2 redesign can be validated adequately due to its alignment with the successful design solution presented in the Santoso study. Both these designs prioritize effective spatial usage, safety, functionality and user-centric design approaches. With the similarities to the Santoso study, the alternative 2 redesign demonstrates a viable design solution.

4. Results

To finalise the research, the findings are synthesized clearly and transparently below. Additionally, the chosen design is reflected upon, and the results are synthesized into actionable insights and recommendations for the lab redesign. This is a culmination of the research phases where information and data were collected and analysed, the model was developed, etc.

Figure 7

2D Overview of Alternative 2



1. Desk
2. Cabinet
3. Coat Rack + Boot Storage
4. Workbench
5. Curing Tank
6. Curing Tank
7. Shelf with Oven under it
8. Fume Chamber
9. Workbench
10. Workbench
11. Sanding Dust Table
12. Direct Shear Test
13. Computer Workstation
14. Workbench with Load Frame (triaxial)
15. Computer Workstation
16. Oedometer
17. New Sink
18. Cabinet
19. Shelf
20. Cabinet
21. Mobile Toolbox
22. Bending Test Machine
23. Trolley
24. Drawer Unit
25. Compression Strength Testing Machine
26. Cabinet
27. Sieve Shaker Machine
28. Dust Collector
29. Weighing Scale
30. Concrete Mixer

31. Bending Test Machine Computer
32. Air Purifier

The selected redesign model was alternative 2. The 2D overview is shown in Figure 7 and the 3D overview is shown in appendix 2. The optimal redesign was determined after an MCDA process. The MCDA process involved scoring alternative designs based on established criteria and weightings derived from stakeholder surveys. To summarize, alternative 1 had a score of 3.702, alternative 2 had a score of 4.203 and alternative 3 had a score of 3.803. As alternative 2 had the highest score, it meant that it aligns most closely with project objectives, stakeholder needs and requirements and other operational requirements, making it the best choice for implementation.

To understand why this was deemed the best alternative redesign option, a comparative analysis is carried out. Alternative 2 will be compared against the other two alternatives.

Workspace Size

Alternative 2 provides workbenches in both research areas while still maintaining plenty of free floor space. Alternative 1 has an adequate number of workbenches as well. However, the locations of the workbenches are skewed more towards the geotechnical side of the laboratory. It still accounts for this with the implementation of a mobile workbench that in theory could be moved closer to the concrete area. This still causes the issue of insufficient free floorspace. Even though the workbench is mobile, alternative 1's design takes up a lot freer space compared to alternative 2. Alternative 3 does not have a workbench close to the concrete area. The mobile workbench for the concrete research group is in an awkward position, right in front of the bend testing machine. For the reasons, alternative 2 is the better option in terms of workspace size and spatial optimisation.

Organisation of Storage Areas

Alternative 2 demonstrated unremarkable but efficient storage organization. It includes some pre-existing cabinetry as well as shelving. Like the other alternatives, it adds a mobile toolbox. For cleaning tools such as brooms and mops, there is a clamp system on the wall which can hold these tools. Alternative 1 lack this and alternative 3 has it as well. All alternative designs utilize the wall space for storage using cupboards. Ultimately, the organisation of the storage areas in alternative 2 is an improvement, however, alternative 1 and 3 offer newer models for cabinets which adhere closer to the requirements than alternative 2.

Cost-Effectiveness

Alternative 2 was considered the most cost-effective design as it had the lowest preliminary costs. These were calculated in appendix 4. Alternative 1 and 3 both had significantly higher costs associated with their designs. As a result, alternative 2 is deemed much more cost effective while still meeting functional requirements.

Ultimately, the selection of this model as the preferred design for the WH114 laboratory at the University of Twente reflects the stakeholders' wishes for functionality and cost-effectiveness. It also addresses and solves many of the concerns the stakeholders had about the current state of the laboratory. It seems that the cost-effectiveness of the design is the main selling point and the main reason why it was deemed the best design choice in the MCDA process.

Ultimately, this study has resulted in the following insights and recommendations.

Firstly, the incorporation of modular elements within a lab space allows for easy adaptation to changing research needs which promoted flexibility and adaptability within a laboratory. Furthermore, storage solutions such as cupboard or closeable cabinetry can be used to maximise space utilization and improve safety. Additionally, user-centric design improvements can ensure that a design meets specific needs and preferences of relevant stakeholders. The usage of modular workstations led to significant improvements in the spatial planning of the laboratory and in turn, enhances workflow efficiency and safety. It was not only modular workstations that led to these results but also improved equipment placements. Utilizing a 3D modelling based approach is recommended for other redesign project similar to this one. The 3D modelling approach aided with planning and visual interpretations. For instance, the vertical space solutions could not have been adequately planned without the use of the aforementioned approach. To summarize, the 3D modelling approach allows for efficient and effective spatial planning which would not be possible in a 2D based approach.

5. Discussion/Recommendations

The redesign of the laboratory aimed to address key issues that were present in the current laboratory. This research aimed to create an optimal design by approaching the design and decision-making using a 3D modelling approach. The main research question for this research was *"How can the spatial layout of Laboratory WH114 be optimized to maximize efficiency and accessibility for both concrete design and production as well as geotechnical analysis and testing?"*.

The sub-questions were *"What are the specific spatial requirements for each activity involved in concrete design and geotechnical analysis, and how do they differ?"*, *"How can feedback from researchers and stakeholders involved in concrete design geotechnical analysis inform the iterative refinement of the spatial layout to better meet their needs and preferences?"* and *''How can 3D modelling be utilized to aid with spatial design?"*.

