From Earth to Education

A Sustainable Approach to Climate Resilient School Design in Rural Zambia

Title	*From Earth to Education: A Sustainable Approach to Climate Resilient School Design in Rural Zambia*
Department	*Aalborg University, Department of Architecture, Design and Media Technology*
Semester	*Msc04 Master Thesis*
Group	*24*
Project period	*03.02.2025 - 2.06.2025*
Supervisor	*Christiane Berger*
Technical supervisor	*Endrit Hoxha*
Thesis pages	*168*
Appendix pages	*9*
Design team	*Anna Wilczewska* *Antje Heyselberghs* *Zin Sadik*

Acknowledgment

Thank you to our main supervisor, Christiane Berger, and our technical supervisor, Endrit Hoxha, for your guidance and feedback throughout this thesis. Your expertise has been invaluable to the development of this project.

A special acknowledgment to the dedicated team behind the Kashitu School project, whose non-profit work in Zambia continues to make a meaningful difference where it is most needed. Your commitment to improving educational opportunities in underserved areas has been a true source of inspiration.

An additional thank you to Will Boase, who connected us with Randi Karangizi and Juliana Achi from LocalWorks. Thank you for providing us with useful answers and insights, which have made a meaningful contribution to our reflective journey.

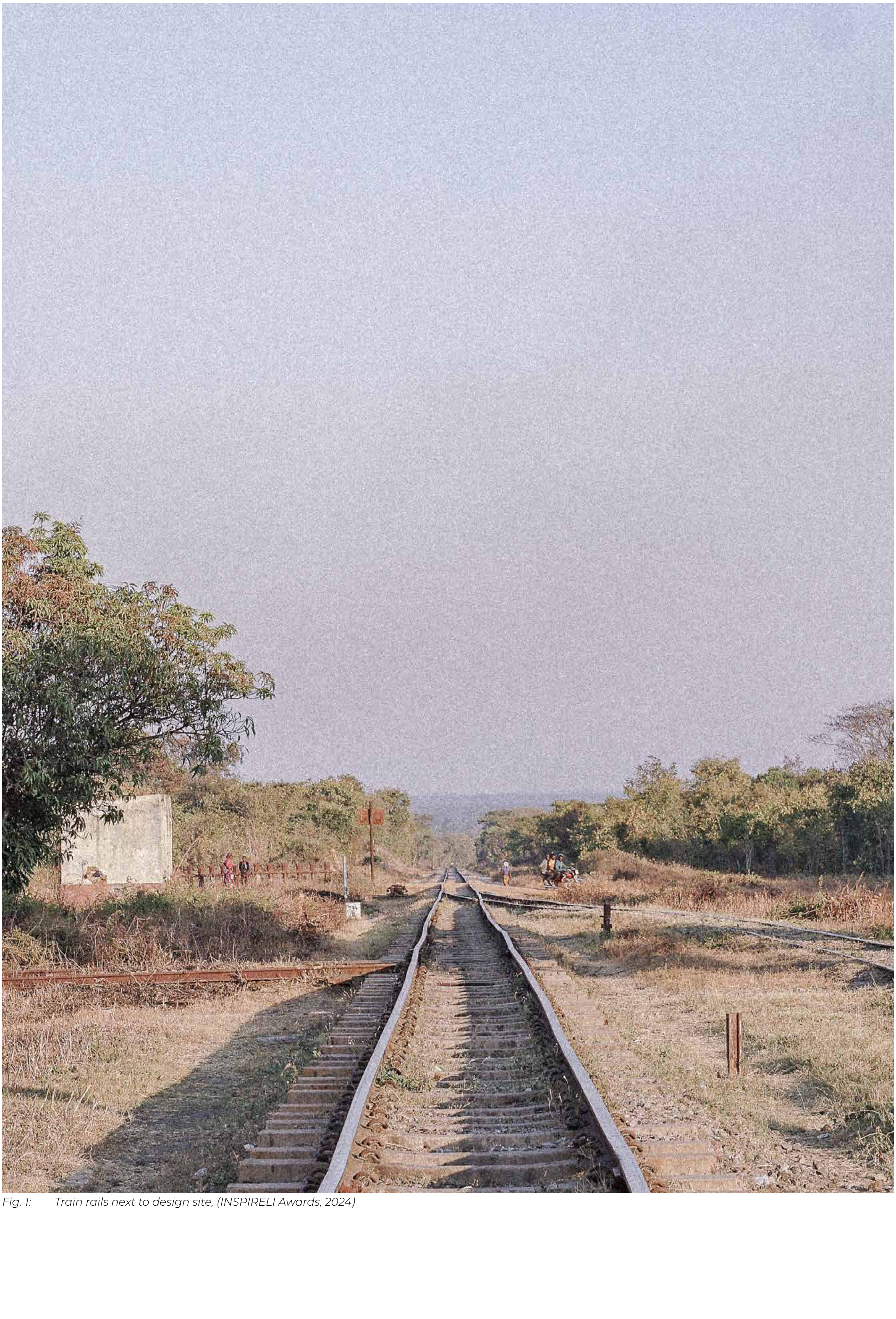

Fig. 1: Train rails next to design site, (INSPIRELI Awards, 2024)

Abstract

This thesis proposes the design of a secondary boarding school in rural Zambia, in which different strategies are integrated to make the design climate resilient as well as providing a high-quality learning environment. The project is designed with a community driven approach, ensuring the needs of the users are fulfilled. An additional focus area is the use of simple construction methods from locally sourced materials, enabling the local community to take part in the building process.

Furthermore, this thesis examines the relationship between a comfortable indoor climate and the environmental costs associated with achieving it in the context of a developing country. The final design seeks to reach a balance between environmental impact, indoor climate and user comfort, offering a solution that is both contextually relevant while still providing the design with architecturally qualitative spaces.

Ultimately, this work advocates for a thoughtful approach to school design. An approach that embraces environmental responsibility, strengthens community engagement and involvement, and creates an educational environment through climate-conscious decisions.

Reading guide

The thesis is divided in eight chapters following the design chronologically. The first chapter introduces the aim of the thesis together with the context of the site. The following chapter covers background knowledge essential to the project, where the third chapter provides an overall analysis of the site and its climate conditions. After this, a theoretical section is presented, including research on relevant materials, regulations, and potential design challenges.

Knowledge gained in the previous chapters lead to the design process chapter, which is divided in two phases. The first phase addresses the broader design development, focusing on the masterplan and school buildings. The second phase delves into more specific design iterations, incorporating simulation-based evaluations.

This design process will then end with a final comparison of all iterations, which will lead to the final design presentation of the thesis.

After presenting the final proposal, and outro chapter will cover a conclusion and reflection, where a bibliography and appendix will close the thesis.

Abbreviation

ACS	Adaptive Comfort Standard
ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
ATC	Adaptive Thermal Comfort
BCS	Buildings and construction sector
CLB	Cross Laminated Bamboo
CS	Climate Studio
EPD	Environmental Product Declaration
GWP	Global Warming Potential
ICEB	Interlocking Compressed Earth Blocks
LCA	Life Cycle Assessment
PMV	Predicted Mean Vote
RH	Relative Humidity
sDA	Spatial Daylight Autonomy
S/V	Surface to Volume ratio
T	Temperature
UDI	Useful Daylight Illuminance
WFR	Window to Floor Ratio

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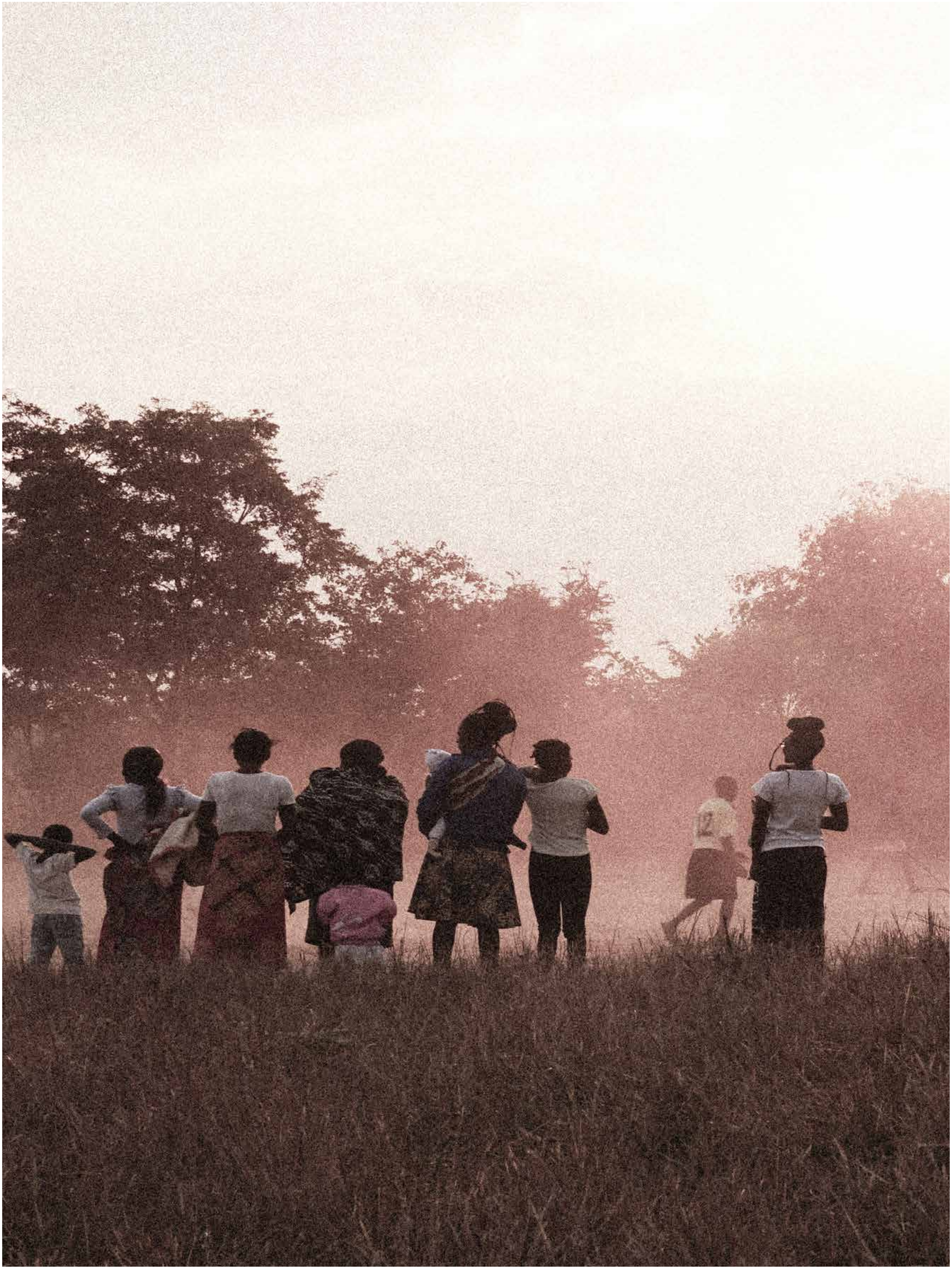

Fig. 2: Locals, (INSPIRELI Awards, 2024)

01 Introduction

COUNTRY
ZAMBIA

BUILDING
SECONDARY SCHOOL

Architecture today, particularly in Denmark where this thesis is conducted, often engages with broad social and environmental ambitions with sustainability at the forefront. But what happens when we shift our focus to regions that lack the same resources and capacity to address these challenges? This question forms the starting point for this thesis and highlights a global imbalance: those who contribute least to climate change often bear their heaviest burden.

Motivated by this reality, the thesis explores how architecture can respond to fundamental needs in a low-resource context. It focuses on designing a climate-resilient secondary boarding school in Kashitu, a rural area in northern Zambia, affected by the harsh climate conditions. This school aims not only to provide quality educational infrastructure, but also to serve as a case study for developing climate-appropriate building strategies that are locally based and resource-aware.

A central theme of the thesis is the balance between creating a comfortable indoor climate, crucial for learning and well-being, while minimizing the environmental and material costs associated with achieving it. In a context where energy infrastructure and material availability are limited, solutions must be technically realistic.

What makes this topic particularly interesting is the challenge of adapting the taught methods used at Aalborg University to a new context, which includes different climate conditions, building regulations, and specific needs of the local community.

In choosing a school as the building type, the project also addresses broader societal goals. Schools are not just learning environments; they are spaces where values are shaped, and futures are built. By integrating sustainability into the design of a boarding school, the project aims to raise environmental awareness from an early age and contribute to long-term development through education.

In summary, this thesis combines social purpose with climate-adapted design thinking, seeking to create an architectural solution that is contextual, low-impact, and meaningful to its users.

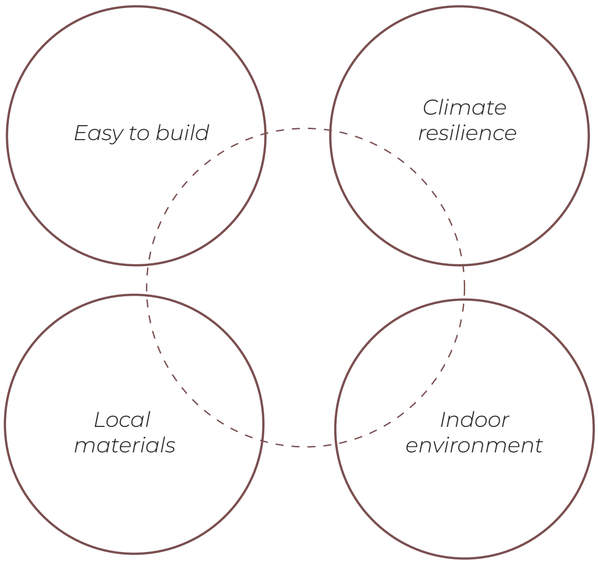

Fig. 3: Design principles of the thesis

Design brief

Architecture competitions can serve as effective platforms for translating user needs into design solutions. The choice of the project site and target user group is primarily influenced by an architecture competition organized by the INSPIRELI Awards.

Unlike theoretical projects based solely on assumptions, the competition brief is grounded in real-world challenges identified by the local community, thereby framing the thesis as a response to specific needs.

The competition outlines several key design principles (INSPIRELI Awards, 2024), including the use of locally sourced materials while being easy to build. Additionally, it emphasizes the importance of climate-responsive design, which align closely with the goals of this thesis, where climate has been approached through a dual lens: enhancing user comfort indoors and adapting to the challenges of the outdoor environment.

It is additionally important to adhere to the Zambian regulations to ensure a contextually appropriate and legal final design (INSPIRELI Awards, 2024). Figure x illustrates the combination of the focal points of the thesis and the competition.

Kashitu – Project site

Zambia is located in East Africa (see fig. 5), making the country vulnerable to warm and rainy seasons. Therefore, it's crucial to investigate, among other things, how to avoid overheating and sufficient cooling through ventilation (Santos, Ferreira and Lanzinha, 2022). How to design with the local climate in mind will be further analysed in this thesis.

Kashitu is a small city in the Copperbelt Province in the north of Zambia, located between the bigger cities Ndola and Lusaka – the capital. The city has a population of 18.000 people and more than eight primary schools (Kashitu High School, 2024). This means that over 1000 students graduate per year from primary school, looking to go to a secondary school. The first secondary school however is about 40 km away, making the project of designing a secondary school extremely relevant for the area in order to ensure for further education. This secondary school will also act as a boarding school providing non-local students residency. (INSPIRELI Awards, 2024)

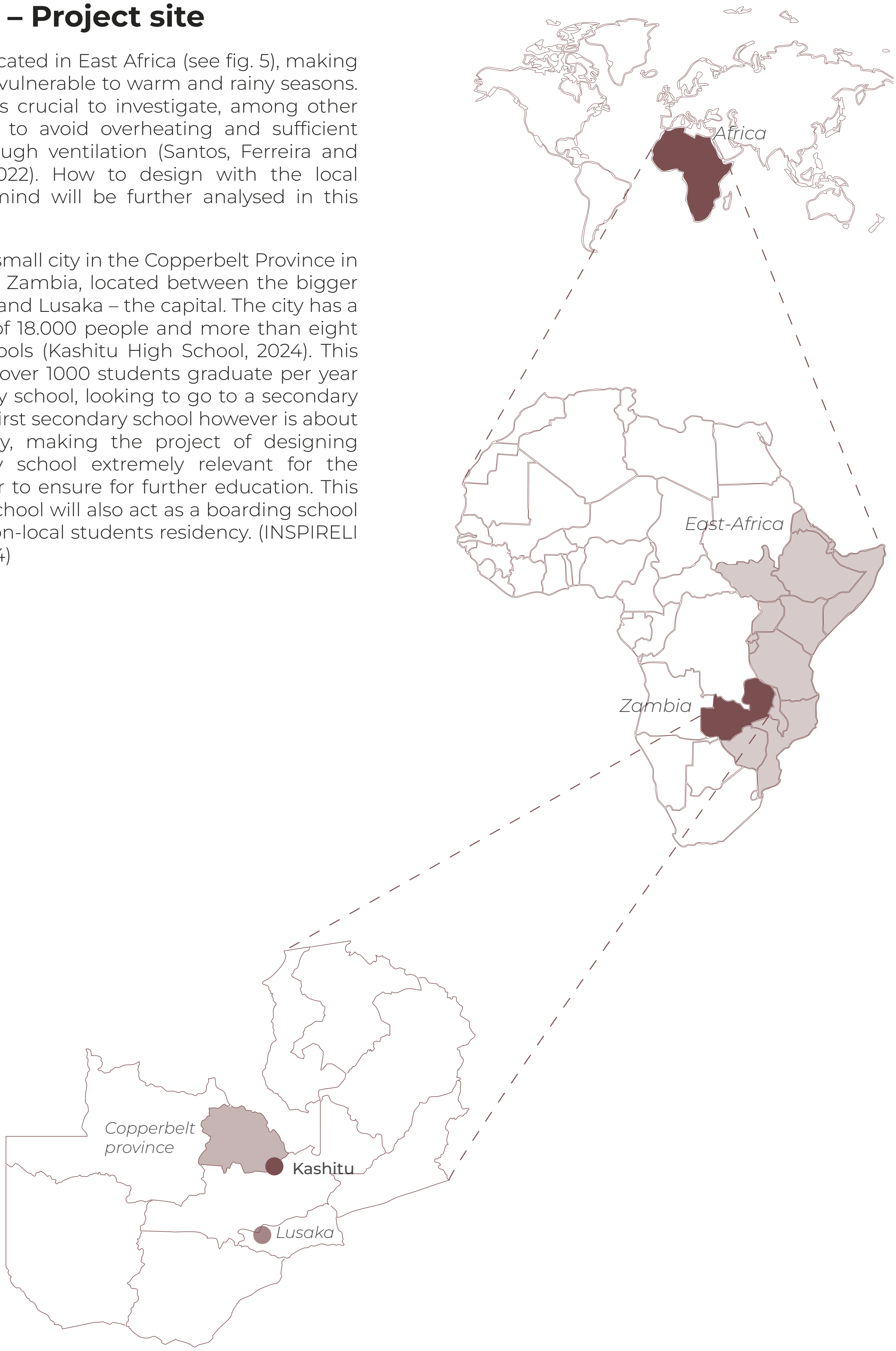

Fig. 4: Location of Kashitu in Africa

Methodology

The methodology applied in this thesis is an adaptation of the Integrated Design Process (IDP), structured around five main phases progressing from problem formulation to final design (see fig. 3). The IDP is grounded in a transdisciplinary approach of architecture and engineering, such as architectural quality, functional aspects, indoor environment and construction (Knudstrup, 2004), all of which is crucial when aiming to create a design that is user appropriate and climate resilient.

The process begins with a thorough identification of the core challenges concerning secondary school infrastructure in Zambia, focusing on the lack of educational spaces in remote areas which are heavily affected by harsh climate conditions. This initial problem framing helps define the scope of the project and the needed beforehand preparation.

As the project takes place in a different country from where this thesis is being written, thorough contextual analysis and theoretical research is conducted, setting the fundamental basis crucial for informing the design direction.

Findings from the previous phases are cooked down to a project outline, which the design will be evaluated against.

The core of this project is the iterative design process structured around qualitative and quantitative evaluations, in which the iterative loop ensure that each stage of iterations advance towards reaching the set goals by continuously testing the building performance and refining the design.

The synthesis phase involves all aspects and pieces of the project falling into place, which is consolidated to the final design proposal in the presentation phase.

The IDP is not a path that leads to an aesthetic or sustainable solution (Knudstrup, 2004) but creates a reflective design process where each phase builds upon the previous, making it easier to consider and integrate different parameters when opting to create a holistic design.