Preparation

The preparation/situation analysis phase in this project played a significant role in creating the foundation for the subsequent phases of the methodology. For example, by clearly delineating the boundaries of the research, a focused and feasible approach to the rest of the research was ensured. The stakeholder analysis was arguably one of the most important aspects of this phase as well. The perspectives and requirements gathered from these stakeholders informed the most important aspects of the design. Therefore, it was important to conduct a thorough stakeholder analysis. An area of improvement could have been that the stakeholder analysis could have used more detailed categorization of stakeholders accompanied with a more thorough analysis of their wants and needs.

The SWOT analysis was conducted as part of the situational analysis. This provided valuable insights into the current state of the laboratory. This SWOT analysis could have been more comprehensive by involving a wider range of perspectives to identify the strengths, weaknesses, opportunities, and threats. This could have been done by involving some of the identified stakeholders.

Data Collection

The data collection phase arguably was the most important phase. It involved gathering information from stakeholders using interviews, surveys as well as observations. It is considered to be a critical phase as it informed the redesign process.

One of the strengths of this phase was the utilization of semi-structured interviews. This allowed for open-ended responses and more in-depth insights into the laboratory space and its stakeholders. Additionally, conducting the short surveys after the interviews provided data that complemented the qualitative findings. This allowed for a more comprehensive understanding about the current situation in the laboratory. However, there are several areas of improvement. For example, a larger and more diverse sample of interviewees would have ensured a broader representation of perspectives and requirements. The number of interviewees was rather low. Additionally, conducting the surveys directly after the semi-structured interviews led to confusions with some of the interviewees. Some of them answered the survey questions as if they were open ended questions. This led to some survey data lacking as they were answered qualitatively and not quantitatively. Additionally, the survey questions could have been better if they included questions regarding cost and sustainability. No data was gathered regarding these topics, although they are an important aspect of the redesigns. This is a major point of improvement.

Integration

The integration phase synthesised and utilized the gathered data to inform the redesign process of the laboratory. One of the strengths of this was the systematic analysis of priorities, requirements, and suggestions for the laboratory redesign. This allowed for the input of stakeholder preferences, standards, and guidelines.

However, there are several points of improvement in this phase as well. The incorporation of an MCDA framework with the prioritization of requirements. This would have resulted in formalized system for the prioritization of requirements based on stakeholder preferences and requirements. Implementing such a system would have provided a more systematic and formal approach to the selection of design solutions.

Additionally, the documentation of this phase could have been significantly improved on. Documenting in detail how stakeholder preferences and requirements were ultimately translated into design requirements would have provided stakeholders with transparent explanations into how their preferences were incorporated into the final design. This would have undoubtedly helped with the pitching of the redesign.

Overall, by addressing these areas for improvement, the system for the redesign of a laboratory can be more structured and collaborative.

Model Development

As mentioned, a significant aspect of this research was the utilization of 3D modelling to visualize and plan the redesign of the laboratory. This approach aided spatial design in numerous ways.

For instance, the visual representation allowed for a clear and detailed visual representation of each alternative design. This helped the understanding of spatial arrangements in this design and the potential impact of them. Additionally, well-defined, and presentable models allow for better communication with stakeholders. It allowed for interactive discussions of the models where feedback could be quickly implemented to refine the design.

The 3D modelling based approach allowed for enhanced precision in creating designs. High levels of detail are crucial for ensuring that functional requirements such as safety standards and equipment placement are met accurately and adequately. Additionally, this approach can be considered to be cost-effective as it allows for the identification of issues virtually rather than physically. This was partly done in the case of the current state model. The 3D modelling approach identifies issues and helps avoid mistakes as scenarios can be tested for feasibility. This pre-emptive problem-solving capability of this approach can help keep projects within a certain time frame and budget.

This answers the sub-question of ‘’How can 3D modelling be utilized to aid with spatial design?’’.

However, while this approach offers several benefits, there are also several disadvantages that were noted. The first being that the approach is cost and resource intensive. The software itself is not accessible to everyone. Without special licenses such as student licenses, the required software can be expensive, requiring a significant investment. This can be a significant limiting factor in budget management as just 1 year of a Revit subscription costs € 3.358 for 1 user (Autodesk, 2021). Additionally, the hardware requirements make it so that a high-performance computer is needed to manage complex models, which also requires time and financial resources.

The model creation process is rather time-consuming as well. The creation of detailed and accurate 3D models proved to be a time-consuming process. One that in this research could have been avoided. During the creation of the current status model, the equipment and furniture were modelled in precise detail, although this helped with the visual representation and accuracy of the model, it led to a time-consuming process that took longer than expected. This could have been avoided by modelling the aforementioned items with less detail but accurate dimensions. This would still result in an accurate 3D modelling approach but with a worse visual appeal. This was done for the new equipment to save on time. Finally, there is a need for some training to be able to effectively use the software. It is not simple to learn and therefore requires time resources in order for a person to be able to use the software efficiently and effectively.

Feasibility

The feasibility of the chosen redesign is technically feasible as it uses a lot of existing resources and infrastructure. This reduces the complexity associated with ordering and installing new equipment. The cost savings approach to this redesign should make it financially feasible and makes it easier to pitch to the university higher ups for example. Additionally, utilizing existing infrastructure simplifies the process of implementing the redesign. As the water and electricity infrastructure remained unchanged, there is no need for any large modifications or installations to the infrastructure. The 3D modelling approach also shows how the redesign is spatially feasible as well. Potential issues were identified during the generation of the redesign so it is unlikely that significant challenges will be met.