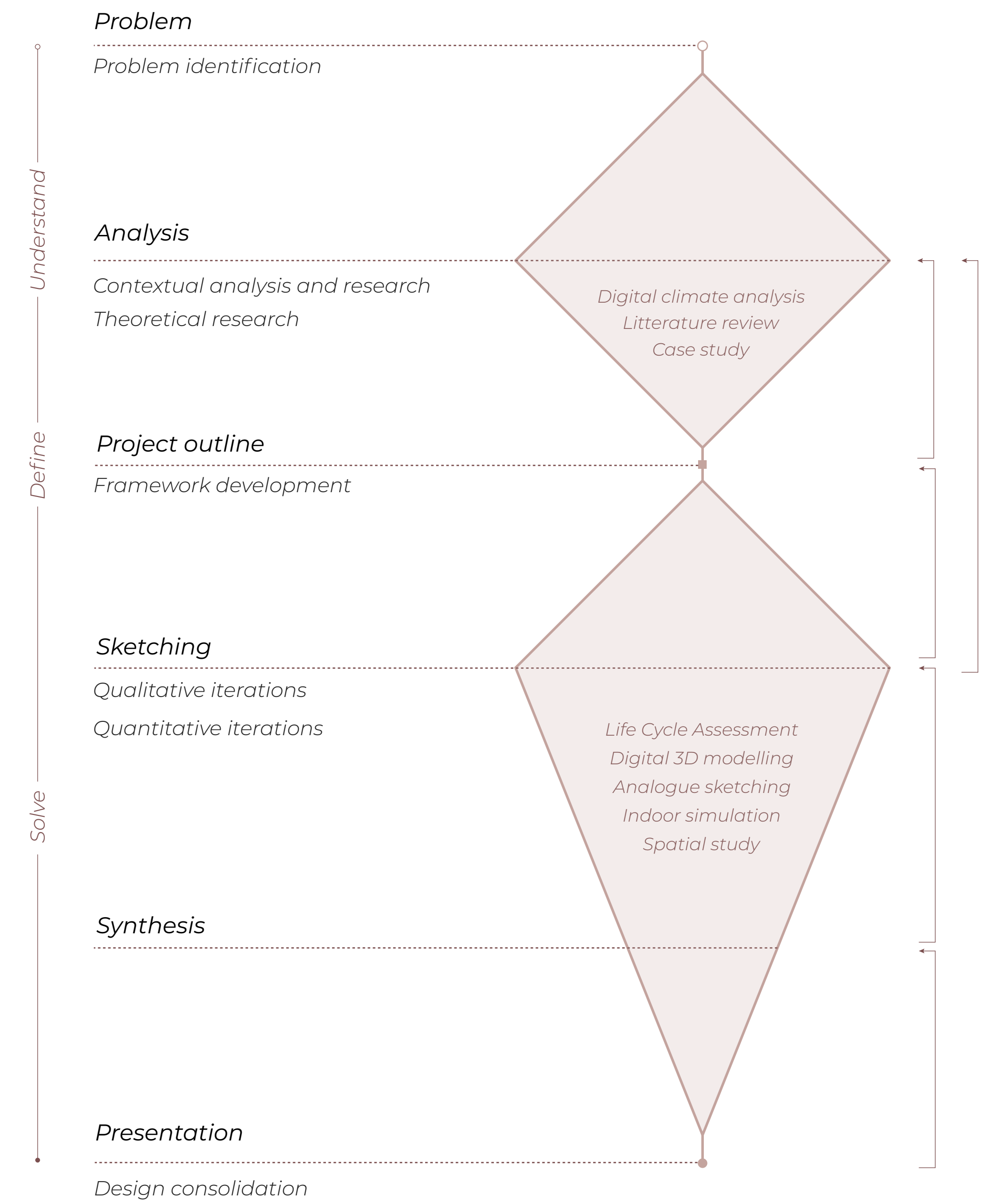

Fig. 5: *Methodology*

User group

In this master's thesis, the competition brief serves as the basis for identifying the building's users and intended functions. Further research has helped to refine and validate the user profiles for the project.

The primary user group consists of students aged twelve to eighteen, including both boys and girls. In addition to the students, teachers and school staff are important stakeholders who require appropriate working conditions and facilities to perform their roles effectively. This includes not only classrooms but also staff rooms, sanitation facilities, and spaces for rest and recreation. Both students and staff will benefit from the inclusion of boarding facilities, while the school will also accommodate non-boarding students who commute daily.

While the design responds to the competition brief, it also incorporates insights gathered from an investigation into the preferences of Zambian students. As illustrated in figure 6, students expressed specific desires for architectural features in their ideal school environment. Many pupils typically spend their breaks outdoors, engaging in group games. Combined with the hot and humid climate, this emphasizes the need for shaded or sheltered outdoor spaces to provide protection from both heat and rain (Save the Children, 2022).

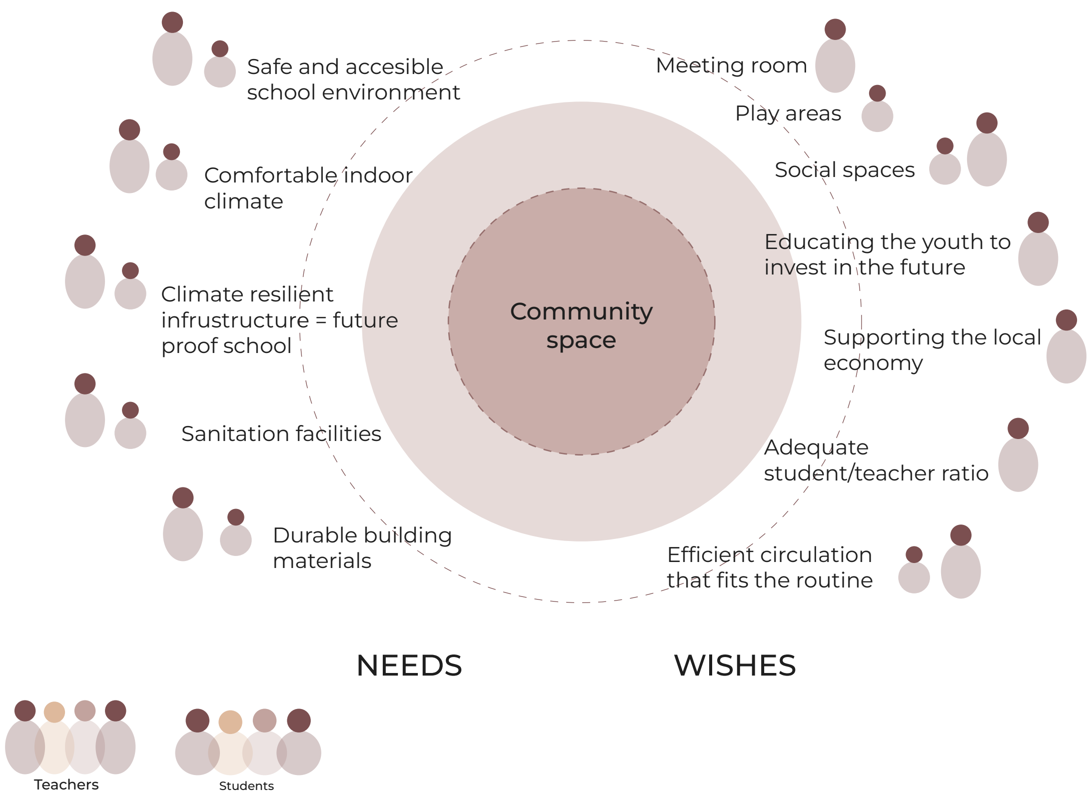

Fig. 6: User group

Fig. 7: Students in classroom, (INSPIRELI Awards, 2024)

Fig. 8: Zambian pupils, (INSPIRELI Awards, 2024)

02 Background

CULTURE
COMMUNITY

EDUCATION
BOARDING SCHOOL

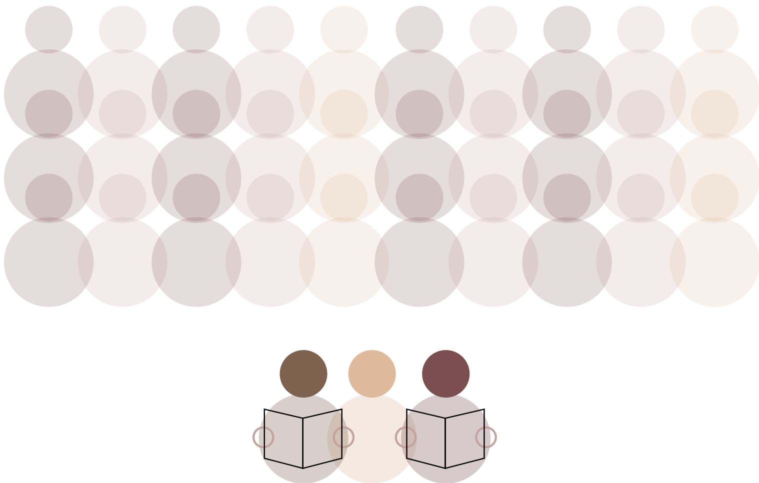

Fig. 9: Background introduction

Understanding the culture and education system in Zambia is crucial for designing a secondary school that meets the needs of the community. This knowledge provides the necessary context for designing a school, and an understanding of the various challenges within the education system. On this basis, informed design decisions can be made, supporting effective teaching and learning while in tandem with the Zambian culture. Ultimately, a well-informed design can enhance educational outcomes and contribute positively to the long-term development of the community.

Zambia is a country characterized by its multilingual, multireligious, and multicultural composition with numerous tribes and ethnic groups, each adhering to different cultural practices and traditions. Because of this, it is not feasible to generalize the term 'Zambian culture' in a manner that accurately represents all the diverse lifestyles, especially when it comes to the differences in the urban and rural ways of life. (Mkandawire, Simooya and Monde, 2019)

Culture is a powerful aspect of society and has its impact on education due to differences in beliefs and tendencies. In some rural areas of Zambia, it is common for families to marry off girls at a young age for various reasons like economic hardships, peer pressure, low value for education etc., meanwhile boys continue with their education, as they are expected to be the main provider for their future family. (Mkandawire, Simooya and Monde, 2019)

Zambian culture

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The community

Communal and social well-being is an important aspect in Zambia, where extended family members normally live in the same household and depend on each other for security and well-being (Mkandawire, Simooya and Monde, 2019).

Zambians are social beings and are known for their strong sense of community, with both joyful and solemn events playing an important role in their culture. Celebrations such as weddings, New Year's, and birthdays bring people together and

Fig. 10: Zambian women, (INSPIRELI Awards, 2024)

strengthen social bonds. During times of sickness and death, the community supports one another through offering comfort and close precense. These events are observed in solidarity and highlight the importance of social dependency and shared experiences in Zambian society.

This social nature is also reflected in sports and games, which bring people together for learning and social bonding. Some activities include football, athletics and volleyball along with traditional indigenous games, all of which foster a community spirit and create joyful moments for the people to look back on. (Mkandawire, Simooya and Monde, 2019).

Therefore, it would be beneficial to accommodate space for indoor events and outdoor activities in order to strengthen the bonds within the school community. However, since there already is a community centre near the site, and the school has private boarding facilities, the focus in this thesis is to gather the school community rather than the overall local community, focusing on activities that improve the school quality.

The Zambian Education System

Since gaining independence from British colonial rule in 1964, the education system has undergone significant transformation, transitioning from being accessible only to the elite to a more inclusive system. Today, The Ministry of Education in Zambia deems education as a fundamental pillar for the development of the nation and in shaping the future of its citizens. (Ministry of Education, 2024)

The Zambian education system follows a 4-7-5-4 structure as shown in figure 11 (Ministry of Education and Management Development Division, n.d.)and Management Development Division, n.d.).

Students aged between three to six years first go through four years of early childhood education, which provides holistic child development in preparation for primary education. (Ministry of Education and Management Development Division, n.d.)

Hereafter, students proceed to seven years of compulsory primary education. This level provides the fundamental teaching of literacy, numeracy and life skills. (Ministry of Education and Management Development Division, n.d.)

After primary education, students complete five years of secondary school - two years of junior and three years of senior secondary. They choose between vocational education, focusing on practical skills, or academic education, emphasizing theoretical learning. (Ministry of Education and Management Development Division, n.d.) In this project, the secondary school will provide both vocational and academic education, each consisting of different functions specified in the project outline further in this report.

Individuals who have completed secondary education can progress to tertiary education, which includes universities, colleges and technical training programs (Ministry of Education and Management Development Division, n.d.).

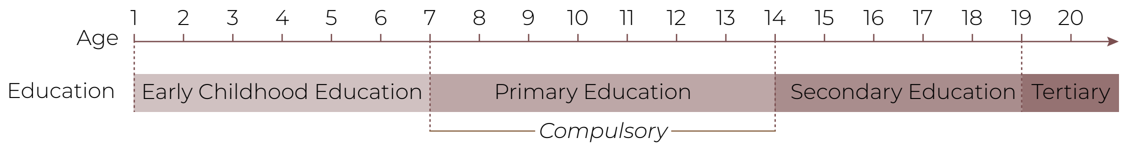


Fig. 11: Zambian Education System, (Ministry of Education and Management Development Division, n.d.).

The boarding school routine

The school routine and organization are important factors in the educational framework, as they guide teachers and learners concerning the timing of each school activity. The structured routine recommended by the Ministry of Education in both day and boarding secondary schools ensures that students have a balanced day in order to enhance educational outcomes, while promoting discipline and a sense of community among students. (Ministry of Education, Science, Vocational Training and Early Education, 2015) Boarding schools have a structured routine, accommodating both academic and residential life as seen in figure 12 and 13

Adhering to a well-defined routine with appropriately timed school activities, ensures that learners can spend their time in school effectively. Knowing the activities taking place throughout the day can help organize the layout and placement of the buildings and their connections during the design phase.

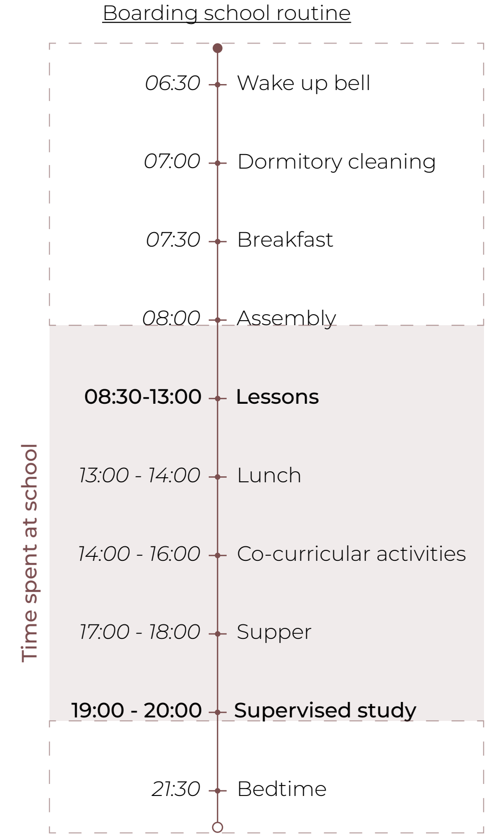


Fig. 12: Boarding school routine, partly based on Ministry of Education, Science, Vocational Training and Early Education, 2015

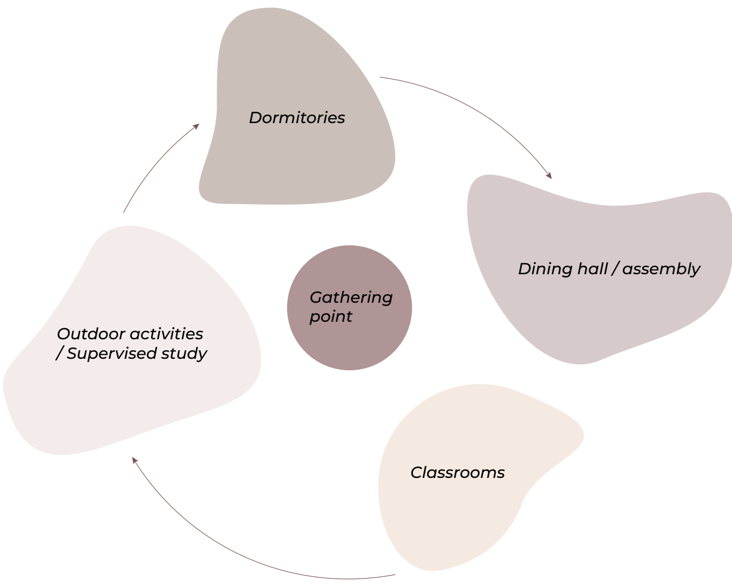


Fig. 13: Adaptation of students routine

Educational statistics and performance

Every year, The Ministry of Education carries out an annual school census to generate education statistics that inform policy development, planning, evidence-based decision-making and priority setting (Ministry of Education, 2024).

The data is used to identify challenges and opportunities in the education sector. By these means, the census data plays a vital role in shaping a robust and responsive education system that can adapt to changing circumstances and improve educational outcomes for all students.

Challenges

Despite the progress that Zambia has made over the past decades, the education system still faces several challenges with room for improvement.

1. Access and equity

Although primary education is free, hidden expenses such as uniforms and books, along with long distances to schools can be restrictive, especially for students in rural areas (Ministry of Education, 2024).

Zambia is experiencing a rapid population growth rate, with 46% of the population under the age of 15. This surge has led to an increasing demand for education and therefore school facilities to enhance educational development. However, the average annual increase in Grade 1 enrolments has not kept pace with population growth, implying that a significant portion of children are left outside the school system. (Ministry of Education and Management Development Division, n.d.) This is also the case for Kashitu, where there is a pressing need for a boarding school in this project's location.

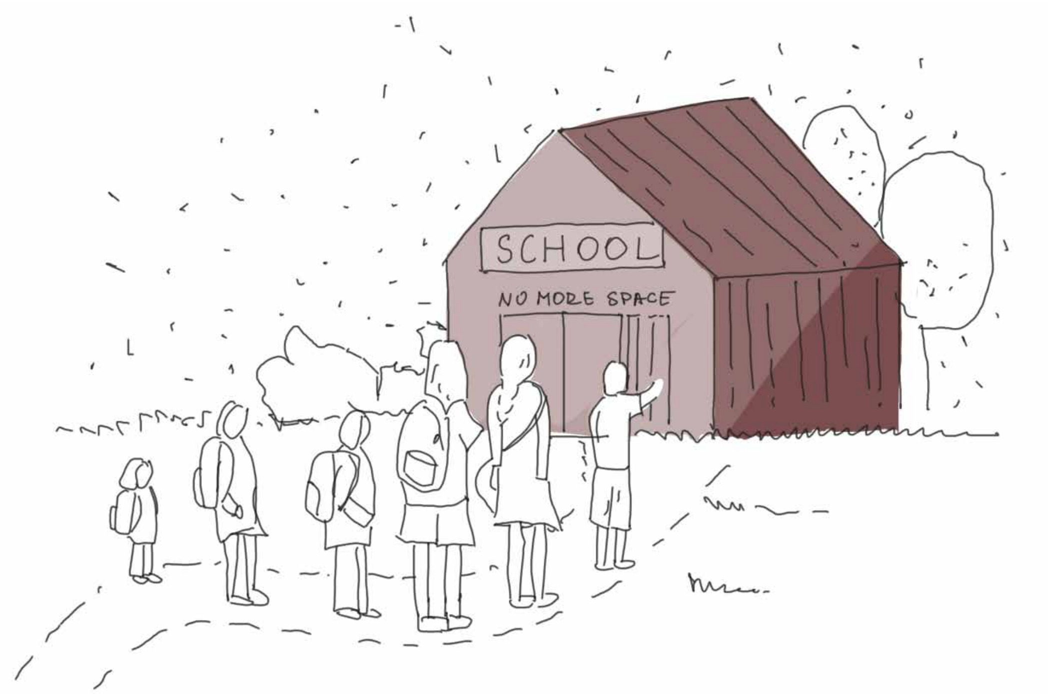


Fig. 14: Acess and equity the Zambian education system

2. Quality of education

The quality of education, especially in public schools, is a pressing issue. Effective learning is hindered by challenges such as insufficient teacher training, overcrowded classrooms, and a shortage of teaching materials. The pupil-to-teacher ratio in secondary schools in the Copperbelt province is the third highest in the country, standing at 37 students per teacher (Ministry of Education, 2024). This high ratio places a significant burden on teachers, making it challenging for them to provide each student with the necessary help and attention to the best of their abilities.

Additionally, many schools lack essential infrastructure, including sanitation facilities and libraries (Ministry of Education, 2024), which is important to keep in mind during the design process.

3. Teachers shortages

Teacher attrition - the rate at which educators leave the profession – has been increasing over the recent years and poses a significant challenge to Zambia's education system. This leads to a shortage of qualified teachers, especially in rural and remote regions. Key contributing factors to teachers leaving the profession include low salaries and financial strain, poor working conditions with inadequate facilities and teaching materials, and limited opportunities for career advancement. (Ministry of Education, 2024).

4. Environmental developments

In 2021, the Ministry faced severe impacts of climate change, resulting in significant infrastructure losses, including school roofs being blown off due to extreme weather conditions such as heavy storms and strong winds. Additionally, heavy rains and flooding blocked the roads, preventing students, especially in rural and climate-prone areas, from attending schools. (Ministry of Education and Management Development Division, n.d.) Due to these reasons, designing a climate resilient boarding school with a good working environment and indoor conditions can mitigate teacher shortages and challenging impacts of harsh climate conditions.

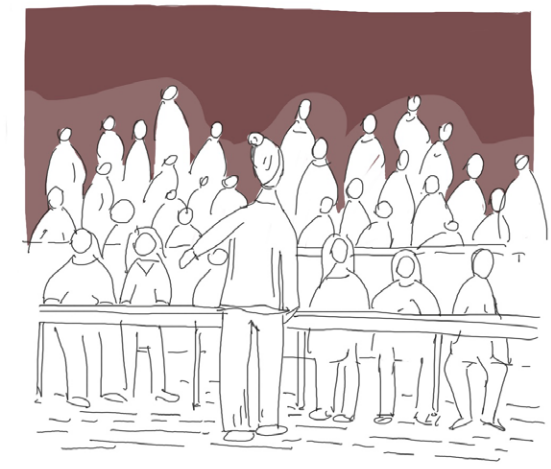


Fig. 16: Overcrrowded classroom

Fig. 17: Teacher attrition

Fig. 15: Climatic challenges

Based on successes and challenges of previous strategic plans and statistics, The Ministry of Education developed the Strategic Plan 2022-2026 embarking on a mission:

“To provide accessible, inclusive, equitable and quality education that enables individuals to attain their full potential and contribute to national development”
- 2022-2026 Strategic Plan, Ministry of Education

Reforms and prospects

Some key objectives in the plan include equitable access for all through Free Education Policy, improved funding and management, upgraded technology systems, enhanced teacher training and investment in educational infrastructure (Ministry of Education and Management Development Division, n.d.).

The education sector has additionally received support from the World Bank through initiatives such as the Zambia Education Enhancement Project (ZEEP), which focuses on constructing secondary schools in rural and remote areas, and the Zambia Enhancing Early Learning Project (ZEEL), which aims to expand early childhood education (Ministry of Education, 2024).

Recognizing the necessary need for sustainable solutions regarding the climate, the Ministry is committed to investing in the development of climate-resilient education infrastructure in high-risk areas, improving access to education for students in rural areas (Ministry of Education and Management Development Division, n.d.).

This projects relevance stems from the pressing educational challenges, prompting the creation of this non-profit architectural competition in an area, where it is deemed a necessity. The competition aligns with the Ministry’s mission to improve education systems, particularly in remote areas, supporting the objectives outlined in the Strategic Plan and contributing to overall national progress.

Designing a school according to Zambian Standards

The Ministry of Education has developed the Standards and Evaluation Guidelines (2015) to be used as basic benchmarks when developing a school as a provider of quality education. The document offers practical advice and guidance for managing the daily operations of schools, covering aspects from educational activities to ensuring a safe and supportive learning environment as illustrated in figure 18.

When designing and constructing school buildings, the safety of children should be a main consideration. All buildings should provide an appropriate environment for teaching and learning purposes in order to provide quality education. The spaces must be user-friendly and accessible to all learners. (Ministry of Education, Science, Vocational Training and Early Education, 2015)

Classrooms and educational facilities must be constructed using durable materials, thereby establishing firm and permanent structures capable of withstanding the daily use and activities of young students (Ministry of Education, Science, Vocational Training and Early Education, 2015). The use of robust materials such as bricks, concrete blocks, and concrete floors ensures the longevity of the buildings, which is essential in maintaining a safe learning environment.

By implementing these overarching measures, schools can create an inclusive and supportive environment that promotes safety, accessibility, and quality of education for all students.

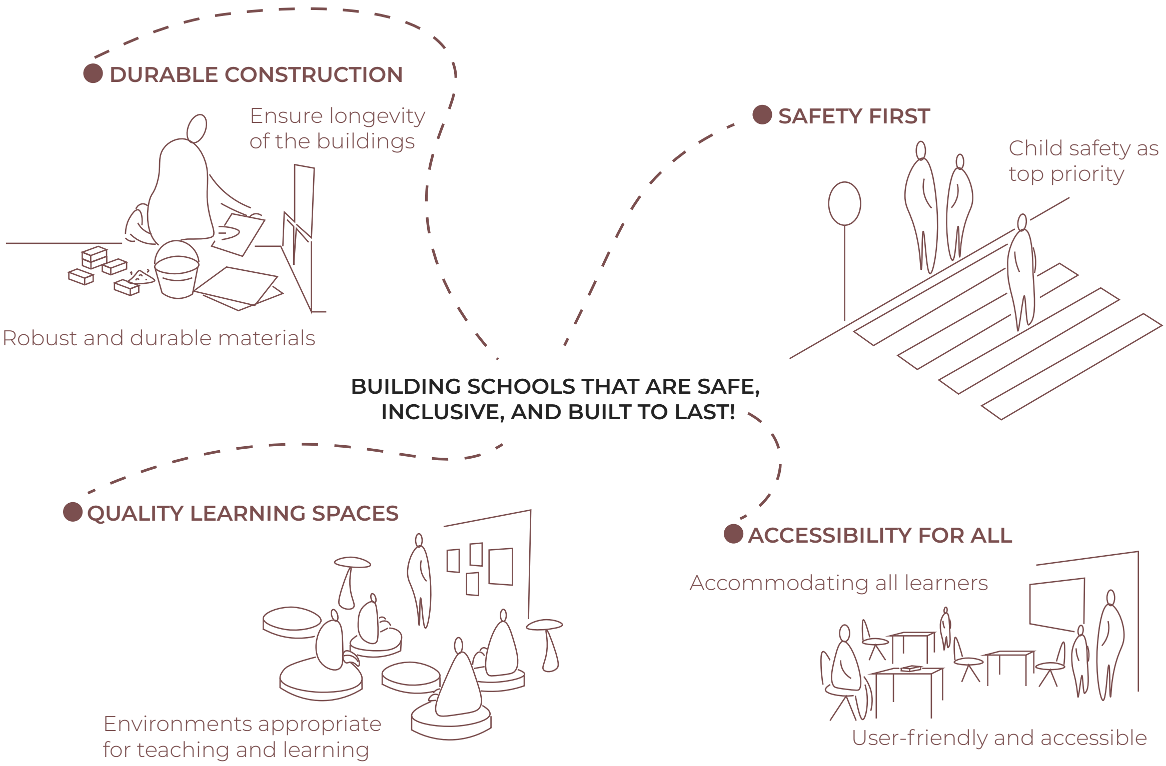


Fig. 18: Zambian school requirements

Conclusion

The Zambian education system has made significant progress in recent decades but still faces challenges such as teacher shortages, inadequate infrastructure, and climate-related issues. In Kashitu, where the demand for education is high, designing a boarding school presents an opportunity to address these problems while ensuring a qualitative environment.

Priorities in school design include using durable materials for climate-resilient structures, creating safe and accessible learning spaces, and accommodating both vocational and academic educational styles. Thoughtful planning of indoor and outdoor facilities will enable a socially engaged school community, while a comfortable indoor environment will improve the work and learning environment. By addressing these factors, the school provides an education quality that meets the needs of the school community, including both students, teachers and staff.

Fig. 19: Pupils attending english class, (INSPIRELI Awards, 2024)

03 Analysis

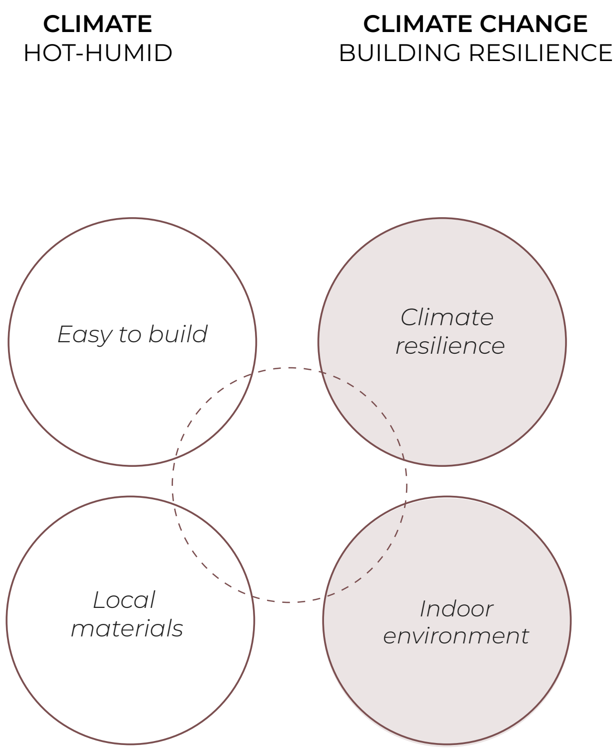


Fig. 20: Visualisation of the focus points in the analysis chapter

To create a contextually appropriate and climate-resilient design, the following chapter will first focus on conducting a detailed climate analysis. This step is crucial for understanding environmental factors that influence building design. Subsequently, a comprehensive site analysis is made to examine the location and its surrounding environment, as well as the increasing environmental issue of local deforestation.

Climate conditions

When designing a school campus in a country with a climate that contrasts with that of Denmark, it is essential to consider the weather conditions in close relation to the needs of the community. This is particularly important when thinking about the indoor climate and the use of local materials, as these two factors must work together to create a climate-resilient building. As the indoor climate is a central focus of this project, a thorough analysis of key environmental factors has been conducted. These include analyses of terrain, sun, rain, temperature, as well as relative humidity and wind, to provide data for the design phase. These analyses are based on weather data from the closest available source, the city of Ndola, which provides a representative climatic profile for the project site.

Climatic zone

It is essential to have a broad understanding of climatic zones and their associated factors. Zambia, a landlock country located in the heart of the African continent, primarily lies on a plateau with an altitude exceeding 1100 meters above sea level. The Kashitu site for the project is classified as a humid subtropical or tropical wet and dry according to the bioclimatic classification system developed by Wladimir Köppen. Consequently, all research and conclusions during the background and theory phase will be based on this classification. (Musonda et al., 2021).

In Zambia, three seasons can be distinguished (see fig. 21): from mid-August to mid-November, country experiences a warm and dry period. This is followed by a rainy season that spans from mid-November to April. After the rains, a cool dry phase lasts from April to mid-August, featuring minimal rainfall.

A hot and humid climate is typically characterized by high temperatures with minimal daily fluctuations, elevated solar radiation, and high humidity levels during the wet season. These conditions can lead to discomfort on particularly hot days and need to be taken into account while designing climate resilient building.

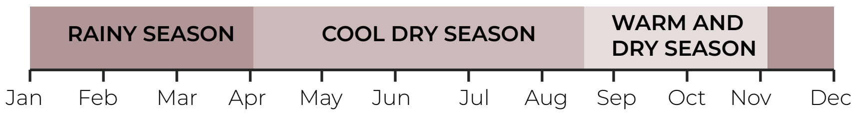


Fig. 21: Seasons of Zambia based on data from 1988-2017, remake based on (Musonda et al., 2021 p7).

Terrain

Topography has a significant impact on climate variability, particularly in areas with considerable elevation differences. This is evident in Zambia, where hills and mountains gradually transition into plateaus and broad, shallow depressions (Chisanga, Phiri and Mubanga, Kabwe Harnadih, 2024).

The project site is characterized by a high plateau that rises over 1200 meters above sea level with steep slopes as seen on figure 22. However, the terrain surrounding it is gradually sloping towards the south from 1400m to 1200 meters. This means that during the rainy season and its heavy rainfall the site can be at flood risk. Therefore, the design should consider some principles to withstand those risks. This will be further examined in regard to climate resilient design in the theory chapter.

Fig. 22: Topography map of Kashitu site and surroundings 1:100000, (QGIS Geographic Information System, 2025)

Sun

When considering climatic conditions and their forces, sun plays a crucial role in integrating architecture with building science discipline (Brown and Dekay, 2014, pp.1–4).

Since the chosen site is located near the equator, the sun's path significantly differs from that of Denmark. Sun path analyses for both the Danish city of Aalborg and Ndola have been made to provide data and comparison for a better understanding. As shown in figure 23, the length of the day in Ndola remains relatively consistent throughout the year. In both June and December, sunrise and sunset times vary only slightly. In contrast, Aalborg experiences a much bigger seasonal variation of almost five hours in sunrise and seven hours in sunset between summer and winter.

In Ndola, the sun is visible from all directions over the course of the year.. This continuous solar exposure requires a rethinking of Danish passive design strategies. As a result, these strategies must be adapted to suit the local conditions and ensure thermal comfort in the Zambian context.

Rain

Since the climate has a rainy season from November to March, it is crucial to understand this factor and its challenges for the design, therefore the precipitation has been measured for this extreme rainy season.

The highlighted area on the map (see fig. 24) marks Copperbelt, one of the regions that experience the most extreme rainfall reaching 1,160 millilitres of rain during rainy season which should be considered while designing a climate resilient building (Musonda et al., 2021)

Temperature

As seen in figure 25, daily temperatures during this rainy season typically range between 20°C and 25°C. After that, a cool dry phase lasts from April to mid-August, featuring minimal rainfall. Temperatures begin to rise significantly in September and October, even though rainfall remains low during this time. Due to Zambia's proximity to the equator, the length of the day remains consistent throughout the year. October is the hottest month, with average daily temperatures reaching up to 30°C, while July is the coldest month, with averages around 11°C. (Kashitu High School, 2024)

In recent years, these cooler periods have become

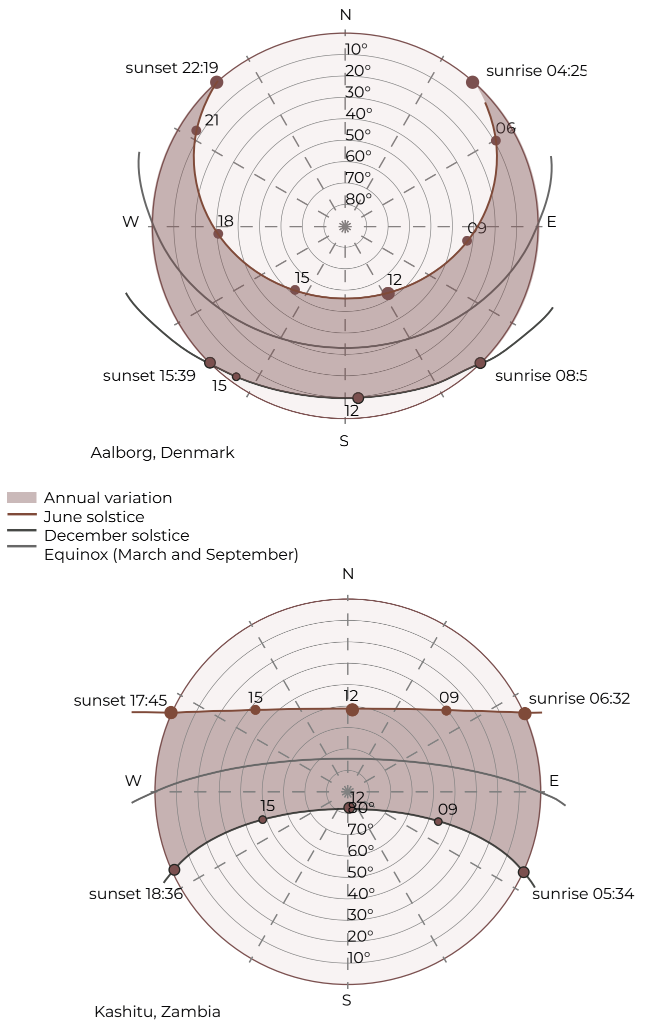


Fig. 23: Sun path analysis of Aalborg and Lusaka, remake illustration based on (Tukiainen, n.d.)

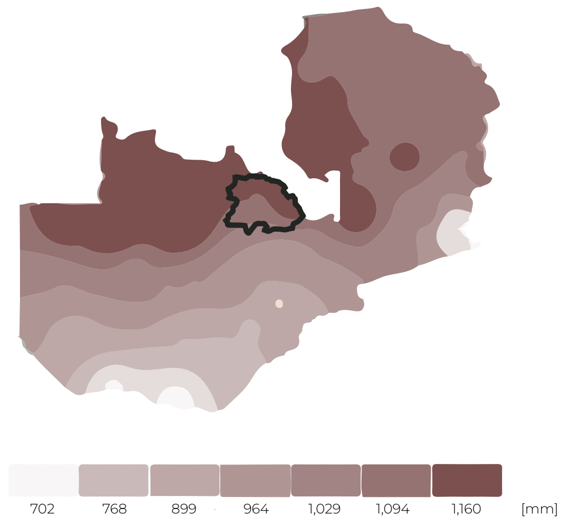


Fig. 24: Rainfall pattern over Zambia for rainy season, remake based on (Musonda et al., 2021)

"It's a cold time, of course, but the cold is beyond because it reaches the extent where children don't go to school and I'm learning at a boarding secondary school. And then it happens that we have to bathe with cold water. It's too much for us to handle so we skip classes sometime."
- Faith, (Save The Children, 2022)

more pronounced, leading to cold waves that are unfamiliar to the local population. This shift in regional climate patterns poses challenges, particularly for buildings such as schools, which often lack proper heating systems and building insulation. As a result, indoor environments can become uncomfortably cold. Reports from students indicate that these temperature drops are affecting their daily lives and educational performance. In this context, it is evident that the impacts of climate change are beginning to directly influence both learning conditions and overall well-being. (Save The Children, 2022)

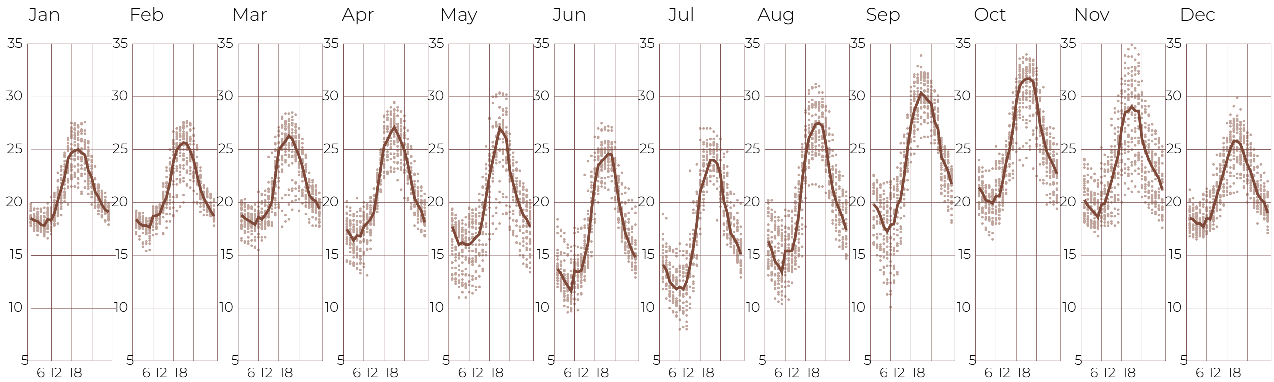


Fig. 25: Daily dry bulb temperature chart, remake based on (Betti et al., 2023)

Humidity

Subtropical climates, characterized by a wet season, can result in high levels of relative humidity. Typically, acceptable relative humidity levels range from 40% to 60% (Akpan, 2023). However, during the wet season, as indicated in the yearly chart in figure 26, these levels can soar to over 90%, exceeding the acceptable range. Consequently, it's essential for design considerations to address the challenges posed by humidity, which can affect both human lives, such as asthma, and mold growth in indoor environments as well as construction.

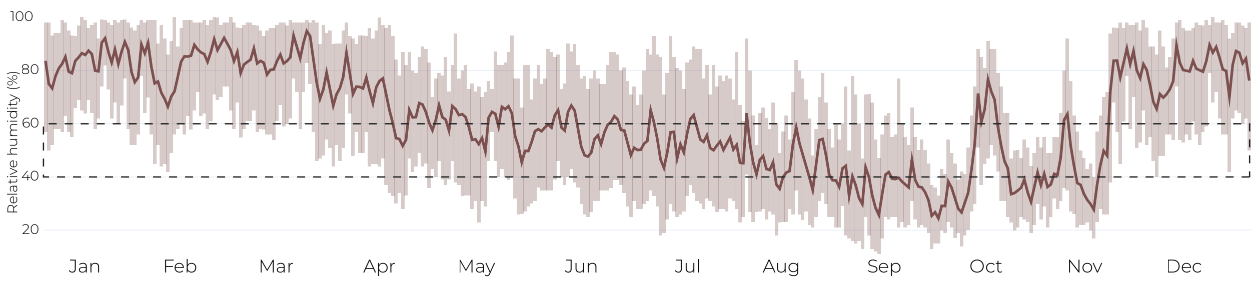


Fig. 26: Yearly relative humidity chart, remake based on (Betti et al., 2023)

Wind

Wind plays a crucial role in hot climates as it facilitates air movement, which helps cool down the environment. When considering a climate-resilient design, it is important to take wind into account, especially when exploring natural ventilation. Consequently, analyses for Ndola have been conducted based on the three main seasons: warm-dry, rainy, and cool-dry.

From mid-August to November (see fig. 27), wind mainly comes from south-east direction with an average speed of 5 meters per second and with maximum speed of 10,7 meters per second. During the rainy season, which lasts from November to April, it can be seen on the chart that west wind gets slower to 3 meters per second and is supported by northern blow with the same speed. The cool dry phase receives wind mainly from the west-south direction with speed ranging from 1.5 meters per second and occasionally reaching almost 8 meters per second.

When positioning the school on the site, it is important to consider the prevailing wind direction, specifically within the angle range of 0 to 30 degrees, in order to maximize natural ventilation.