A recommendation for future research will be that in order to get the best possible design, it would be useful to go through a similar but more refined process as in this research. Then gather the most optimal aspects of each alternative design and work off of that to create one optimal design. This would be significantly more time consuming but would lead to a properly feasible and optimal design.

Systems Engineering Based Methodology

The systems engineering process in this research provided a clear framework for addressing the redesign of the laboratory. The structured approach ensured that all aspects of the design were considered throughout the entire process. One of the research sub questions was “How can feedback from researchers and stakeholders involved in concrete design geotechnical analysis inform the iterative refinement of the spatial layout to better meet their needs and preferences?” The systems engineering process allowed for stakeholder feedback to inform the spatial layout and ultimately the redesign of the lab. Through the incorporation of input from various stakeholders such as students, researchers and university faculty, the established process ensured that the redesign meets the needs of all users. The collaborative approach this research took with stakeholders helped in identifying and addressing potential issues early on.

Some disadvantages noted about the systems engineering based methodology was the fact that it was time-consuming, had potential for over-engineering and could have done more for an optimal design.

The process was time-consuming, especially during the data gathering and modelling stages. This extensive work led to less time being spent in other areas of work. This could have potentially reduced the quality of work done Additionally, the process was quite thorough which could have led to over-engineering during the creation of some of the alternatives. This means that more features are added than what is necessary. This could have led to the increased costs in the alternatives and could have complicated it unnecessarily. This is likely what happened with alternative redesigns 1 and 3, where they had high budgets and a lot of features but were ultimately not deemed to be the best fit solution.

6. Conclusion

The conclusion of this Bachelor Assignment on optimizing laboratory space through a 3D-modelling approach for the redesign of the WH114 Laboratory at the University of Twente has highlighted several key points.

The first is the achievement of the research objective. The research objective aimed to improve the functionality and efficiency of the laboratory and by utilising the 3D-modelling approach outlined in this report, the research objective was successfully addressed.

Secondly, the data gathered from students and faculty provided valuable insights into user perspectives regarding the current state of the laboratory. These insights have led to improved laboratory redesigns. To summarize, through the engagement of stakeholders in the iterative refinement of the spatial layout, the study ensured that there would be a comprehensive understanding of the diverse perspectives and requirements. The involvement of stakeholders not only enhanced the quality of the redesign but also led to a more user-centric laboratory space.

The utilization of 3D modelling was key in this research. It allowed for precise visualization of the designs but also the status of the lab. It also proved instrumental in planning the spatial layouts for both concrete design and geotechnical analysis. The 3D modelling and BIM approach facilitated informed decision-making as it allowed the designer and stakeholders to consider unique design options, integrate feedback and ensure the practical implementation of the redesigned laboratory.

The findings of this research not only contribute to the redesign of the WH114 laboratory but also offer valuable insights for future laboratory design. The structure and process established in this research can be used to gather user perspectives, regulatory requirements, and best practice guidelines to optimize and enhance the functionality, safety and overall user satisfaction of not only laboratories but other institutional spaces as well.

The decision to select alternative 2 as the optimal redesign was based on a comprehensive MCDA process. This involved scoring multiple design alternatives against a set of criteria. Through this MCDA process, alternative 2 was selected as the best redesign. Alternative 2 has a simple yet effective arrangement of workstations which minimized unnecessary movement and supported efficient lab activities. It provided adequate workspace for conducting experiments. This aided with crowding and improves overall safety and productivity as a result. The redesign also enhanced storage solutions by ensuring that tools and materials are easily accessible while maintaining safety and order. The placement of equipment was also strategically design to reduce movement in the lab and facilitate smooth transitions between tasks. Ultimately the main selling point of this redesign was the fact that it was evaluated as the most cost-effective redesign.

In order to get the best possible design, the strongest aspect of each alternative could be considered and one optimal redesign could be synthesised from these.

In conclusion, this Bachelor Assignment has successfully shown the value of a systematic approach, incorporating stakeholder analysis, data collection and 3D modelling in optimizing a laboratory space. The insights gained from this research will undoubtedly inform improvements in the WH114 laboratory and serve as a foundation for enhancing design practices of similar spaces in the future.