„The people whose health is being harmed first and worst by the climate crisis are the people who contribute least to its causes'' (WHO, 2023)

Climate predictions and its stressors on people's everyday lives

Unfortunately, due to climate change, the conditions in Zambia are challenging for the Kashitu region. The dry and wet seasons have become more unpredictable than ever, covering the land with floods. These floods severely impact local infrastructure, especially roads, leaving communities cut off from essential services such as education and healthcare. As a result, schools are frequently forced to close, disrupting both learning and employment. Teachers often go unpaid during the rainy season, and after months without a salary, many choose to resign, leaving the educational system ineffective. The disruption of inability to access health care not only endanger physical health but also take a toll on mental well-being, leaving many residents in prolonged states

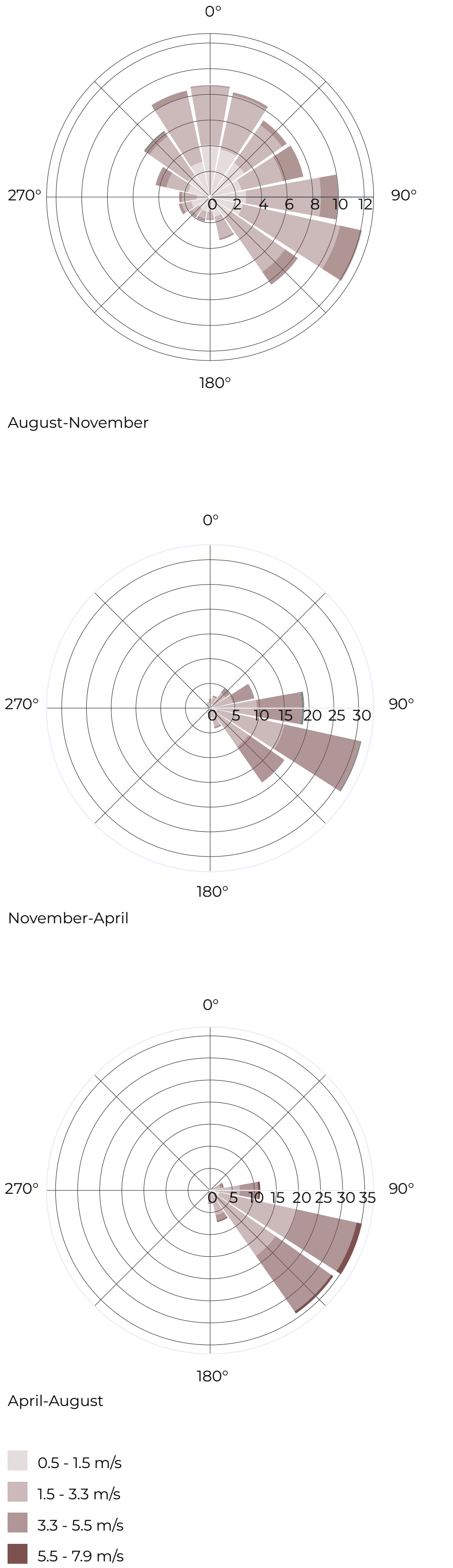


Fig. 27: Wind analysis for three seasons, remake based on (Betti et al., 2023)

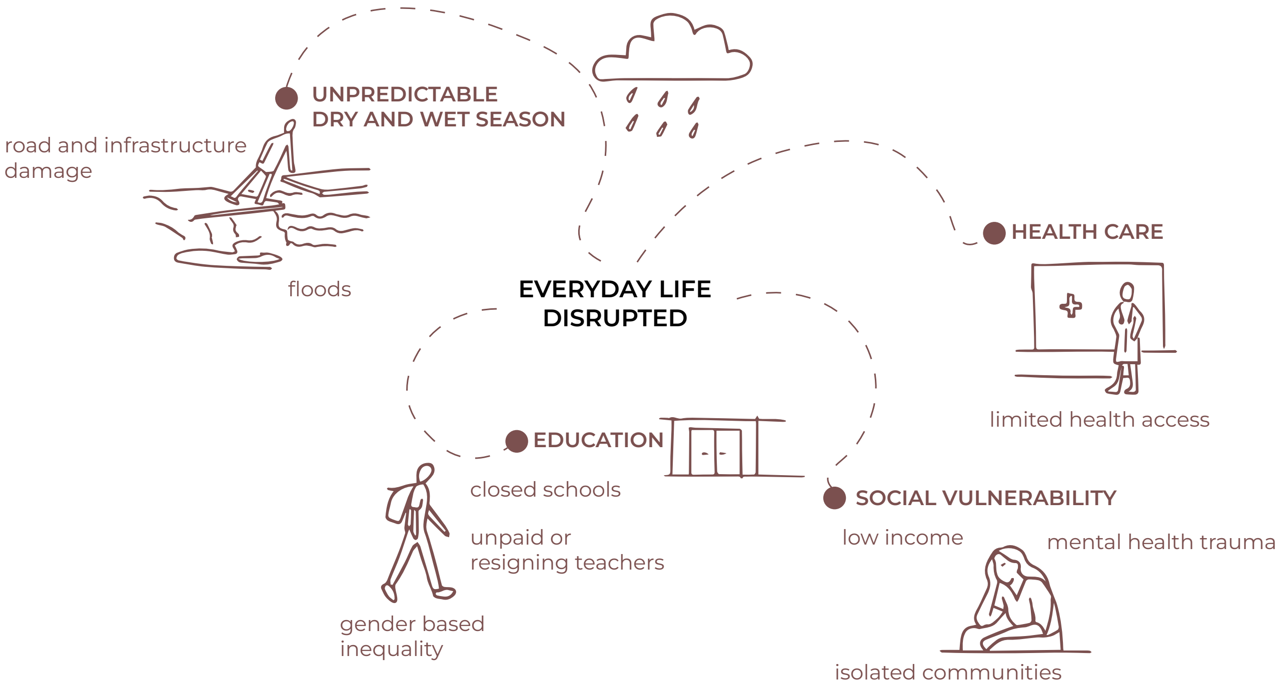


Fig. 28: Climate stressors., remake based on the (WHO, 2023)

of stress. (Rawlins and Kalaba, 2021)

These challenges are called climate stressors, which are indirect consequences of climate change that pose threats to the economic and social stability of communities, affecting everyday life as illustrated in figure 28.

Children and adolescents not only face the burden of growing up in a world shaped by the environmental damage of previous generations, but they are also expected to confront increasingly severe climate impacts throughout their lives.

Research shows that individuals born in 2020 will experience climate-related events two to seven times higher than those born in 1960. This heightened exposure places children at greater risk of long-term harm. Due to their rapidly developing brains, vulnerability to diseases, and limited ability to avoid risks or adapt to environmental threats, children are especially susceptible to the emotional and physical impacts of climate change (Pinchoff et al., 2023).

Fig. 29: Mapping of site location and surroundings 1:5000

Site analysis

The site, indicated with the dashed line (see fig. 29), covers an area of around seven hectares, which corresponds to 70.000 square meters. It is located close to the border of two provinces, with a railway line running parallel to this border. A nearby train stop enhances accessibility to the site, which is important given the shortage of secondary schools in the region.

The topography lines on the map indicate minimal change of height every five meters, suggesting a relatively flat landscape. The surrounding area includes a small number of buildings, primarily serving as a nursery school and community housing. Additionally, a church is located just south of the site, situated at the intersection of two roads. The site itself is divided in two building stages, with this thesis focusing exclusively on the first stage. T As a result, the program described in the following chapter will apply only to Phase One, which covers approximately 3.7 hectares. Phase Two is intended to include accommodation for teachers; therefore, sleeping facilities for staff will not be addressed within the scope of this thesis.

The school campus is enclosed by a fence, which helps define the site as a dedicated space primarily for students and staff. The school should also remain accessible to occasional visitors such as parents. However, the design approach prioritizes the needs and experiences of regular school users, ensuring a student and teacher centered environment.

The site location is surrounded by trees and green areas but will however not remain this way, as the level of deforestation is an increasing issue in the area. For this reason, it is not reliable to depend on the surrounding trees for shading and wind sheltering. This topic is further examined in the next section.

The way of living and its effect on landscape

When investigating the site, understanding the landscape is essential. As seen on figure 30, the area is predominantly covered by fields and Miombo woodlands. Unfortunately, traditional agricultural practices have resulted in significant deforestation across Zambia, including the project site, leading to many cleared areas devoid of trees. This issue can be attributed to three primary factors: charcoal production, timber logging, and land clearing for slash-and-burn agriculture (Rawlins and Kalaba, 2021). Charcoal production has a side effect not only on the landscape's visual appeal but also on local biodiversity and communities. Small traders are engaging in unsustainable wood harvesting practices and illegally selling their products across the border. (Biggar, 2022)

***„ Previously, this area was forest. You could not see very far as our forest was very dense. Now it is all gone. We can't even find a tree anymore for charcoal making. We destroyed everything and now we have no trees left.''
- Joffrey Nyanga, charcoal-maker living in Mushindamo district, North-Western province, Zambia (Gonzalez, 2021)***

While this practice may offer economic support to household with limited access to electricity, many communities may not be fully aware of its long-term environmental costs. Besides air pollution, the deforestation of Miombo woodlands results in a loss of soil organic carbon, reducing soil fertility and harming ecosystems as well as biodiversity. Soil carbon plays a crucial role in water retention during heavy rainfall, and its loss leads to less water storage capacity, increasing the risk of flooding. (Biggar, 2022)

These pressing issues highlights the importance of having a sustainable approach when designing. To refrain from contributing to further deforestation, it would be beneficial to utilize local materials or sustainably sourced raw materials in the design process.

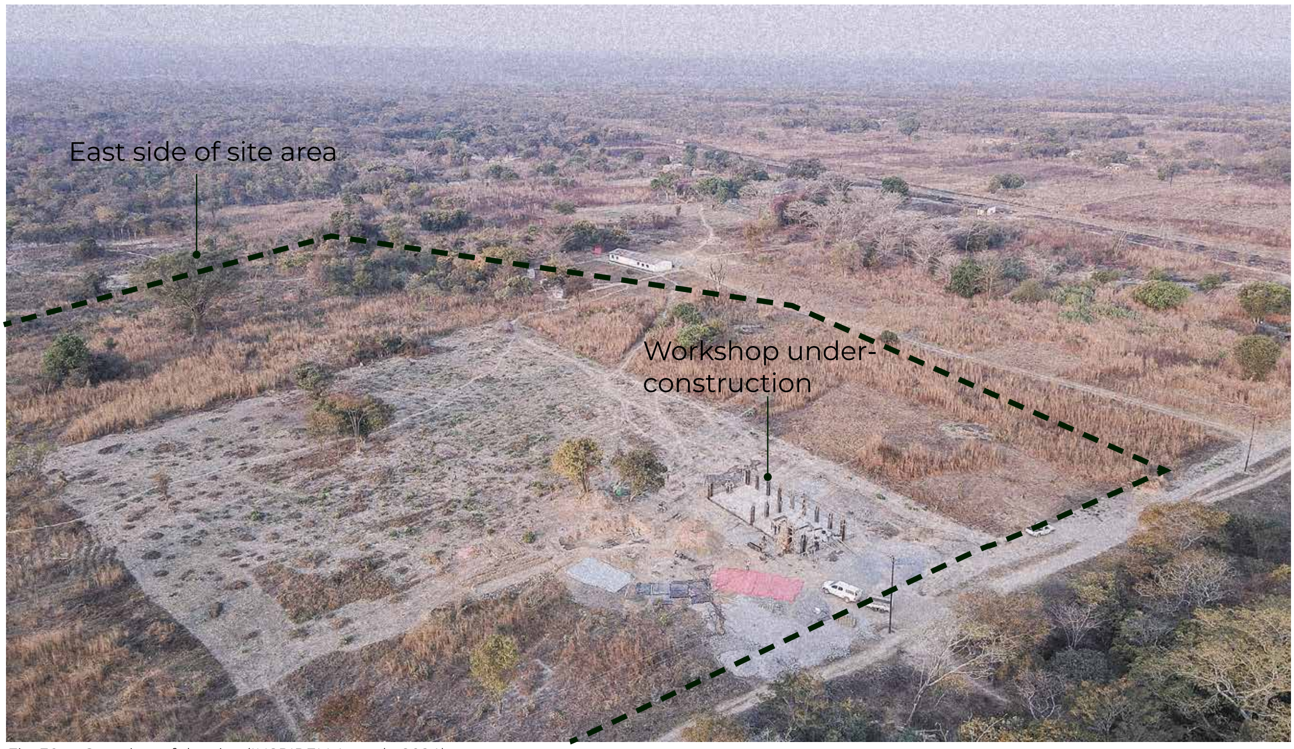


Fig. 30: Overview of the site, (INSPIRELI Awards, 2024)

Conclusion

The Zambian climate and the Kashitu site conditions demonstrate the urgent call for designing with a climate-resilient approach. The region's hot-humid climate, marked by a prolonged rainy season, is further complicated by alternating cool and warm periods, high solar radiation and strong winds (see fig. 31). These factors call for an interplay between sustainable design and indoor climate.

Given the site's high sun exposure, with peak temperatures occurring in the evening, strategic building orientation and the inclusion of passive shading elements, such as overhangs or shutters, can reduce solar heat gain and improve the indoor climate. Elevated humidity levels, especially in the evenings, further emphasize the importance of effective natural ventilation. In addition, the heavy rainfall calls for design solutions that address water management and resilience to prevent damage and create a safe environment.

When designing the building, roofs and walls should incorporate thermal insulation to address the low temperatures experienced during the dry season. Additionally, to support sustainable development in Zambia and reduce deforestation, the design should prioritize the use of local, low-embodied-energy materials, which will be introduced in the following chapter.

Fig. 31: Subconclusion on analysis

Fig. 32: Zambian children, (INSPIRELI Awards, 2024)

04 Theory

LOCAL MATERIALS
COMMUNITY-DRIVEN DESIGN

INDOOR CLIMATE
PASSIVE STRATEGIES

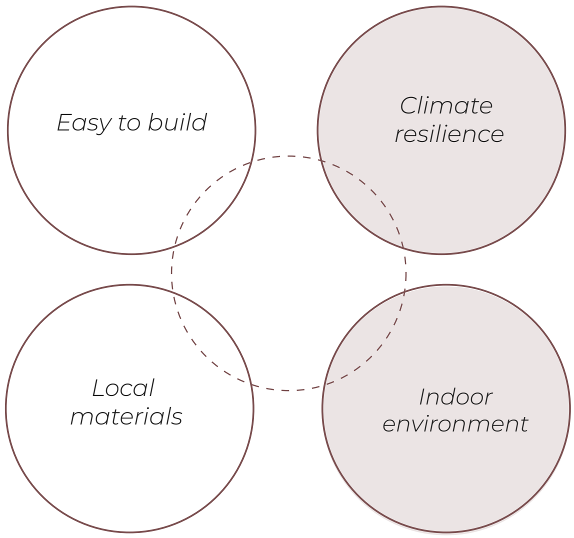


Fig. 33: Visualisation of the main focus points in the theory chapter

The analysis part gives knowledge about the climate conditions on site and its stressors. In the theory chapter, an investigation on local materials as well as traditional building practices and community-driven design will be conducted to cover two other main focuses of this thesis; the use of local materials and ease of building.

The theory chapter will end by investigating specific requirements and design principles regarding a qualitative indoor climate, as well as investigating on climate resilience principles. This ensures all main focuses are being covered, as seen in figure 33.

Local materials

The theory chapter starts with an explanation of emissions caused by the construction sector in general and why it is therefore beneficial to use local materials to decrease the global warming potential and to respect the local traditions while implementing vernacular architecture. After this introduction, research on five locally available materials is shown, together with their properties and availability.

African Building Sector

The buildings and construction sector (BCS) plays a crucial role in the total energy production of global emissions being responsible for over 35 percent of it and 40 percent of all solid waste. Additionally, only nine percent of global raw material extraction is circular, losing a lot of potential for better human wellbeing and climate change (Westerholm, 2023).

The planet's boundaries are limited, and BCS impacts are reducing biodiversity, changing climate patterns and everyday life. Therefore, an urgent call for a change from a linear to a circular building model can significantly reduce the consequences of take-make-waste approaches leading to positive environmental benefits (Westerholm, 2023). Therefore, calculations regarding the global warming potential of materials will be taken into account when designing a new educational project.

Africa is responsible for only less than three percent of global greenhouse gas emissions. However, due to rapid population growth which is the highest in the world (see figure 34), urbanisation and wealth combined with the current built environment and infrastructure contribute to climate change, giving a call for a circular approach. Therefore, it is crucial to design with sustainable solutions to meet social needs without contributing more to the climate change. A circular approach can especially be beneficial because of its social and economic impacts which are significant in developing countries (Westerholm, 2023).

Vernacular Architecture

Traditional African architecture is based on the bio-climatic approach where construction materials are manufactured out of local raw materials. However, this circular method mostly occurs in the rural areas where in urban context, carbon-intensive materials are replacing local resources, contributing to climate change (Westerholm, 2023). Since this thesis is designing in a rural area, research about these local materials is essential.

Low carbon, local materials represent traditional building practises among various African countries, where building a house by its owner and neighbours help is often being seen (Westerholm, 2023). This, together with the cultural context, describes a concept of vernacular architecture, where the aim is to design a climate-resilient building that utilizes local materials while respecting local traditions (Ghisleni, 2020).

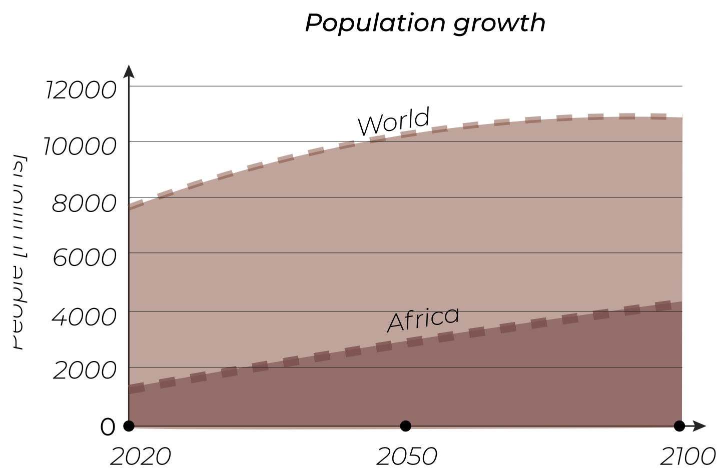


Fig. 34: Projected population growth chart, remake based on (Westerholm, 2023).

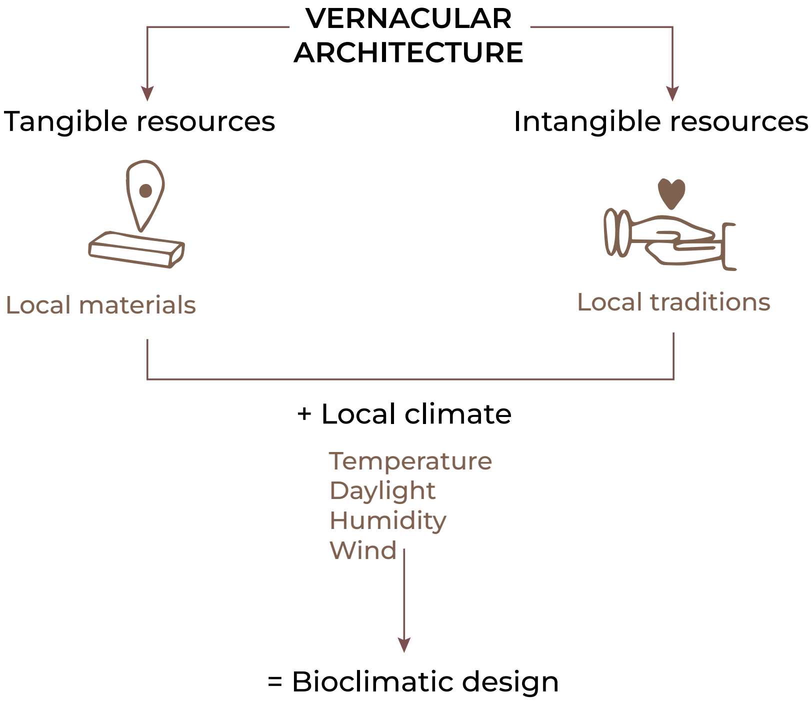


Fig. 35: Use of theory of tangible and intangible recourses, based on (Gregorio, Domenico and Pierluigi De Berardinis, 2023)

Vernacular architecture is structured around two categories of resources: tangible and intangible (see figure 35). Tangible resources refer to physical materials available for construction, while intangible resources encompass knowledge, traditions, and design principles. (Santos, Ferreira and Lanzinha, João C. G, 2024).

This can mainly be seen in the rural areas where traditional dwellings are built locally, giving a possibility to return the materials to nature when they are not needed anymore. (Westerholm, 2023). Both recources will be examined in the following chapter.

The palette of traditional materials

Nowadays, especially in Europe, the focus on using bio-based materials has been increasing with the replacement of carbon-intensive materials. This is in contrast with Africa, whose approach is moving towards imported, unsustainable sources while leaving the traditional practises of bioclimatic architecture behind. This is caused by how traditional architecture is perceived by locals – as handmade and not professional with the vernacular look. However, the production of bio-based materials is growing fast there which could give a lot of opportunities regarding lowering emissions (Westerholm, 2023). These local bio-based materials are researched on in detail in the following chapter to provide knowledge about their limitations and possibilities.

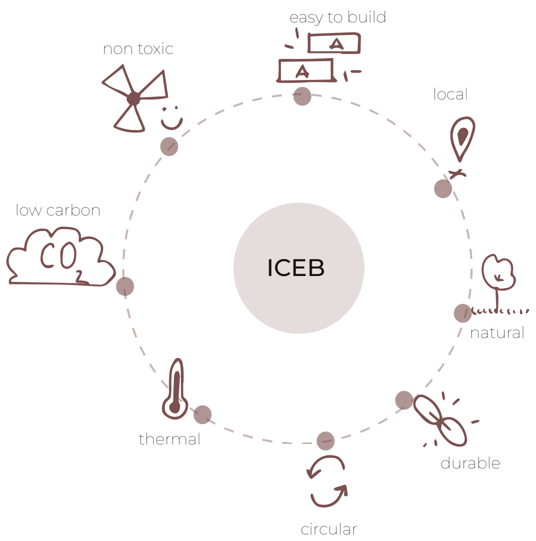


Fig. 37: Earth properties, remake based on (Westerholm, 2023).