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8. Appendices

Appendix 1 – Requirement Allocation Sheet

Table 4

Requirement Allocation Sheet

ID	Description	Criterion (Measurable)	Performance	Priority
1	**Functional Requirements**			
1.1	Unobstructed Entrances/Exits	Entrances and exits must be clear of objects and equipment	No obstructions	High
1.2	Improved Ventilation Systems	Additional Air Circulation Device(s)	Proper air circulation and dust control	High
1.3	Dust Collectors	Insert Dust Collector System in Tables and Workbenches	Effective dust control	High
1.4	Equipment Labels	Clearly label all equipment	All equipment labelled	Medium
1.5	Storage Shelves	All storage shelves must have a passive restraining system to prevent content from toppling over	Sliding doors on shelves	Medium
1.6	Storage Labels	Clearly label all storage areas	All storage labelled	Medium
1.7	Clear Safety Instructions	Post clear safety instructions at key locations	Visible safety instructions	Medium
1.8	No Equipment on Floor	Ensure all equipment is stored off the floor	Clear floors	High
1.9	Equipment Positioning	Ensure equipment is positioned to prevent the need to reach over hazardous materials	Safe equipment placement	High
1.10	First Aid Kit	Provide a first aid kit in a visible and accessible location	First Aid Kit accessible	High
1.11	Anchored Equipment	Ensure all equipment requiring anchoring is adequately anchored	Secure equipment	High
1.12	Fixed Storage Shelves	Ensure all storage shelves are rigidly fixed	Stable storage shelves	Medium
1.13	Lockable cabinets	Provide lockable cabinets for important materials	Secure storage	Medium
1.14	Sprinkler Effectiveness	Ensure objects do not block or reduce the effectiveness of sprinklers	Unobstructed sprinklers	High
1.15	Ventilation Effectiveness	Ensure objects do not block or reduce the effectiveness of ventilation	Unobstructed ventilation	High
1.16	Oven Placement	Ensure ovens are not placed near flammable objects/equipment	Safe oven placement	High
1.17	Regular Equipment Maintenance	Ensure regular maintenance schedules for equipment	Well-maintained equipment	Medium
2	**Space Requirements**			
2.1	Designated Zones	Create specific zones for different research activities	Separate areas	High
2.2	Removal of Unused Equipment	Remove unused equipment to free	Clear space	High
2.3	Curing Tank	Ensure the curing tank is properly placed to optimize space	Efficient use of space	High
2.4	Vertical Storage	Install vertical storage solutions for better organisation	Organized Storage	Medium

2.5	Adjustable workbenches	Provide adjustable workbenches for ergonomic flexibility	Ergonomic workbenches	Low
2.6	Accessible Water Supply	Ensure easy access to water supply in all necessary areas	Convenient water access	High
2.7	Spot for lab carts	Designate spots for lab cart to keep it out of the wat	Cart storage spot	Low
2.9	Adequate Table and Chair Space	Ensure sufficient table and chair space for working and conducting experiments	Enough workstations	Medium
2.10	Space for Aggregates	Ensure space for aggregate materials	Organised Aggregate Storage	Medium
3	**Regulatory and Compliance Requirements**			
3.1	Adherence to ISO 17025	Ensure compliance with ISO 17025 standards	ISO 17025 compliant	High
3.2	IEC 61010 Compliance	Ensure additional and existing equipment is compliant with IEC 61010	IEC 61010 Compliant	High
3.3	NEN-EN 12845:2015+NEN 1073:2018 nl Compliant Sprinkler Installation	Ensure sprinkler installations comply with NEN-EN 12845:2015+NEN 1073:2018 nl	Compliant sprinklers	High
4	**User Requirements**			
4.1	Workbench for Triaxial Setup	Provide a dedicated workbench for triaxial setup	Specialized workbench	High
4.2	Space for permeability test	Ensure sufficient space for permeability tests	Adequate test space	High
4.3	Table for sample preparation	Provide a table for sample preparation	Sample preparation table	High
4.4	Removal of Unused Oven	Remove unused oven to free up space	Clear space	Low
4.5	Geotechnical Tests Useable in Parallel	ensure geotechnical tests can be conducted in parallel	Parallel test capability	High
4.6	Storage for Small Tools/Equipment	Provide storage solutions for small tools and equipment	Organized small tools	Medium
4.7	Storage for Personal Equipment	Provide storage for personal equipment	Personal equipment storage	Low
5	**Technological Requirements**			
5.1	Adequate number of electrical outlets	Accommodate current electrical requirements with an additional 20-40% capacity	Sufficient electrical outlets	High
5.2	Additional desktops	Provide additional desktops as needed	Minimum 2 Desktop Computers	Medium
5.3	Improved Weighing Scales	Provide new and accurate weighing scales	1 Scale	Medium
5.4	Additional Generators	Provide additional generators for vacuum bells	One additional vacuum generator	High
5.5	Sieve Shaker	Provide a sieve shaker machine	1 Sieve Shaker present	High
5.6	Soil Consolidation Machine	Provide a soil consolidation machine	Consolidation machine present	High
5.7	Direct Shear Test	Provide Direct Shear Testing Equipment	Direct Shear Testing Equipment present	High
5.8	Direct Shear Test connected to PC	Ensure Direct Shear Test equipment is connected to a PC	Connected testing equipment	High

5.9	Compression Testing Machine	Provide a Compression Testing Machine	Compression Machine present	High
5.10	Recirculating Fume Cupboard	Provide a fume cupboard	Fume cupboard present	Medium
6	**Operational Requirements**			
6.1	Maintenance and Upkeep	Ensure easy-to-clean surfaces and accessible equipment	Easy maintenance	Medium
6.2	Energy Efficient LED lighting	Install energy-efficient LED lighting throughout the lab	Efficient lighting	Low
7	**Budget and Resource Constraints**			
7.1	Cost Consideration	Maintain Low Costs	Within budget	High
7.2	Use recycled materials	Use recycled materials where possible	Sustainable materials	Medium

Appendix 2 – 3D Images of Current Status and Alternative Designs

Current Status

Figure 8

View of Concrete Area

Figure 8 shows the current setup of the concrete area. It includes a large shelf against the wall with a drawer and an oven situated beneath it. To the right of this shelf there is a masonry saw and a dust vacuum. Infront of the door on the right, there is a sieve shaker on the floor. The position of the sieve shaker is a problem as it blocks the pathway to the door. On the right side of the room there is a shelf for the sieves and a compression testing machine. On the very left side of Figure 8, a shelf can be seen with the concrete mixer in front of it. The position of the concrete mixer prevents people from accessing the shelf comfortably.