Fig. 36: Map of use the traditional earth construction in Africa, remake based on (Westerholm, 2023).

Earth – ICEB blocks

Over 40 percent of the Zambian population still lives in houses made from earth, even though a shift to concrete is seen in the last century. As seen in figure 36, earth architecture is well known in Zambia. Earth can be seen as a material connected to poverty. However, its properties like low embody energy, ease to recycle, and other (see figure x) give a chance to design a climate resilient building with a circular approach while using it as a construction material (Westerholm, 2023).

Additionally, earth can create cooler and more comfortable indoor environments than imported building materials. With the ongoing climate change in mind, using local materials also ensures that the local communities have knowledge about them, making it easier to adapt, maintain, and repair them. (Gibberd, 2025).

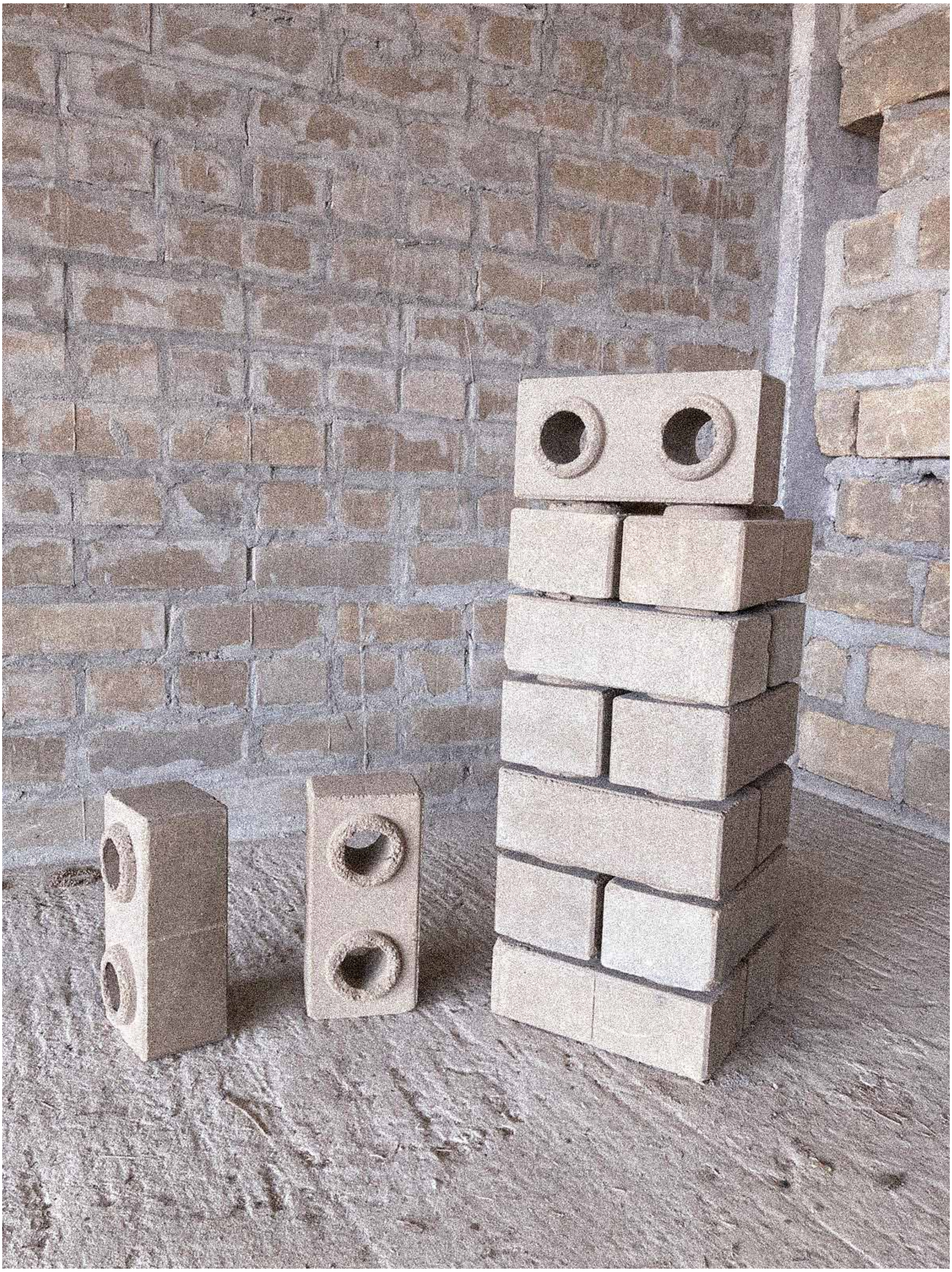


Fig. 38: Iceb blocks, (INSPIRELI Awards, 2024)

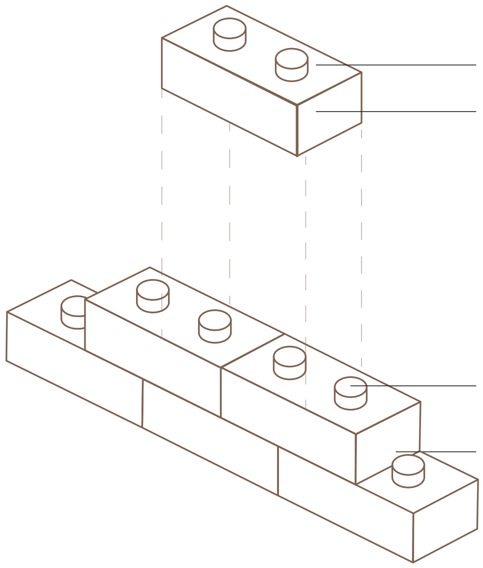


Fig. 39: Visualization of ICEB construction, based on (Kashitu High School, 2024)

While having a circular approach in mind and the competition brief which states to use unburnt earth blocks, interlocking Compressed Earth Blocks (ICEB) will be researched on more, providing data about its challenges and possibilities. This type of earth block is traditional and can be made using a manual brick press machine, as seen in figure 40. The blocks are made from a mixture of water, earth and cement and can just be dried outside (Westerholm, 2023). The addition of this amount of cement was developed and tested to ensure bricks that can withstand extreme weather conditions by their strength, while at the same time protecting the bricks for termites. The holes in it allow for concrete filler, if reinforcement should be necessary (Kashitu High School, 2024)

Additives to improve its properties as well as different ratios of the composition are possible due to the availability of raw materials. This easy method offers a solution for creating durable, affordable, and environmentally friendly buildings by leveraging the inherent properties of locally sourced soil (Irwan, Zamer and Othman, 2016).

The soil and cement stick together because of chemical properties and are compressed together to make a constructive material. They blocks are assumed to be easy to build because of their shape, making them easy to stack. (Irwan, Zamer and Othman, 2016). Not only do they have a shorter construction time, but they are also more energy efficient in the constructing process than other building blocks and they have the advantage of no need of firing, saving emissions (Westerholm, 2023).

ICEB are already introduced on site where experts helped the local community build the first multi-functional house. This means that the principle of ICEB is already determined, and it therefore is logical to use the same blocks when designing.

The competition encourages the use of ICEB with a size of 140 x 290 mm as a main load bearing structure which can be complemented with additional structural or non-structural elements if needed. Research upon earth as a construction material confirms this choice because of its availability and the way it can be produced on site without heavy machinery and its properties.

Fig. 40: Manual brick press (INSPIRELI Awards, 2024)

Global warming potential

Research shows that locally sourced and produced earth materials have the lowest embodied energy compared to other earth constructions (figure 41). Unfortunately, while adding cement and transportation considerations, this value can increase. This is illustrated in figure 41, where compressed stabilized blocks which include cement (CsEB) have a higher GWP in comparison to compressed earth blocks (CEB) or rammed earth. However, they still are significantly lower than fired blocks or concrete blocks, making them a good material to build with in areas where soil is available.

While focusing on sustainability and quantitative aspects of earth material, its impact on social aspects can't be omitted. As mentioned, Zambia is a country facing a lack of social and economic capacity. The production of ICEB, can provide jobs for many people, decreasing social iniquity and supporting sustainable development. Adapting the use of interlocking blocks can reduce costs of building processes and has a significant lower embodied energy compared to other constructions (see fig. 42).

Additionally, no need for firing not only lowers the embodied energy for the material but also slows down the deforestation mentioned in the analysis chapter. For burning the bricks, charcoal is needed, and as counted, to produce approximately 10,000 bricks, five trees need to be cut down which contributes to climate change (Chishala, 2024).

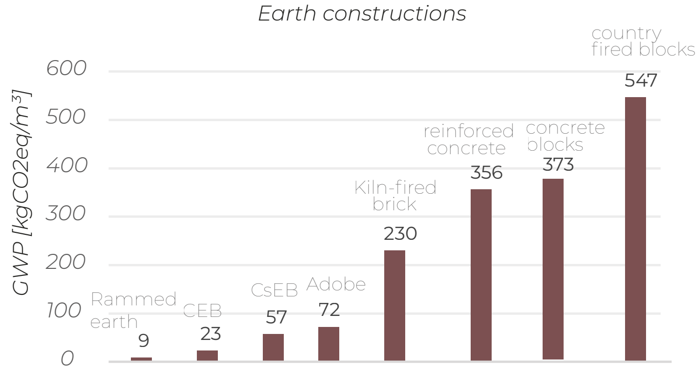


Fig. 41: Data of embodied emissions cause by 1m3 of earth block, remake based on (Westerholm, 2023, pp. 21)

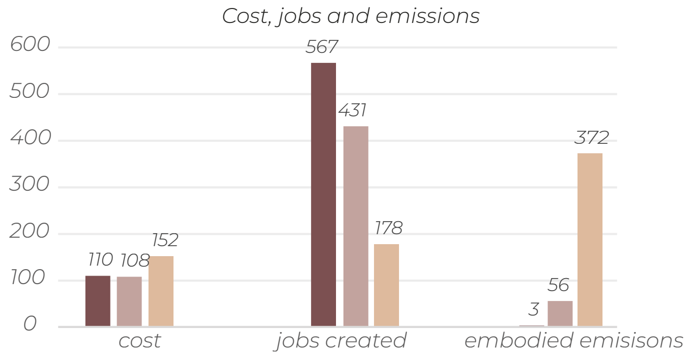


Fig. 42: Data of cost in euros/m³, job in numbers generated by the sector and embodied emissions in kgCO2eq/m³ of CEB and concrete, remake based on (Westerholm, 2023, pp. 21)

Stone

Stone is a traditional material known for its maximum durability and no need for maintenance and manufacturing. It has been used in Africa as a structural material for hundreds of years and offers a lot in terms of circularity and bioclimatic architecture (figure 43). It has a naturally low carbon footprint and can be easily reused and put back into nature. Its high thermal capacity is beneficial in hot, humid climates, helping to keep the space cool during the day and warm at night. Stone can therefore be considered in the design phase, either for the building or for urban designated areas because of its low water absorption (Westerholm, 2023).

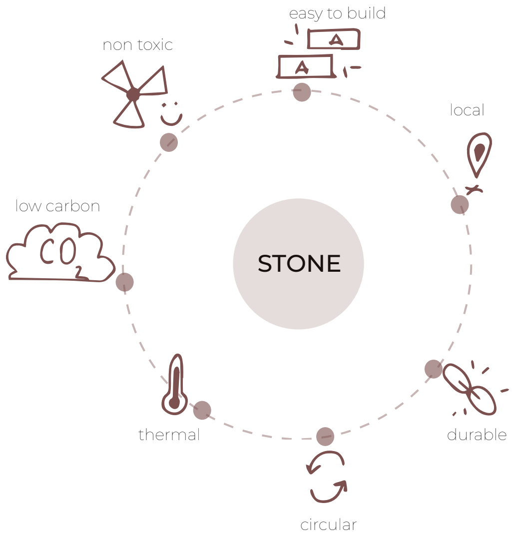


Fig. 43: Stone proprieties, remake based on (Westerholm, 2023).

Fig. 44: Sorting out stones, (INSPIRELI Awards, 2024)

Wood

Africa provides many wood species that can be locally used and are sustainable for building design, especially in Zambia where wood is a traditional material for load-bearing structures and other building elements. It can be assumed that in a country that has a problem with deforestation, using wood with a holistic approach is harmful, but the purpose of its use matters. Nowadays, almost 90 percent of the trees are cut to use as fuel. Using this source as a fuel releases carbon into the atmosphere, whereas relying on wood in construction can lower the emissions due to its carbon-storing capacity. Timber is carbon-negative (see fig. 45), which means that it stores more carbon than it uses for the production and processing stage. Therefore, choosing timber as a construction material can be climate-smart (Westerholm, 2023).

Moreover, sustainable wood production can create over 25 million job opportunities, enhancing economic and social wellbeing. However, it is crucial that the wood is harvested sustainably, with an emphasis on minimizing waste (Westerholm, 2023).

Choosing this material in the design gives the possibility to not only contribute to sustainability, but also to a better indoor climate in a way that it reduces humidity levels and creates a well-being environment. (Ligna-systems, 2025) However, when desiging with this material, other factors like thermal capacity and their general performance in a hot-humid climate should be taken into consideration.

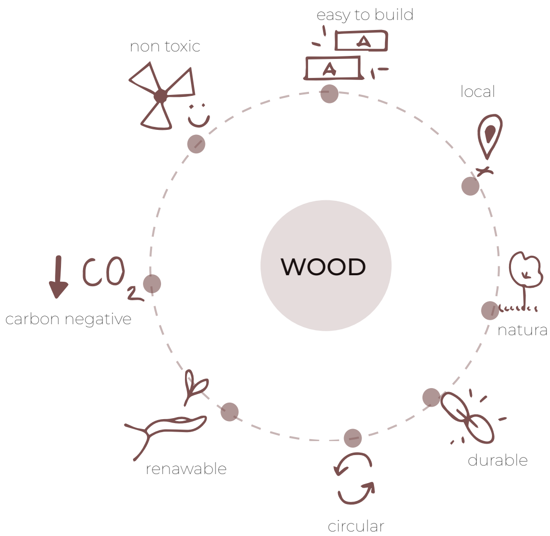


Fig. 45: Wood proprieties, remake based on (Westerholm, 2023).

Fig. 46: Wood species among Zambia, remake based on (Pelletier et al., 2019)

Bamboo

When considering tangible materials in vernacular architecture, bamboo has always played a crucial role in traditional African building approach. As seen in figure 48, it can be locally harvested in Zambia. An aesthetic advantage is that it directly expresses the history through its ancient appearance. (BambooU, 2022). Its proprieties are common to what is previously mentioned for wood; however, bamboo is more efficient compared to wood in terms of carbon sinking (Westerholm, 2023). It has the potential to store double the amount of carbon when being compared to wood. Another advantage can be seen in.

While bamboo is already a commonly used construction material, it has the advantage of extending its lifespan by turning it into pulp (Westerholm, 2023) which should be considered as an advantage when using it as a building material. Bamboo provides a range of construction solutions because of its high strength and low weight. It can therefore be used in the construction of roofs as well as wall constructions. Additionally, recent developments provide opportunities for cross-laminated bamboo (CLB) (Westerholm, 2023).

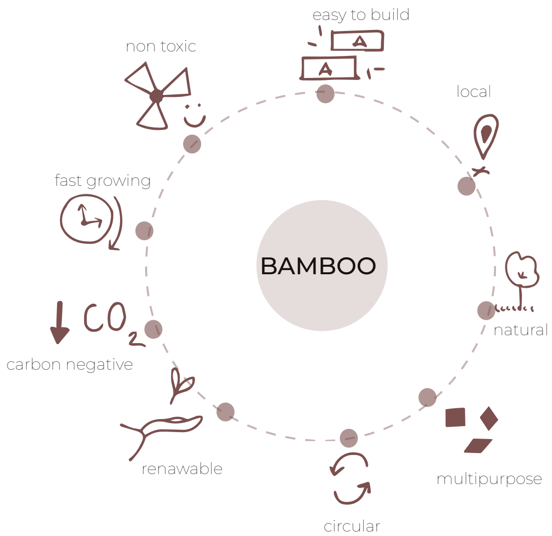


Fig. 47: Bamboo proprieties, remake based on (Westerholm, 2023).

Fig. 48: Bamboo distribution in Africa,rremake based on (Westerholm,

Straw

Africa has been historically using straw in architecture (see fig. 50), mainly seen in roofings. This thatching method comes from traditional practices and is very affordable in terms of economy. The structure lies in stacked layers of straw (maize, wheat, rye, oats etc.) which are harvested locally. (Westerholm, 2023).

Using straw as a building material can be beneficial in terms of having a low environmental impact. The fact that it is harvested locally and can be seen as a renewable source, allows for upcycling and avoids waste which describes its low embodied carbon footprint, as illustrated on figure 49 (Westerholm, 2023).

However, when designing a school building, fire safety has to be considered when using such a flammable material (Westerholm, 2023). Therefore, it might be difficult to satisfy requirements regarding fire safety when designing a building that is mainly used by children. However, following the idea of vernacular architecture, the design could think about using straw in outdoor areas.

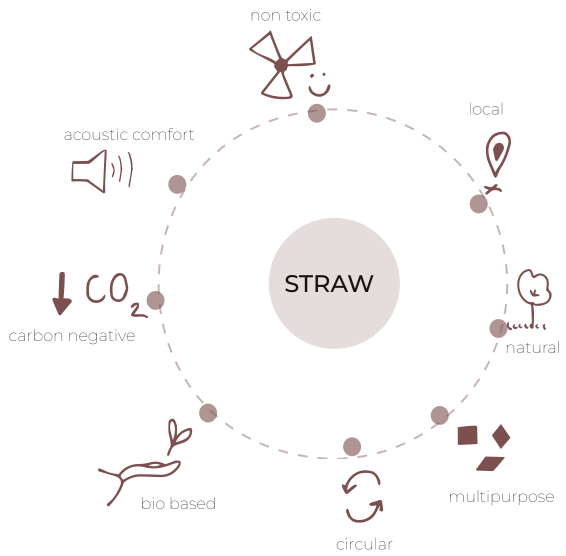


Fig. 49: Straw proprieties,remake based on (Westerholm, 2023).

Fig. 50: Traditional straw architecture, (Kashitu High School, 2024)

Traditional building principles

Due to the absence of a proper framework and the necessity for local communities to construct the buildings themselves, the used construction principles are rather simple. These principles are rooted in older generations and traditions, leading to slight variations in techniques. However, certain overall principles are applied consistently as all buildings must address the common challenges posed by the local climate (Gregorio, Domenico, and Pierluigi De Berardinis, 2023).

Examples of overall principles concerning construction is the use of wood or soil, combined with additives (see fig. 51). Walls are often protected from water and termites by adding a protection layer or material to the lower part of the wall. Examples of these additives are carbolite or lime. When using bamboo as a construction material, it should be treated and made sure that it is not in direct contact with the soil to prevent rotting. The roof can protect the higher part of the wall if it has a suitable overhang, but it must also have a slope that is steep enough to eliminate the water on the roof itself. These roofs are often constructed out of plant fibre, bamboo, or reeds. In a case like this when bamboo is not used for structural purposes, it is often cut in half and weaved in bundles, which is then often used for covering purposes. Dry plant fibres can be made into bundles and can then be bound as a way to join elements together, often used in roofs (Gregorio, Domenico, and Pierluigi De Berardinis, 2023).

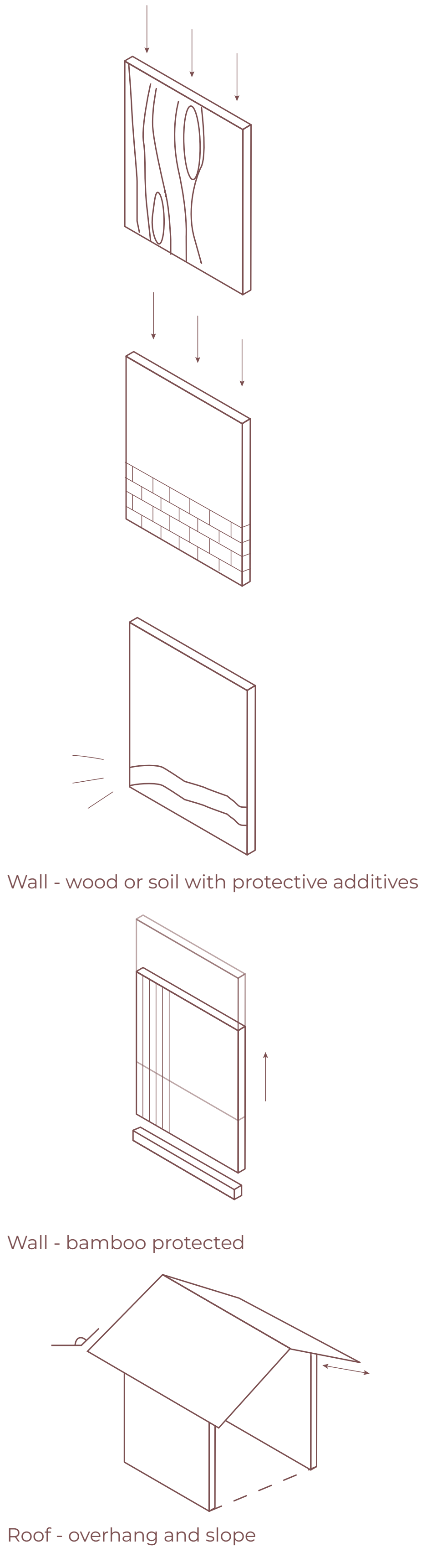


Fig. 51: Illustration of construction principles, remake based on the research of (Gregorio, Domenico, and Pierluigi De Berardinis, 2023)

Fig. 52: Locals engaged into contruction process, (INSPIRELI Awards, 2024)

Sub conclusion

It can be concluded that while designing a climate-resilient building with a sustainable approach in mind, it is essential to think about using local materials with a low global warming potential. This can help improve the socioeconomical capacity of Zambia while at the same time lowering the trend to use imported, non-sustainable materials.