Figure 9

View of Geotechnical Area

Figure 9 showcases the current situation of the geotechnical area. On the very left side of the figure, the 3 geotechnical tests can be found. These can currently not be run in parallel due to their inefficient set up. In the background, there is a desk which has a desktop computer (not shown in model) used when conducting the experiments. To right of it, there is a door to the hallways, a sink and a shelf. The curing tanks are located to the right of the shelf. The workbench in the very front of the Figure includes vacuum generators for use in vacuum bell experiments. Behind this workbench there is a wooden tool holder which takes up a lot of space.

Figure 10

View from Main Entrance

Figure 10 gives a clear overview of how the bending test machine takes up a lot of space of the laboratory. It is the large machine in the middle of the room with the beam. This machine is currently unused and therefore, the trolley is often placed around it.

Alternative 1
Figure 11

View of Geotechnical Area (Alternative 1)

Figure 11 shows the redesigned geotechnical area in alternative 1. Next to the new sink, there is an oedometer with a computer workstation next to it. There is a cupboard located above it for storage purposes. Next to the computer workstation, there is a workbench with a rack. Next to this workstation, there is a sanding table with a cupboard above it. To the right of this table there are three cabinets, two being closed and one being open. Close to the main entrance, the oven can be found. In the middle of the figure, the fume chamber can be seen with a mobile workbench and a mobile toolbox at the end of it.

Figure 12

View from Main Entrance (Alternative 1)

Figure 12 shows the view from the main entrance. On the very right side of the figure, there is a coatrack + boot storage. This item is mobile and can be moved to any area of the lab. Next to this item, on the left, there is a cabinet that was present in the current state model as well. A big change is the workbench in the middle of the laboratory. The workbench in the back, is not mobile. It is the workbench with the vacuum generators. In the back right side of the figure, the other two geotechnical tests can be found. The direct shear test and the triaxial load cell. These are connected to a computer workstation.

Figure 13

View of Concrete Area (Alternative 1)

Figure 13 shows the redesigned concrete area. The biggest change is the removal of the boot rack and the placement of the curing tanks. The large rack on the right side of the concrete area has remained in place. Instead of the oven, the concrete mixer is placed under this rack. This allows for more free floor space and less clutter in the lab.

Alternative 2

Figure 14

View From Main Entrance (Alternative 2)

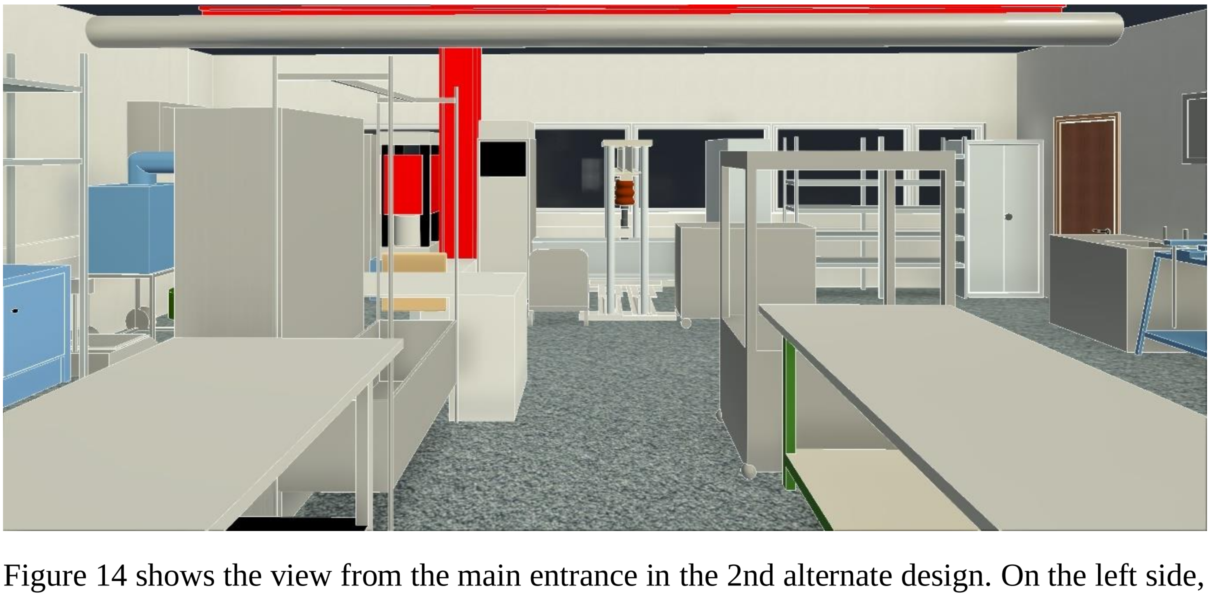

Figure 14 shows the view from the main entrance in the 2nd alternate design. On the left side, the mobile workbench is located, and on the right the stationary workbench with the vacuum generator is located. These workbenches essentially separate the research areas. Next to the mobile workbench on the left, there is a coat rack with boot storage. Behind this, there is a desk. On the left side of the coat rack there is a closed storage cabinet. Behind the stationary workbench on the right, there is a fume chamber. In the middle of the room, the bending test machine is located.

Figure 15

View of Concrete Area (Alternative 2)

Figure 15 shows the concrete area. The left side of concrete area was already explained in the previous figure. There is a desk, a coat rack, closed cabinet storage and a workbench. At the very end of the area, the boot rack was removed and the concrete mixer and curing tanks were placed. On the right side of the wall, not a lot was changed. The shelf remains in place along with the oven and the drawer unit. The shelf remains in place as it is useful for the storage of aggregates which have to be stored on the floor in small containers due to their weight. These containers can be rolled under the shelf which makes it a useful storage solution. On the left side of the figure, on the left side wall of the stationary workbench, a clamp system for the tools is visible. This will hold brooms and other cleaning tools.

Figure 16

View of Geotechnical Area (Alternative 2)

Figure 16 shows the geotechnical area of the redesign. The three geotechnical test are located at the wall right next to each other. The oedometer is placed next to the sink which allows for effective use of that testing equipment. There are 2 computer workstations next to these 3 testing equipments. There are several storage cupboards on the wall to account for the lack of storage on that side of the geotechnical area. On the right side, the sanding dust table can be found alongside a small desk/workbench. Both these items have got storage cupboards above them.

Figure 17

View of Geotechnical Storage Section (Alternative 2)

Figure 17 shows the storage area for the geotechnical section. It includes a closed cabinet, open cabinet as well as a shelf. These three storage solutions are all reused and are not newly purchased equipment. The mobile tool box is located on the left side, in front of the bending test machine.

Alternative 3
Figure 18

View from Main Entrance (Alternative 3)

Figure 18 shows the view from the main entrance in alternative 3. On the right side of the pathway there is the stationary workbench. The placement of this has not been changed from the current state of the laboratory. Similar to the alternative 2 design, the fume chamber is located right behind this workbench. On the right side of the workbench, there is a coat rack. This presents some issues as it takes up some workspace. As it is mobile, it can be moved out of the way, however, this risk blocking workspace in another area. This is a disadvantage with this design. In the middle, in front of the bending test machine, a mobile workbench is located.

Figure 19

View of Geotechnical Area (Alternative 3)

Figure 19 shows the geotechnical area in alternative design 3. Similar to the alternative 2 design, the three geotechnical tests are located right next to one another. This design lacks vertical storage solutions. The main reason for this is that the design would start to get costly if more cupboards or other vertical storage items were placed. Like the other designs, there are 2 computer workstations present. On the very right side of the geotechnical area, there is a workbench with a vertical rack.

Figure 20

View of Geotechnical Storage Area (Alternative 3)

Figure 20 shows the geotechnical storage area. All three storage cabinets are lockable. In the middle, there is a sanding dust table. The positioning of this could be considered inconvenient as it is far from the general workspace area. On the left, it can be seen that the mobile workbench is positioned right in front of the bending test machine.

Figure 21

View of Concrete Area (Alternative 3)

Figure 21 shows the concrete area of alternative 3. In the background, the curing tanks can be seen. This is similar to what the other redesigns have done. The trolley is placed there along with the clamp system to hold cleaning equipment such as brooms. The shelf that was on the right side of this area was moved to the middle. The concrete mixer was placed under this shelf. On the backside of the shelf, cabinets were placed in order to have a surface that items in the shelf can lean against. If this were not the case, the stored items would be at risk of falling out. This would pose a safety concern and would violate safety guidelines. There is still a risk present for items that are placed at the top. On the right side, more lockable cabinets are placed. The oven remained in place and a cupboard was installed above it. This also could pose a risk as the oven could be hot and reaching the cupboard could be difficult for shorter people.

Appendix 3 – MCDA Weighting Calculation

Using the average rankings collected during the surveys, the MCDA weightings are derived for each criterion.

The acquired ranking data linked to each criterion is shown below:

- Layout and Functionality – 3.36 (From Current Layout and Functionality Satisfaction)
- Workspace Size – 4.5 (From Importance of Workspace Size)
- Organisation of Storage Areas – 4.5 (From Importance of Storage Areas)
- Equipment Placement – (3.83 from Importance of Equipment Placement + 3.93 from Satisfaction of Equipment Placement)/2 = 3.88
- Workflow Efficiency – 3.83 (From Workflow Efficiency)
- Safety – 3 (From Safety of Current Layout)

- Cost – 4 (Since no specific data for cost importance was gathered, a neutral importance of 4 is assumed. This is because the budget determines the feasibility of the redesign heavily.)

These values were normalized for efficient weighting calculations during the MCDA process.

First, the values were summed up:

$$3.36 + 4.5 + 4.5 + 3.88 + 3.83 + 3 + 4 = 27.07$$

The weight of each criterion was calculated by dividing each value by the total sum. This results in the following:

- Layout and Functionality: $\frac{3.36}{27.07} = 0.124$
- Workspace Size: $\frac{4.5}{27.07} = 0.166$
- Organisation of Storage Areas: $\frac{4.5}{27.07} = 0.166$
- Equipment Placement: $\frac{3.83}{27.07} = 0.141$
- Workflow Efficiency: $\frac{3.83}{27.07} = 0.141$
- Safety: $\frac{3}{27.07} = 0.111$
- Cost: $\frac{4}{27.07} = 0.148$

Appendix 4 – Cost Estimations for Each Alternative

Table 5

Cost Estimation Table for Alternative 1

Items/Category	Number	Cost	Cumulative Cost
Cabinetry			
Computer Workstation	2	€ 1,225.00	€ 2,450.00
Material Cabinet	2	€ 800.00	€ 1,600.00
Cupboard	3	€ 409.00	€ 1,227.00
Small Cabinet	2	€ 2,550.00	€ 5,100.00
Mobile Toolbox	1	€ 789.00	€ 789.00
Cabinet	1	€ 2,350.00	€ 2,350.00
File Cabinet	1	€ 699.00	€ 699.00
Workbenches/Tables/Desks			
Workbench for Triaxial Setup	1	€ 1,075.00	€ 1,075.00
Soil Workbench 1	1	€ 1,395.00	€ 1,395.00
Workbench 1 Additional Rack	1	€ 1,675.00	€ 1,675.00
Sanding Dust Table	1	€ 1,730.00	€ 1,730.00
Mobile Workbench	1	€ 1,525.00	€ 1,525.00