This approach can be achieved by utilizing local materials and traditional techniques. Local, African materials offer low embodied energy, although, some of them have their challenges. Research shows that ICEB have a low embodied energy and are beneficial in terms of indoor climate. Furthermore, wood and bamboo can be used for loadbearing or lightweight structures, while straw due to fire safety concerns and stone because of its low water absorption is preferred in outdoor areas to maintain the local and traditional character of vernacular architecture.

As conducted, all these materials have a positive impact not only on the environment but also on society. The production of them can offer a numerous of job positions for locals, enhancing their well-being and promoting the green sector.

Designing with local materials is one of the main focusses of this thesis. They will be evaluated in terms of their properties, as well as aesthetics and global warming potential later on in the process. However, when only using local materials does not translate into a comfortable indoor environment, imported materials will be considered. It is important that these will also be evaluated on the previous researched aspects, especially regarding the global warming potential. A balance between keeping the building sustainable in terms of LCA but ensuring a qualitative indoor climate is a challenge that will be prominent in the design process.

Community-driven design

Community - driven design goes back to the essence, which is to look at the needs of the people it serves. No matter how hard an outsider tries to understand the local community and its needs, it will always be a challenging task to map this out (Allu, 2024). Therefore, involving the local community, especially in the first phase of the design when identifying the needs, is essential for a usable design.

In order for the design to work and serve the actual needs of the people, a common approach is to source everything locally, including the manpower and construction techniques. This aligns with the competition principle, where stated that "the technology has to be simple enough, so that local workers can learn to build the construction with minimal supervision during the construction process only" (INSPIRELI Awards, 2024).

Case study – Mzuzu University Health Centre

The case study regarding a university health centre is built in Malawi, a country located east of Zambia. The project was designed and constructed in two phases, where a so called 'kit of parts' was created during the first phase to make possible future expansions easier. This expansion in the second phase could then use the already established strategies and only improve where necessary. Conversations as well as measurements were done in the ten years between the phases to have this data to be able to improve (FoBE and Fielden Foundation (FCBStudios), 2015).

The ease of the building practise is prominent in this project where a prototype for future expansions is made, explained step by step so that a small team of local craftsman can efficiently fabricate buildings without the use of cranes or scaffolding. Modular timber frames are used in combination with blocks to stabilize the construction (FoBE and Fielden Foundation (FCBStudios), 2015).

Another focal point in this case study is not to contribute to the usual practise of importing expensive products, a process that harming

Fig. 53: University Health Centre Malawi view on building (FoBE and Fielden Foundation (FCBStudios), 2015).

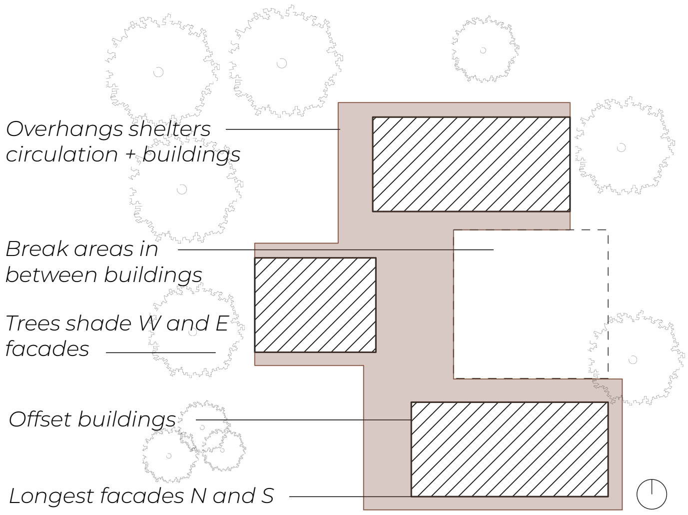


Fig. 54: Remake plan University Health Centre Malawi (FoBE and Fielden Foundation (FCBStudios), 2015).

the environment. Instead, local, and sustainably produced building materials are used. The project tries to avoid using cement or hardwoods and instead uses wood and compressed earth blocks.

The used softwood timber is handcrafted from locally sustainable pine plantations, whereas the soil blocks use a hydraform press, which is operated manually. Both interlocking and non-interlocking soil blocks are used, where the first one mentioned has the advantage of not needing cement mortar in between the blocks, because they are stabilized by the interlocking principle. The floors are avoiding the use of concrete and instead use fired clay tiles, produced in a local pottery (FoBE and Fielden Foundation (FCBStudios), 2015).

The hospital site is assumed to have similar climatic conditions as Zambia, also regarding the overheating problem. To design with this climate in mind, the building is oriented to the west and east, having the biggest facades with openings to south and north, as seen in figure 54. To protect the minimized facades from overheating on the east and west side, trees are places in these orientations to ensure shadow. The buildings on site are also placed with an offset from each other to have sufficient wind in between (FoBE and Fielden Foundation (FCBStudios), 2015).

Besides the orientation of the buildings, the construction itself also contributes to ensuring a comfortable indoor climate. The roofs for example are made from galvanised aluminium-zinc sheets to reflect the solar radiation, lowering the heat transfer going into the building (FoBE and Fielden Foundation (FCBStudios), 2015).

This case study is intriguing because it emphasizes community involvement both in the design phase as well as during the construction. This is clear by the ‘kit of parts’ that is made to have an easy understandable construction phase. Not only does the master plan give an insight into the placement of the buildings, but it also provides information about the placement of outside areas and overhangs to protect the building from overheating. This, together with the local and sustainable use of material, makes this case study extremely relevant for this thesis.

Designing a school in a subtropical climate

In general, people spend more time indoors than outdoors, making the indoor climate a crucial factor that affects daily life. Poor environmental conditions can lead to headaches and decrease learning and work effectiveness. David Cali emphasizes that achieving a balance between a room and its surroundings is essential for a good indoor climate. (Møller, 2023)

As previously mentioned, developing countries often lack environmental consciousness; however, Denmark faces poor learning conditions in primary schools as well. Research found that CO2 levels in over 50 percent of classrooms were significantly above the recommended limits (Masseeksperiment, 2021). This shows that no matter what climatic zone and capacity, indoor climate problems can occur. (Møller, 2023)

In hot, humid climates, it can be challenging to apply established strategies that work for this climatic zone, as the design must prioritize heat reduction and cooling. Therefore, when designing with the aim of a comfortable indoor climate, it is important to focus on the most critical factors, as researched on in the following chapter.

Bioclimatic architecture

In order to provide an adequate learning environment, passive and bioclimatic architecture will be followed as a part of the sustainable approach. The first the term bioclimatic architecture was used, was in 1963 by Olgyay and was ten further developed by Givoni in 1996 (Butera et al., 2023). It focuses on integrating natural cycles and making efficient use of them while minimizing harm to the environment (see fig. 55). The primary goal is to ensure human comfort, which is assessed through factors such as temperature, humidity, wind speed, solar radiation, passive heating and ventilation. (Butera et al., 2023)

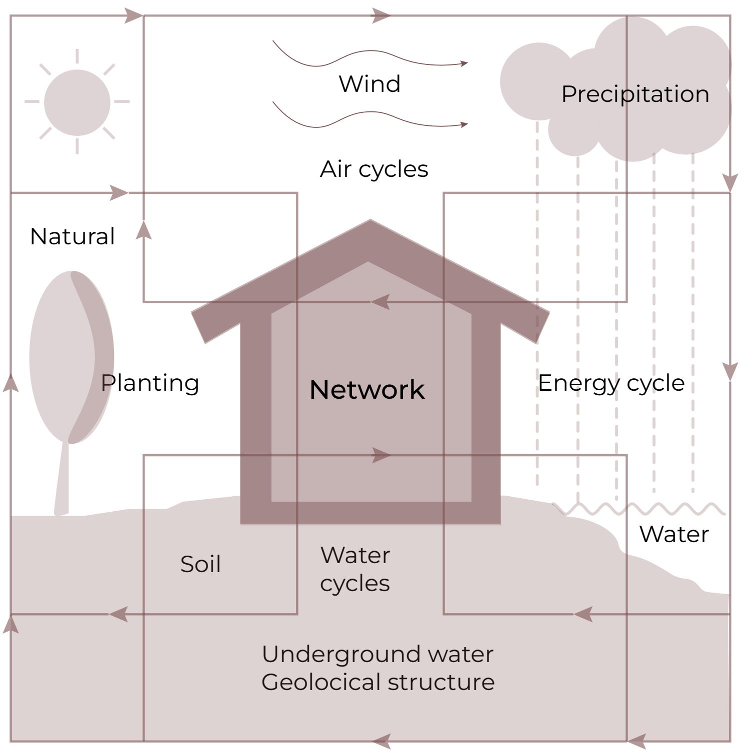


Fig. 55: Bioclimatic architecture diagram, remake based on (Butera et al., 2023)

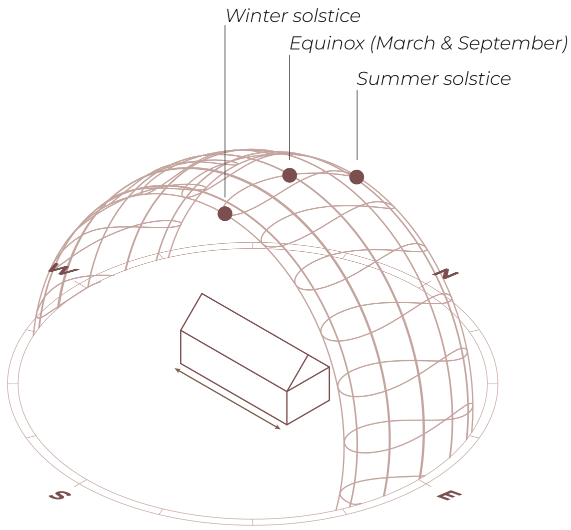


Fig. 56: Placement of the building according to the sun based on (Butera et al., 2023)

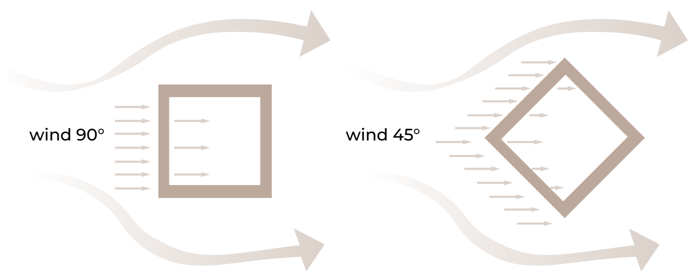


Fig. 57: Placement of the building according to wind based on (Butera et al., 2023)

Building placement

The right placement of the building on site matters not only in terms of the way the volume is perceived in the space but also how outdoor conditions affects the indoor climate. When making decisions about volume and its function distribution, some factors need to be taken into account. The east and west facades of a building are at risk of overheating due to solar radiation and peak temperatures in the evening. Therefore, it is recommended to locate the longest facades toward north-south and the shortest facades east-west (see fig. 56). Unfortunately, often the optimal building orientation for sunlight does not align with the best orientation for wind. (Butera et al., 2023) This is also the case for the thesis site location, where the prevailing wind comes from south-east, as seen in the wind analysis (fig. 27)

By minimizing the surfaces that face east and west, one can reduce overheating and glare caused by the low sun. (Butera et al., 2023) As a result, a focus should be on maximizing natural ventilation while providing adequate sun protection. Research also shows that in a hot humid climate, the first priority should be on allowing for sufficient wind, where the second priority is to shade (Butera et al., 2023, p.57). Rotating the building away from the main wind direction can allow the building to catch more wind, as illustrated in figure 57 (Butera et al., 2023).

Additionally, it is beneficial to consider the surface-to-volume ratio (S/V) to decrease material usage, lower costs, and ultimately reduce energy consumption. (Butera et al., 2023)

Openings

Since approximately 40 percent of unwanted heat enters through glazing and openings, it is essential to design these elements carefully to minimize high solar radiation while still allowing for efficient natural ventilation. In hot-humid climates, windows should be designed to expand horizontally and be operable, enabling occupants to control their adaptive opportunities. Since the site is located where mosquitoes spread malaria and other diseases, flyscreens should be installed on all openings to reduce the risk of infection. The relationship between openings and ventilation, therefore placement and size of windows are significant factors to consider in the design process. (Butera et al., 2023)

Ventilation

When considering the bioclimatic architecture approach, passive design strategies should be implemented to achieve adequate indoor quality. Natural ventilation is a common strategy for African schools; however, it often results in a low air change because it depends on outdoor conditions like wind and temperature. This is however important since a poor indoor quality in combination with overcrowded classrooms can lead to ineffective learning conditions. (Toyinbo et al., 2019)

When researching regulations for Zambia, the most recent standard referenced to is the South African Regulations SANS 10400-O:2011 (South African Bureau of Standards, 2011). Regarding the lack of data on current indoor climate conditions in Zambian schools, these standards will be adhered to in regard to ventilation values (see figure 58).

Type of occupancy	*minimum requirements*	
	air changes per hour	*L/s per person*
Educational buildings		
classrooms	*2*	*7,5*
labolatories	*2*	*7,5*
libraries	*2*	*6*
Food and eating		
Dining rooms	*10*	*7,5*
Cafeterias	*10*	*7,5*
Kitchens	*10*	*17,5*
Other		
storage	*10*	*7,5*
laundries	*10*	*7,5*

Fig. 58: Required ventilation values remake based on (South African Bureau of Standards, 2011)

Daylight

When considering the window placement in the design, the daylight factor is crucial, especially at educational facilities because of its significant impact on visual comfort and educational performance.

Useful daylight illuminance (UDI) and spatial daylight autonomy (sDA) are two important daylight metrics used in building design to evaluate the effectiveness of natural light in a space. Where the useful daylight illuminance measures the percentage of time, the daylight autonomy provides insight into spatial daylight. (Mardaljevic et al., 2012) (Reinhart and Walkenhorst, 2001)

For UDI (see fig. 59), the recommendation is to reach 80 percent of occupancy hours, where the range is between 100 to 3000 lux (Verso et al., 2014). As for daylight autonomy, it is recommended to reach an average of 50% with a target illuminance of 300 lux (IESNA, 2013).

In African countries, especially in hot humid climates, sky illuminance and risk of glare can pose challenges and disturbances, especially in the context of educational buildings like classrooms. (Butera et al., 2023) This is important to consider in order to create an efficient learning environment.

Facade materials also play a crucial role in daylight evaluations. Light-colour surface increases the level of illumination which allows the design to use smaller windows. (Butera et al., 2023)

Humidity

General well-being is significantly influenced by humidity levels. In Zone I, as analysed previously (see Analysis Chapter fig. 26), relative humidity levels can soar to nearly 90 percent. When combined with high temperatures, this can lead to issues such as mold and damp clothing. Some countries have developed methods to prevent these problems, such as moisture traps in cupboards and fans that provide a cool breeze. (Walder, 2023)

There is a relationship between humidity and temperature (see fig. 60) - when the relative humidity level is increasing to maintain a comfortable indoor climate, temperature has to drop, otherwise, users will experience sticky air. It has been conducted that the human body considers adequate conditions when the humidity range is between 40 and 60 percent (Santos, Ferreira and Lanzinha, João C. G, 2024).

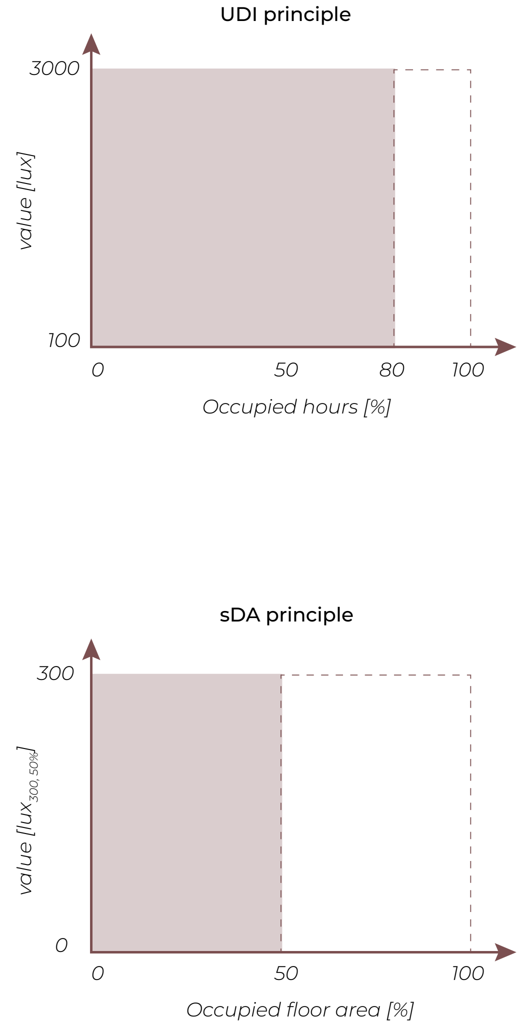


Fig. 59: UDI and sDA principles illustrated

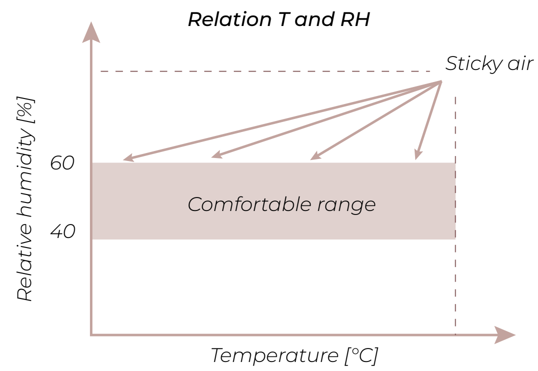


Fig. 60: Simplified relation between Temperature and Relative Humidity, based on theory from (Santos, Ferreira and Lanzinha, João C. G, 2024).

Shading

In a climate with approximately the same length of the day throughout the year and a high risk of solar radiation, external shading devices are a necessity.

Windows should be protected by using shading devices, overhangs, or verandas. When designing, a windows placement close to the ceiling should be considered to avoid glare and high illumination. (Butera et al., 2023)

In addition, every facade of the building demands its unique design. However, since west and east windows should be avoided in the design, similar conditions and therefore shading strategies are used for both north and south facades. Research shows that horizontal overhangs protect windows in this orientation the best. As shown in the sun diagrams (see figure 23), the sun in north and south is at its highest point, making horizontal shadings the most efficient. Shading devices placed directly on the window can be an option to possibly protect the building from overheating as well as glare, as seen in figure 61. The colour of the shading devices has an effect on daylight, indicating that light tone reflects the most (Butera et al., 2023).

Temperature

It has been found that thermal discomfort influences educational and work performance (see fig. 62). Pupils struggle with performing well on tasks when heat stressors lead to failure of exams. Suboptimal classroom conditions are directly linked to a lack of concentration, but also to absence at school and even sickness. (Wargocki, PorrasSalazar and ContrerasEspinoza, 2019)

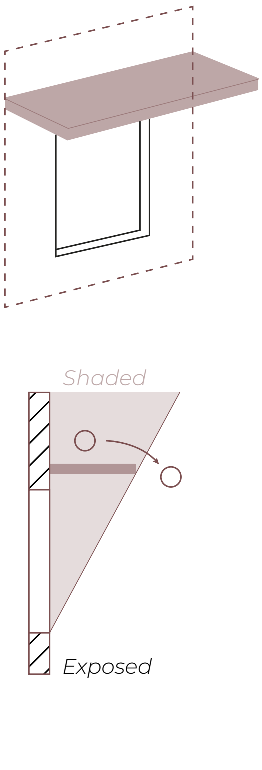


Fig. 62: Horizontal shading devices, remake based on (Butera et al., 2023)

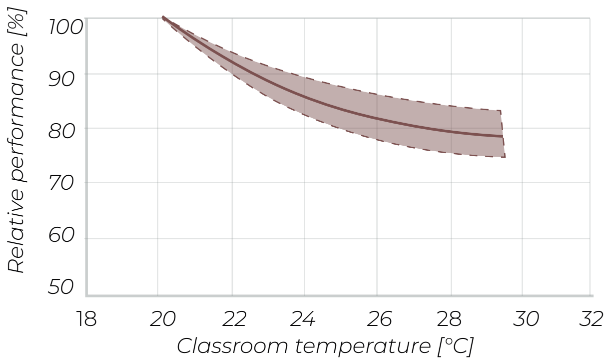


Fig. 61: Performance of schoolwork as a funtion of temperature in classroom, remake based on (Wargocki, PorrasSalazar and ContrerasEspinoza, 2019)

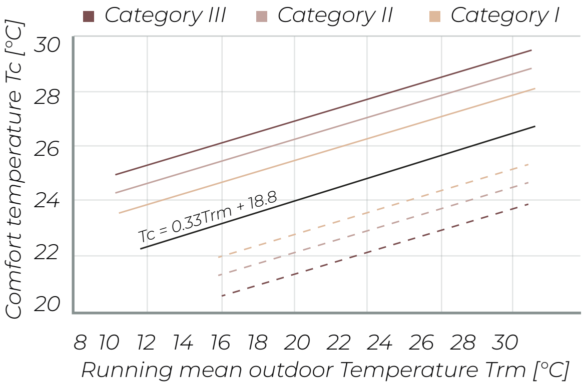


Fig. 63: Simplified relation between Temperature and Relative Humidity, based on theory from (Santos, Ferreira and Lanzinha, João C. G, 2024).

Adaptive Thermal Comfort Theory

Another option is to look at more theoretically based assumptions or ranges of the acceptable temperatures of indoor climate. A first theory is based on the Predicted Mean vote model (PMV), which determines a comfortable indoor temperature based on steady state conditions. This model is primarily used for mechanically cooled buildings. and is good for buildings where there is also mechanical ventilation possible that can ensure that the temperatures stay within this range which is commonly used in standards like ASHRAE Standard 55 and ISO 7730 (Berger et al., 2023).

However, this thesis will continue with the Adaptive Thermal Comfort Model (ATC), which includes the capacity of people to change their preferences and tolerances. Meaning that there is room for the psychological dimension of adaptation, depending on the contextual climate, recognizing that comfort depends on context. This model can in that way be seen as a revision of the previous standards, including a new adaptive comfort standard (ACS), which is especially relevant in hot climates where natural ventilation is prominent, as is the case in this master thesis. This model takes into account the mean outdoor dry bulb temperature when calculating on the comfortable temperature, meaning that the comfortable range changes depending on the outdoor conditions (Brager and De Dear, 2001).

Figure 63 shows the different ranges of the adaptive thermal comfort theory where category one refers to the smallest range, meant for more

Sub conclusion

As mentioned in the beginning of this chapter, creating a comfortable indoor environment is essential for effective learning. An essential aspect to include in the design is to place the buildings in a way that the west and east facades are minimized, while at the same time rotating the building to a degree of 45 to maximize the ventilation inside. The balance between ventilation, daylight and shading is a crucial factor to investigate further when designing the windows size and placement. The ventilation rate as well as the UDI and sDA will therefore be taken into account when designing.

Overhangs or shutters can be used in the design to protect from overheating and glare. Horizontal shading devices are seen to be most efficient on north and south facades. The acceptable indoor temperature range will depend on the outdoor temperature of that specific time, whereas the humidity levels inside are ideal when being between 40 and 60 percent.

Climate resilience design

As mentioned in the background chapter, Zambia faces heavy rainfalls due to climate change. While collecting data about the risk of floodings, it has been discovered that Zambia does not provide any maps which might indicate the zones of high risk of floods in general. However, the Ministry of Green Economy and Environment regularly uploads maps in Facebook throughout the year, indicating the potential high-risk flood areas for specific days in the year (Ministry of Green Economy and Environment, 2025). Figure 64 shows a map of Zambia on the 23rd of January 2025 where Kashitu is right at the border of a high and low risk area, showing the importance of integrating climate resilient strategies regarding rainfall in the design.

Exposure to flood water can be dangerous to life since it contains sharp objects and leaves faeces (Barsley, 2020). Solutions will therefore be investigated to create a safe environment for both children and teachers.

Water resistance

The proprieties of a material can significantly impact the building's resistance to flood and heavy rainfalls. However, since the design aims for designing with local materials, it is assumed that those can withstand most extreme weather conditions but however can be improved by using other design solutions. Those can be distinguished between landscape and building design solutions.

Landscape design

Designing a climate resilient school is not only about indoors but also about outdoors, since the landscape can play a crucial role in mitigating the rainfall when designed properly. Adequate water management can allow students to participate in school activities daily without skipping classes due to weather conditions (Barsley, 2020).

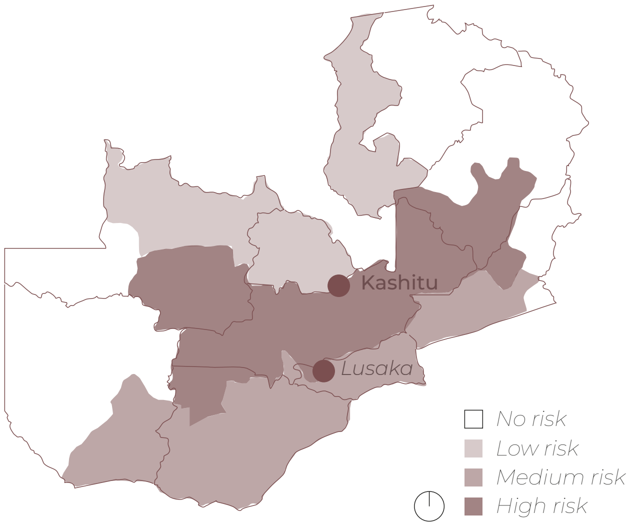


Fig. 64: Indicatation of flood risk areas on 23 of January 2025, remake based on (Ministry of Green Economy and Environment, 2025)

As seen on figure 65, the site topography is slightly lower in the south-east direction meaning that it would be beneficial to direct the storm water accordingly during rainfall. (Clegg and Collin, 2024, pp.1–244)

However, using the heights is not the only way to go. Heavy rainfall in Kashitu can be managed by designing detention basins together with retention or balancing ponds.

Detention basins are simple to construct and easy to maintain and can be used for multiple things. During the dry season it just remains dry, while in the wet season it ensures that water coming from pipes does not spread out all over the site but gets collected. It can also give another character to the landscape design of the site. Since it relies on pipelines, its placement should be considered closer to the buildings. (Barsley, 2020)

Retention ponds have a softer character, since they rely on changing water levels and aren't supplied by gutters or any piping systems. It can be built with different types of plants according to the water level (Barsley, 2020). This solution can be used in urban design closer to outdoor activities to enhance biodiversity while at the same time give another value to green areas.

Water storage system

In a climate with a rainy season, collecting water is essential, especially in the country where water supplies can be lacking. Therefore, the urban design will investigate rainwater harvesting systems (RWH) to allow the school buildings to not rely only on the local water systems. This can lead to decreasing the water bills while being sustainable smart (Caribbean Environmental Health Institute, n.d.).

Collected water by those tanks will be used for all of the purposes from flushing, to cooking and drinking since this system contains special filters and first flush diverters. (Caribbean Environmental Health Institute, n.d.).

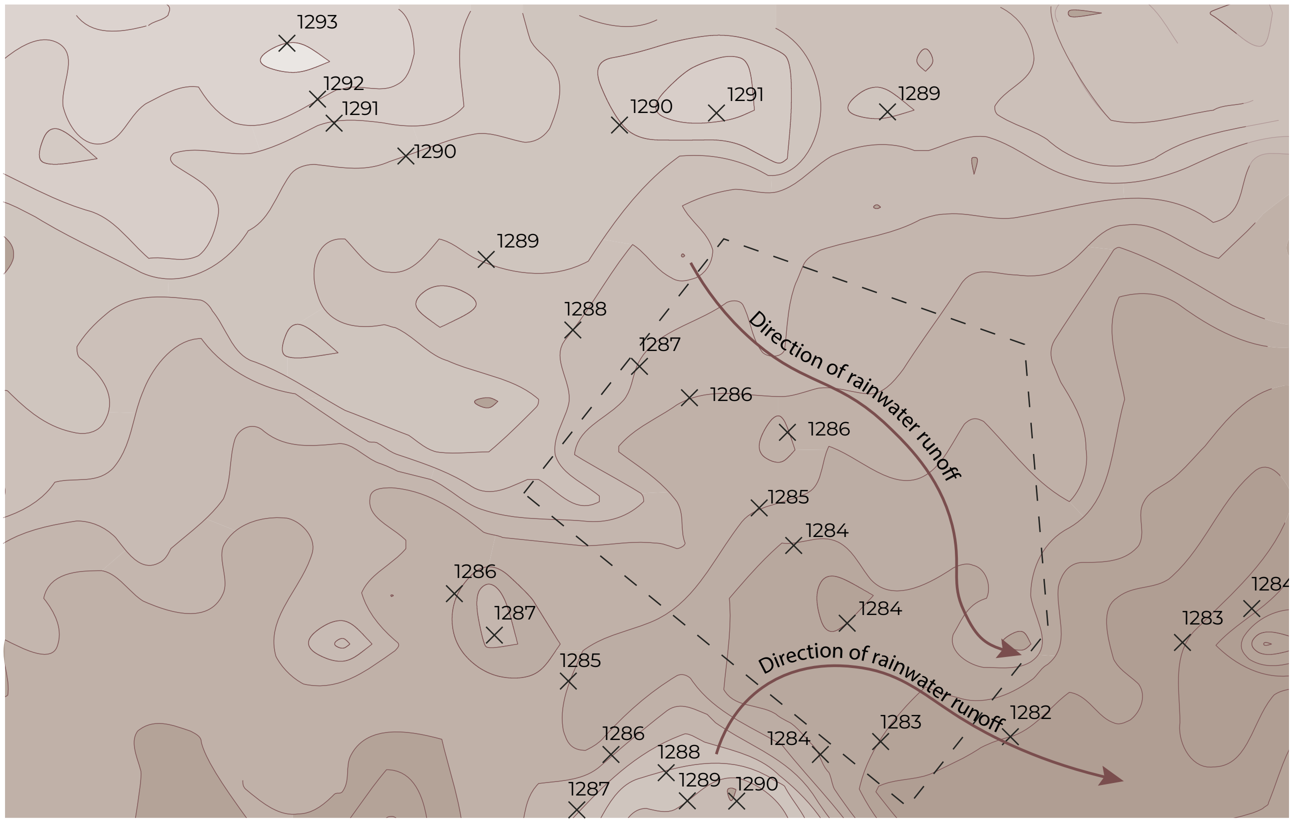


Fig. 65: Elevation map of designed plot [meters], based on data (QGIS Geographic Information System, 2025)

Building level strategies

A first solution can be to raise the whole floor and specifically the floor finishing. This makes sure it stays dry and will not be influenced by floodings. This is however only possible when the flood risk is not too high, avoiding having difficult access when entering the building (Barsley, 2020).

1. Raising the floor

Instead of just the floor, the whole structure can be raised as well as seen in figure 66. This can however be more difficult to build and might have problems when designing with heavy wall materials like ICEB. This solution could however, work on the sides where the wall stays continuous to the floor (see figure 66). Instead of having to add several steps to reach the ground floor when raising the whole building, the lower part of the wall construction can be built out of a material that can withstand moisture. This can also be beneficial for the architectural expression and can break the facade.

2. Raising the building

Instead of just the floor, the whole structure can be raised as well (see fig. 67). This can however be more difficult to build and might have problems when designing with heavy wall materials like ICEB. This solution could, however, work on the sides where the wall stays continuous to the floor. Instead of having to add several steps to reach the ground floor, the lower part of the wall construction can be built out of a material that can withstand moisture. This can also benefit the architectural expression and can break the facade.

3. Amphibious design

Another option when designing regarding rainfall and flooding, is raising the whole building up. This solution can be implemented by building wooden pillars (see fig. 68). This can give another architectural expression, especially when focusing on outdoor areas which can be connected to those structures. However, using ICEB as a main structural material regarding walls, affects the applicability of this solution because of its weight. Therefore, this option should be omitted.

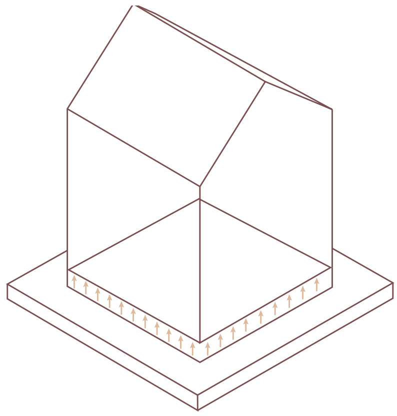


Fig. 66: Raising the floor, building level strategies against flooding, remake based on (Barsley, 2020).

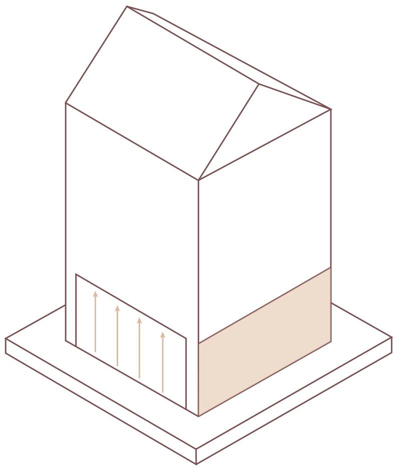


Fig. 67: Raising the building, level strategies against flooding, remake based on (Barsley, 2020).

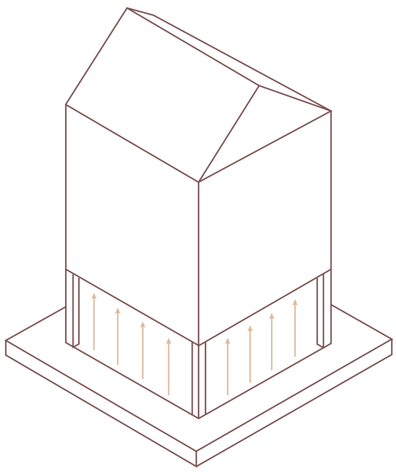


Fig. 68: Amphibious design, level strategies against flooding, remake based on (Barsley, 2020).

Fig. 69: Construction site, (INSPIRELI Awards, 2024)

05 Design outline

*How can a **climate-resilient** school building in Zambia, with the **use of local materials**, be designed with an **easy-to-build**, **community-driven approach** to ensure a safe and **high-quality learning environment?***

Problem statement

Building upon the preceding research, analysis, and theoretical foundation, a design outline has been established. This begins with a problem statement, which defines the focus of the project and provides clear definitions of key terms relevant to the scope. Furthermore, a set of design criteria has been formulated to serve as guidelines, ensuring the project progresses in the intended direction throughout the design process. This is futher supported by a function diagram and a detailed room program.

Defining terms

Climate resilience

Climate resilience in this project refers to the capacity of the school's design and infrastructure to withstand the region's environmental challenges, including extreme weather conditions and the impacts of climate change. Climate resilience in this context ensures the school remains functional, safe, and comfortable for the users.

Local materials

Local materials are defined as those sourced from Copperbelt and nearby provinces, chosen to reflect the area's natural and cultural context while reducing transportation costs and environmental impact. This project emphasizes sustainability by using responsibly sourced local resources to prevent ecological harm, such as deforestation. This approach supports the local economy and ensures the design aligns with its environment and community.

Easy to build

'Easy to build' promotes the use of simple construction methods that are easy to understand and implement in order to allow local builders, even those with limited construction experience, to participate in the building process. This is connected to traditional building techniques, respecting local construction knowledge and incorporating familiar methods.

Community-driven

The construction phases of the project being community-driven means they are shaped by the needs of the local community. The programmatic functions of the building are built upon these needs to ensure the project is relevant, useful, and contextually appropriate.

High quality learning environment

The project prioritizes a comfortable indoor climate to ensure a high-quality learning environment. This is directly related to indoor temperature, natural daylight, humidity, and ventilation. In addition to these measurable factors, the design must also incorporate architectural qualities that create a welcoming atmosphere. Practical considerations are equally important to ensure that teachers and students feel comfortable within the space.

Design criteria

1. Indoor environment

1.1 Temperature

Maintain classroom temperatures within the comfort range defined by adaptive thermal comfort theory for as much of the occupied time as possible.

1.2 Daylight

Ensure at least 80% of UDI with the range 100-3000 lux and at least 50% of sDA with a target of 300 lux.

1.3 Humidity

Aim to keep indoor relative humidity within the optimal 40–60% range throughout the year, accounting for wet and dry season.

1.4 Natural ventilation

Enhance airflow along prevailing wind directions to ensure effective natural ventilation throughout the building.

2. Material selection

2.1 Local

Use local materials. If unavailable, opt for imported materials with low embodied energy.

2.2 Durability

Use durable materials to withstand daily use and ensure longevity.

2.3 ICEB

Use ICEB as a building material with a size of 290 x 140 millimetres to ensure consistency with existing structures and compliance with competition requirements.

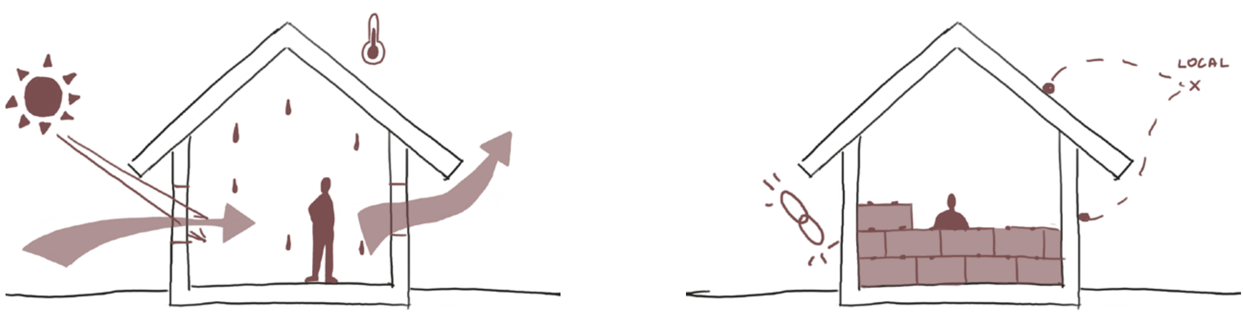


Fig. 70: Design criteria

3. Withstand extreme climate

3.1 Safety

Use design principles to withstand extreme weather conditions.

4. User centric design

4.1 Design for children

Design a school that promotes safety and comfort for children through the integration of all necessary functions.

4.2 Traditional architecture

Respect traditional building practices and the rural context through architectural expression.

4.3 Easy to build

Use simple and efficient construction methods, enabling inexperienced local builders to easily assemble the structure.

4.4 Community

Center the design around the school community to support social connections.

Program

The decision to design a school in a developing country has been driven by the Kashitu INSPIRELI Award competition. Consequently, the design program, including function diagram (see fig. 71) and room program (see fig. 72), is based on the competitions function requirements. This design program plays an important role in the design process by organizing spatial relationships, defining programmatic needs, and ensuring that all necessary functions are appropriately accommodated within the designed space.

Additionally, the Ministry of Education has established standard benchmarks for secondary schools, defining recommended floor areas for educational and sanitary facilities, as well as staff provisions. Further inspection of the provided material has led to the incorporation of additional practical functions into the program, such as reception and break areas, to enhance the overall school environment.