Other Objects			
Garment Rack with Boot Storage	1	€ 3,023.00	€ 3,023.00
Sink with heavy duty workstation	1	€ 3,350.00	€ 3,350.00
Dust Collector Table Insert	2	€ 308.00	€ 616.00
Fume Chamber	1	€ 4,806.00	€ 4,806.00
Air Purifier	1	€ 199.95	€ 199.95
Scale	1	€ 819.00	€ 819.00
TOTAL			€ 34,428.95

Table 6

Cost Estimation Table for Alternative 2

Items/Category	Number	Cost	Cumulative Cost
Cabinetry			
Computer Workstation	2	€ 1,225.00	€ 2,450.00
Material Cabinet	0	€ 800.00	€ -
Cupboard	5	€ 409.00	€ 2,045.00
Small Cabinet	0	€ 2,550.00	€ -
Mobile Toolbox	1	€ 789.00	€ 789.00
Cabinet	2	€ 2,350.00	€ 4,700.00
File Cabinet	0	€ 699.00	€ -
Workbenches/Tables/Desks			
Workbench for Triaxial Setup	1	€ 1,075.00	€ 1,075.00
Soil Workbench 1	0	€ 1,395.00	€ -
Workbench 1 Additional Rack	0	€ 1,675.00	€ -
Sanding Dust Table	1	€ 1,730.00	€ 1,730.00
Mobile Workbench	1	€ 1,525.00	€ 1,525.00
Other Objects			
Garment Rack with Boot Storage	1	€ 3,023.00	€ 3,023.00
Sink with heavy duty workstation	1	€ 3,350.00	€ 3,350.00
Dust Collector Table Insert	1	€ 308.00	€ 308.00
Fume Chamber	1	€ 4,806.00	€ 4,806.00
Air Purifier	1	€ 199.95	€ 199.95
Scale	1	€ 819.00	€ 819.00
Clamp System for Cleaning Tools	1	€ 69.95	€ 69.95
TOTAL			€ 26,889.9

Table 7

Cost Estimation Table for Alternative 3

Items/Category	Number	Cost	Cumulative Cost
Cabinetry			
XXL Cabinet	3	€ 1,075.00	€ 3,225.00
Computer Workstation	2	€ 1,225.00	€ 2,450.00
Material Cabinet	1	€ 800.00	€ 800.00
Cupboard	4	€ 409.00	€ 1,636.00
Small Cabinet	0	€ 2,550.00	€ -
Mobile Toolbox	1	€ 789.00	€ 789.00
Cabinet	1	€ 2,350.00	€ 2,350.00
File Cabinet	0	€ 699.00	€ -
Workbenches/Tables/Desks			
Workbench for Triaxial Setup	1	€ 1,075.00	€ 1,075.00
Soil Workbench 1	1	€ 1,395.00	€ 1,395.00
Workbench 1 Additional Rack	1	€ 1,675.00	€ 1,675.00
Sanding Dust Table	1	€ 1,730.00	€ 1,730.00
Mobile Workbench	1	€ 1,525.00	€ 1,525.00
Other Objects			
Garment Rack with Boot Storage	1	€ 3,023.00	€ 3,023.00
Sink with heavy duty workstation	1	€ 3,350.00	€ 3,350.00
Dust Collector Table Insert	1	€ 308.00	€ 308.00
Fume Chamber	1	€ 4,806.00	€ 4,806.00
Air Purifier	1	€ 199.95	€ 199.95
Scale	1	€ 819.00	€ 819.00
Clamp System for Cleaning Tools	1	€ 69.95	€ 69.95
TOTAL			€ 31,225.9

Appendix 5 - Interview Analysis

Table 8

First Set of Interview Response Summary

Researchers or Student	Roles and Responsibilities	Main Activities	Describe current layout	Any challenges or inefficiencies in setup	Equipment or Tools Used
Faculty 1	Responsible for the technical setup and maintenance of all geotechnical test machines Assisting and	Teaching and research	Disorganised with many unused and underutilized spaces. Specific areas, like the big corner and	Inability to move carts filled with materials. Limited space for using multiple geotechnical test machines in parallel.	Sieve Direct shear test Air vacuum Desktop

	instructing others on how to use the equipment. Managing storage and reorganization of the lab		parts with storage and an unused oven, are not optimally used. Limited space leads to cramped conditions for equipment and activities.	Storage areas obstruct access to essential plugs and are poorly placed.	Computer connected to direct shear test. Various sensors and data loggers
Faculty 2	Chair of the Soil Micromechanics group. Supervision and coordination of lab personnel including PhD and postdocs who conduct soil mechanics experiments.	Conducting soil tests using standard apparatus such as shear tests and triaxial tests.	Confusing and suboptimal. Water supply is inconveniently located Equipment like oven is not placed near related experiments. Difficult to conduct multiple experiments at the same time	Sink is small and inconveniently located, leading to messiness. A lot of space is occupied by unused items. Lab space is not optimized for larger groups, making it challenging for student activities. Experiments intersect which makes it hard to run them simultaneously. Small tools and materials are scattered, lacking designated places, hindering efficiency.	Standard soil mechanics equipment (shear cells, triaxial apparatus, permeameters) Custom devices for specific experiments Fume chamber
Student 1	Conducting experiments related to soil properties. Using experimental data to inform simulations	Determining soil properties such as void ratio, mesh size and cohesion. Performing specific experiments like C-mixing for mesh size and direct axial pressure experiments for cohesion and friction angle.	The lab is spacious and well-equipped. There is a need for better organization to make it easier to follow which experiment is next and what equipment is required for each task.	Difficulty finding necessary equipment. Time wasted due to lack of categorization and organisation of tools and materials.	Rulers Containers Sieve Sand
Student 2	Conducting experiments on soil and clay mixtures Preparing samples and subjecting them	Sealing sand samples Using vacuum bells to remove air from samples	Generally good but sometimes difficult to find equipment	Inaccurate and old weighing scales Limited use of vacuum bells due to a single generator	Sealing tools for sand Vacuum bells Weighing scales

	to freeze-thaw cycles	Weighing mixtures			
Student 3	Conducting a bachelor thesis using direct shear test and soil sieving	Soil sieving Shear testing. Mixing soils Weighing and measuring materials	The layout is generally okay, with sufficient space to move around	Insufficient chairs and table space Shelves are not easily accessible	
Faculty 3	Assistant professor with construction management group. Oversees construction materials classes.	Experiments related to concrete mix design.	Disorganised with underutilized space and equipment. Safety issues related to ventilation.	Overcrowding during experiments, the lab does not support multiple people conducting experiments simultaneously.	Mixer Compression Machine Sieves Aggregates Weights Curing pool Equipment for soil testing
Student 4	Conducting the Cone Penetration Test	Starting the experiment by filling the sand cylinder and using a laptop to initiate the test.	Somewhat satisfactory Have to move across laboratory frequently	Moving around the lab space No accessible desk space	Laptop Dust vacuum machine. Large tank for sand Weighing scales Small tools

Table 9

Second Set of Interview Response Summary

Researchers or Student	Suggestions or Ideas	Critical Aspects that Need to be Reconsidered	Desired Equipment Placement improvements or workflow improvements	Future Equipment Upgrades or Additions	Workflow Challenges or Bottlenecks
Faculty 1	Create an online calendar for booking equipment time to improve scheduling and accountability.	Safety for users Dust protection for equipment like the triaxial machine.	Keep the direct shear test equipment where it is, with a desktop. Place the triaxial	Software for triaxial machine improvements Additional computers and organized	Limited ability to use multiple machines simultaneously due to cramped space.

	Establish safety recommendations and instructions for all tools, possibly in a folder on the wall.	Ensuring that storage areas do not obstruct essential utilities.	machine on a solid, fixed table, with its own computer and data logger, connected to water. Separate sections for different research areas to avoid interference. Install closed cabinets with sliding doors for storing computers and tools safely. Improve the placement of storage areas to avoid blocking essential utilities.	cabinets	Need for better scheduling to accommodate multiple users and external researchers. Current setup of soil machinery does not allow for the machines to be used in parallel.
Faculty 2	Allocate enough space around each piece of equipment, including areas to set up samples. Designate places for small tools and additional materials to improve accessibility. Cleaner space for equipment that should not be exposed to dust	Improving safety by improving workflow and keeping the lab clean Optimize space to prevent interference between different experiments. Implement systems to manage and reduce dust in the lab	Move the triaxial cell to a more suitable location. Improve the placement of containers and storage shelves. Create designated areas for each device and its setup	Lacking space for permeability tests, need it in the future.	Multiple experiments interfere with each other. Difficulty in accessing and organization tools and materials. Limited space for teaching activities
Student 1	Improve the lab layout to categorize equipment clearly. Regular cleaning to maintain a productive work environment.	Organizing equipment to enhance workflow. Better design to facilitate ease of use and clarity.	Clear categorization and labelling of equipment for easier access and identification. Improving the layout to make equipment more accessible.	No specifics mentioned	Main challenge was the inefficient organisation leading to wasted time. Difficulty in quickly locating tools and equipment
Student 2	Better organisation in the lab More space and	Organisation and returning equipment to its proper place.	Current placement is fine, better organisation needed.	New and more accurate weighing scales	Sharing the single generator for vacuum bells.

	chairs for working on Laptops			Additional generator for vacuum bells.	Waiting for equipment due to limited availability.
Student 3	More table spaces. Additional shelves, not just along the walls but also in the centre of the lab.	Providing more space to sit and work, not just for using machines but also for processing data on laptops.	Upgrading the old computer connected to the direct shear test machine. Improving the scales Cleaning the soil sieves as they are not exceptionally clean		Limited use of vacuum bells due to having only one usable bell, which causes delays when multiple people need to use it.
Faculty 3	Remove unused equipment to create more space. Install shelves to protect equipment from dust. Separate working spaces for soil mechanics and concrete experiments Move curing pool to optimize space. Rearrange or replace shelves for better storage. Relocating large compression machine	Clearing floor Improving ventilation Ensuring water access	Move unnecessary equipment to create more space. Keep the large table for soil and concrete experiments. Potentially move large compression machine and other large equipment Ensure easy access to water and adequate space for curing tank. Rearrange or replace shelves	Improved ventilation system	When using lab solely for concrete experiments there are no significant challenges. Sharing the lab with the soil mechanics group can cause issues.
Student 4	Add workspaces which allow for work with a laptop, rather than using a plank on a container. Ensure storage areas are more accessible and organized	Cleaning and tidiness of the lab Accessibility of storage space	Reorganize or relocate equipment. Improve the accessibility and organization of storage areas	Better scales	Weighing process is inefficient. Navigating the lab can be challenging due to clutter