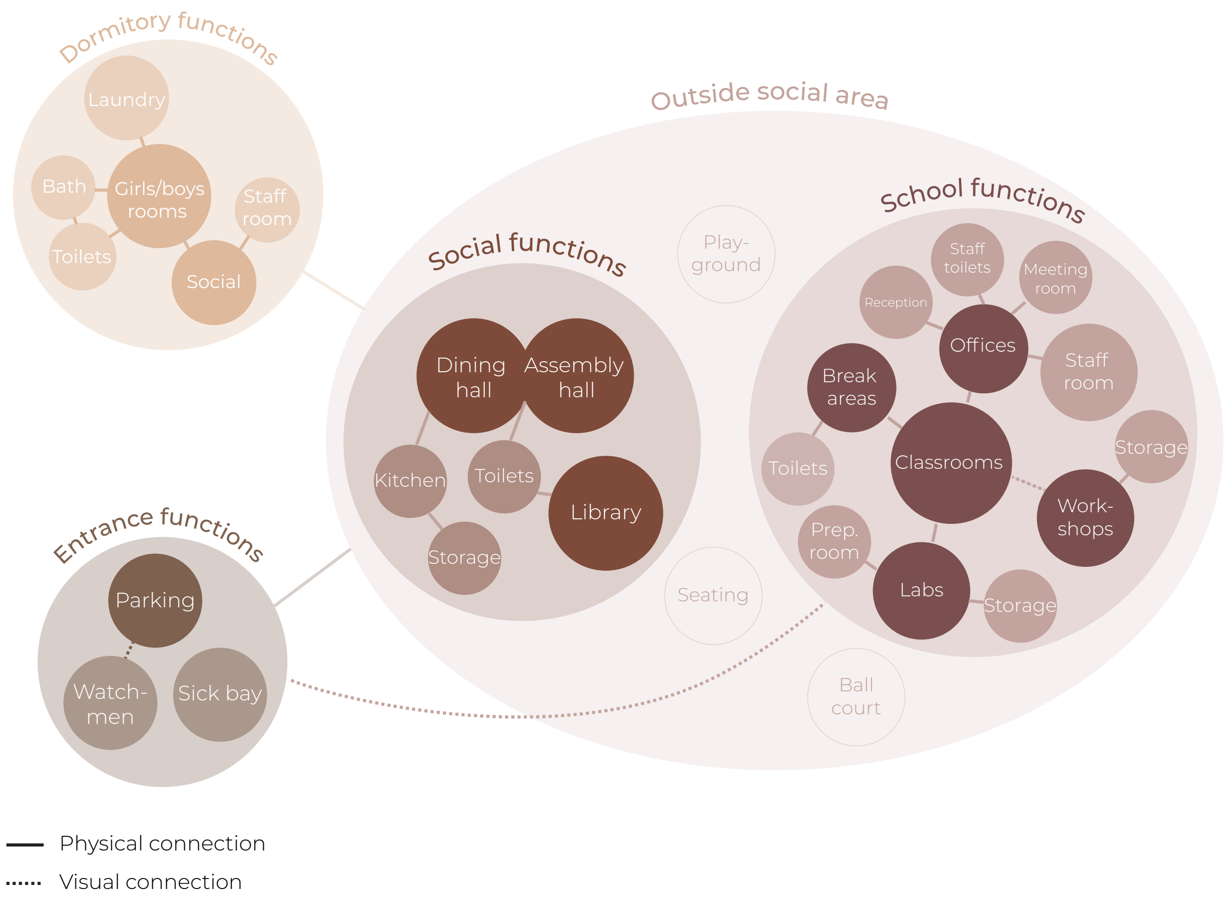


Fig. 71: Function diagram

Facilities	Amount	Area [m²]	Total [m²]	Capacity (for one room)
School functions				
· Classrooms	11	110	1180	30 pupil+1 teacher
· Laboratories	3	123	369	30 pupil+1 teacher
· General office	1	28	28	4
· Headteacher office	1	28	28	1
· Staff room	1	80	80	22
· Staff toilets	2	4	8	2
· Girls toilets	10	4	40	10
· Boys toilets	8	4	32	8
· Handicap toilet	1	6,5	6,5	1
· Cooking workshop	1	150	150	50 pupil+1 teacher
· Metal workshop	1	150	150	50 pupil+1 teacher
Summary			*2071,5*	
Social functions				
· Library	1	455	450	400 pupil
· Assembly/dining	1	875	875	400 pupil+29 staff
· Storage	1	20	20	-
· Kitchen	1	60	60	5 cooks
· Girls toilets	10	4	40	10
· Boys toilets	6	4	25	6
· Handicap toilet	1	6,5	6,5	1
· Staff room	1	10	10	3
Summary			*1486,5*	
Girls dormitory				80 girls
· Rooms	20	20	400	4 residents
· Common area	1	30	30	80 residents
· Toilets	4	2,2	8,8	1
· Bath	4	2,2	8,8	1
· Laundry room	1	8	8	4
· Staff facilities	1	20	20	1 house parent
Summary			*475,6*	
Boys dormitory				80 boys
· Rooms	20	20	400	4 residents
· Common area	1	30	30	80 residents
· Toilets	4	2,2	8,8	1
· Bath	4	2,2	8,8	1
· Laundry room	1	8	8	4
· Staff facilities	1	20	20	1 house parent
Summary			*475,6*	
Entrance functions				
· Watchmen building	1	7	7	2 watchmen
Outdoor functions				
· Parking lot	1	700	700	26 veichles
· Playground	1	900	900	400 pupil
· Ball court	1	1380	1380	-
Summary			*2980*	
Total			*7425,2 m²*	
Site area			*37324*	
Building coverage ratio			*19,9%*	

Fig. 72: Room program

Fig. 73: Construction site, bird view, (INSPIRELI Awards, 2024)

06 Design process

Phase 1

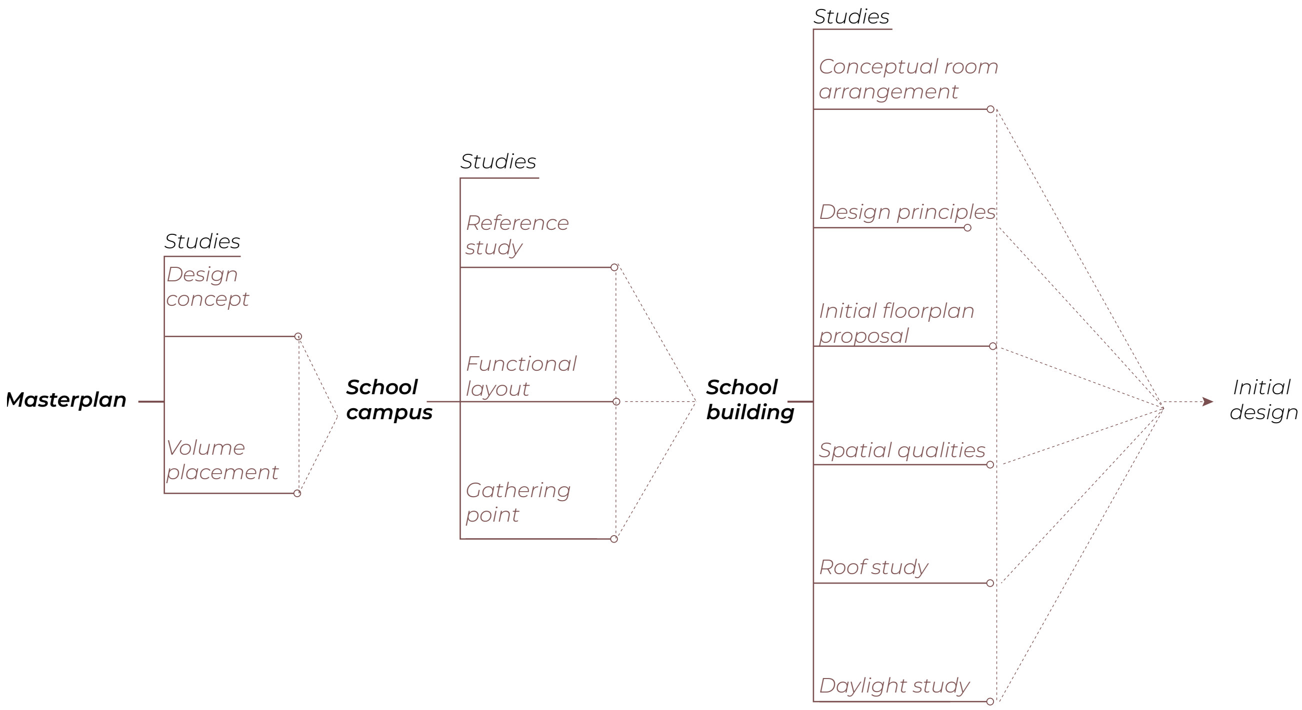


Fig. 74: Design aproach for phase 1

The following design process unfolds on the basis of the project, outline and includes iterations and studies of different scales and aspects, ranging from a masterplan level to a detailed design layout (see fig. 74). The chapter begins with the exploration of design concepts and volume placements, followed by a closer look at the schoo l campus and buildings. As a conclusion, a finalized initial design proposal will be defined, setting the starting point for further iterations, which will be seen in the second phase.

Existing site

As previously mentioned, the project site (see fig. 75) is divided into two building phases, with the second stage designated for teacher accommodation. The design process focuses exclusively on the first phase, as this is where the school campus will be situated.

A closer look of the site shows that two buildings have already been constructed on site in relation to the secondary school, including a workshop area and a residence for the secondary school watchmen. These buildings are constructed of ICEB as a single wall structure (see fig. 76). The workshop area will be used as a base for future constructions, providing a space where materials can be crafted and stored. These existing buildings, along with the proposed entrance, serves as a starting point for the site concept and layout.

Since this master thesis' focus is designing a school facility, all competition-required functions unrelated to the school will be addressed at a masterplan level. This approach ensures a cohesive urban design while allowing for greater detail within the school's focus areas.

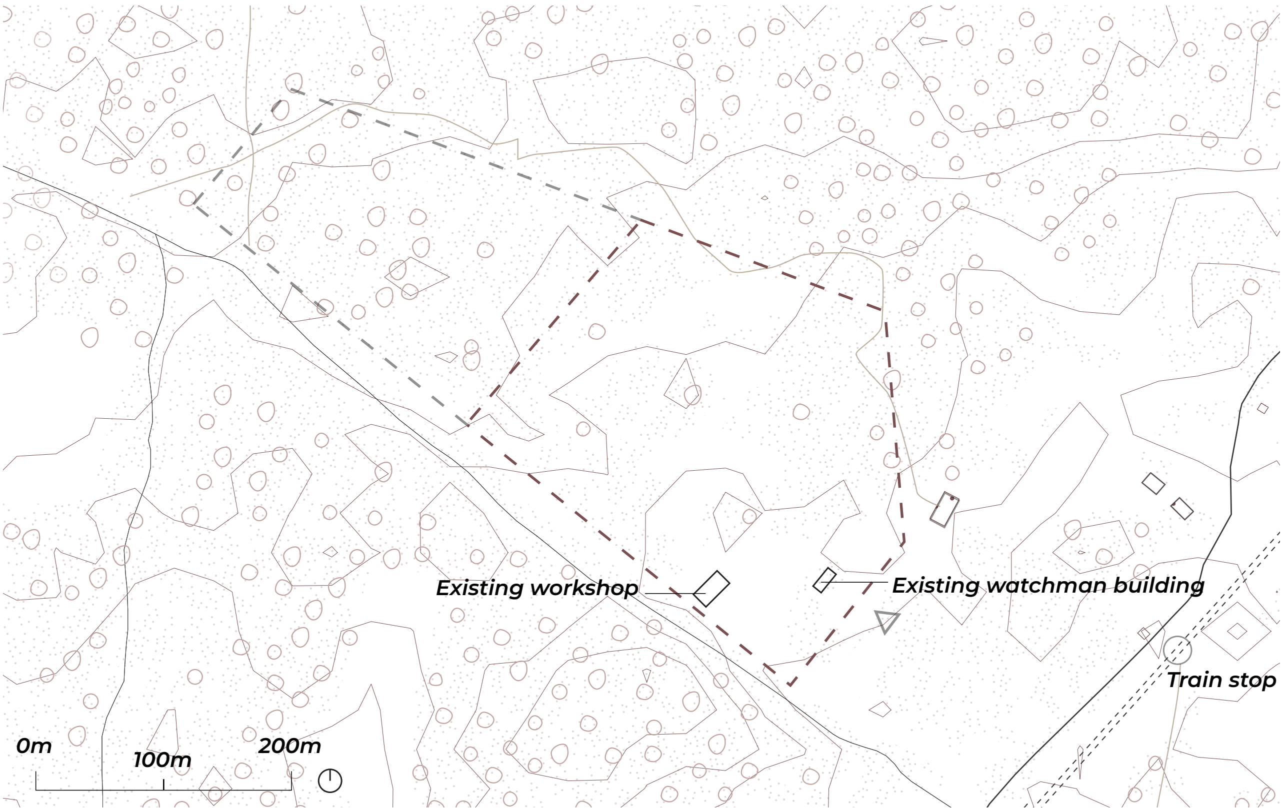


Fig. 75: Existing project site

Fig. 76: Construction site, detailing, (INSPIRELI Awards, 2024)

Masterplan

The masterplan serves as the structuring of the project, ensuring that the school campus is well-connected considering its users as well as the climate. In this regard, the design concept provides a clear vision, used to define the project's identity and the development of the design.

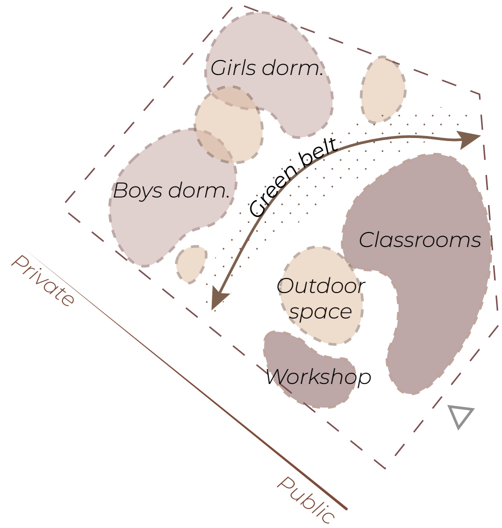


Fig. 77: Concept – The green belt

Design concept

The green belt

The first concept (see fig. 77) situates the school facilities closest to the road in the southeast corner in order to provide easy access for non-boarding students. This naturally positions the domitories northwest of the site, creating a more private and secure area only for boarding students. The existing greenery surrounding the site is extended through the middle as a green belt, creating a natural division between the school buildings and the dormitories, while providing a recreational value to both sides.

A disadvantage of this concept is that the main school building is located at the site's edge, potentially limiting social interaction across the campus. However, integrating the outdoor spaces along the green belt, for instance small gathering spots, could reverse this effect and encourage movement and connections between zones.

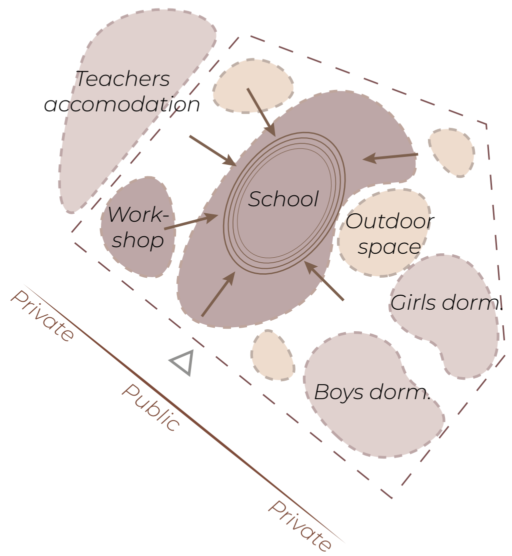


Fig. 78: Concept – Centralized school

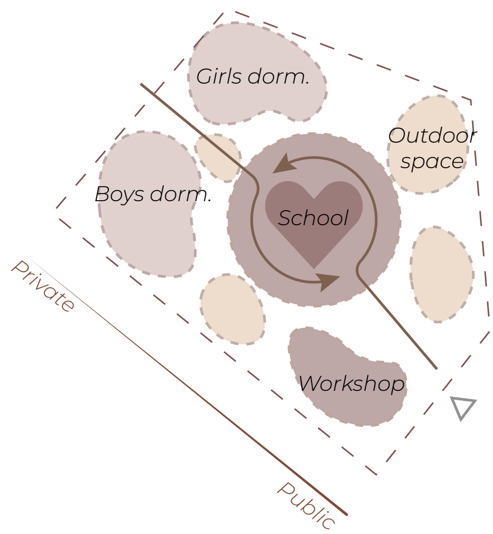


Fig. 79: The final concept

Centralized school

In the following concept (see fig. 78), the school is centrally positioned, with dormitories on one side and the teachers' accommodation, from building phase two, on the other. As the private dormitories now have been placed in the opposite end compared to the first concept, it implicates a reconsideration of the site entrance, which has been moved to the southwest to fit the new circulation patterns.

This location of the dormitories can however feel more unsafe and less private in comparison to the first concept, since they now are placed near the main road.

Relocating the entrance has the disadvantage of not using this main road as an attracting point to the school. A centrally located school on the other hand create a social gathering point, fostering social interaction in the school community

The final concept

This leads to the final concept (see fig. 79) where all zones are located around a main gathering point. The outdoor spaces and activities across the site serve as a connection between the different zones.

Positioning the school at the heart of the site while creating a clear circulation path leading to the main road, ensures good accessibility and maintains the central character of the school. Meanwhile, placing the dormitories in the northeast, like in the first concept, creates a logical transition from public to private when arriving from the main entrance.

Volume proposal

Building upon the design concept, defined building volumes can now be positioned on the project site. The following proposed building placements represent a selection of sketches during the sketching phase, all of which was evaluated with the analytical and theoretical background in mind. This encompasses incorporate passive strategies, harnessing the advantages of the local climate, as well as the general building appearance and the flow they stimulate in outside areas.

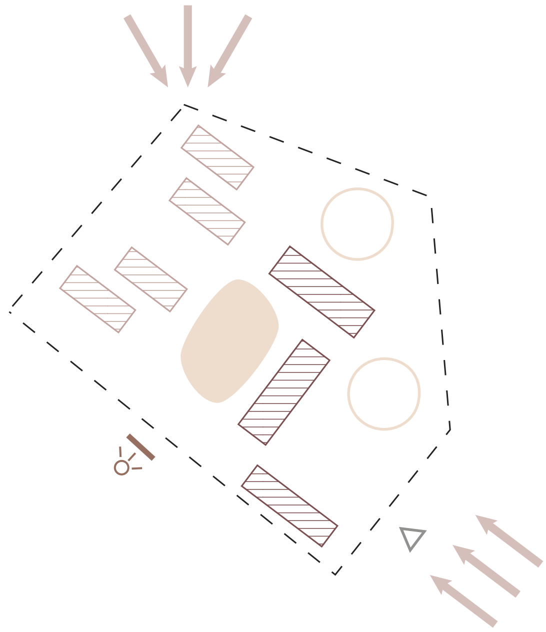


Fig. 80: 1st layout iteration

1st layout

In the first layout (see fig. 80), the school buildings are placed with their facades parallel to the entrance. Through this positioning, the buildings create a natural gathering point and a closed façade towards the road. This arrangement allows the buildings to open up to the social area they define

This positioning, however, is not favourable in terms of climatic conditions. Placing a building perpendicular to the prevailing wind direction capture less airflow, resulting in reduced natural ventilation effect. Additionally, theoretical studies (see page x) indicate that orienting long facades towards the east and west can lead to indoor overheating, highlighting the need for a more strategic placement.

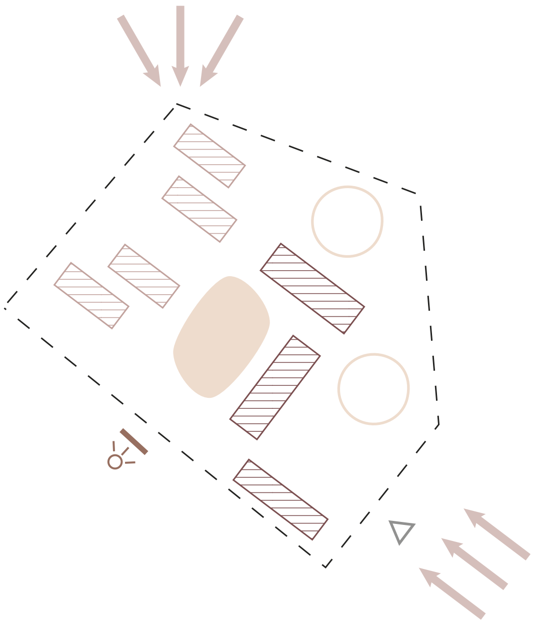


Fig. 81: 2nd layout iteration

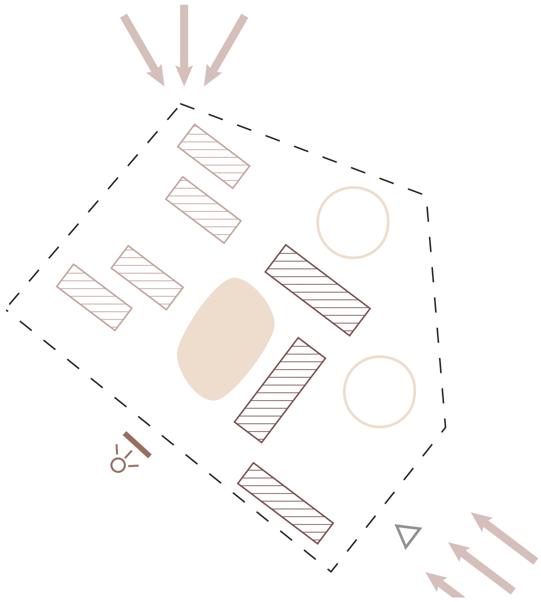


Fig. 82: 2nd layout iteration

2nd layout

The second layout therefore prioritizes placing the building volumes in an optimal position regarding sun and wind (see fig. 81). But doing this also means that there is no natural social area created by the school buildings, due to them being positioned in a line.

In the second layout, the placement of building volumes is optimized for sun exposure and wind conditions, enhancing natural ventilation and reducing overheating. The linear positioning however prevents the creation of a naturally defined social area, limiting opportunities for a social gathering space for the school community.

3rd layout

The third layout (see fig. 82) integrates the strengths of the previous layouts, with a climate-conscious orientation that optimizes both sun and wind conditions, while simultaneously creating a social gathering point. The buildings are oriented towards the heart of the site, with a placement that surrounds the main flow through the middle of the site.

Initial masterplan proposal

The previous iterations have shaped the initial masterplan proposal (see fig. 83), grounded in the design concept. This plan prioritizes a building placement following the defined zones of the project site, creating a coherent environment. The educational facilities are centrally positioned as a focal point on the site, all oriented towards a social gathering point which fosters a strong sense of community among the students.

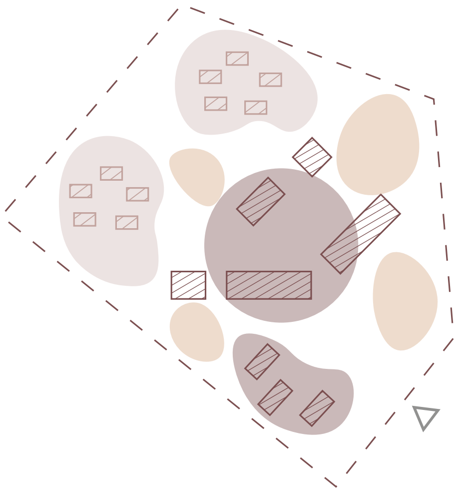


Fig. 83: Chosen concept on site

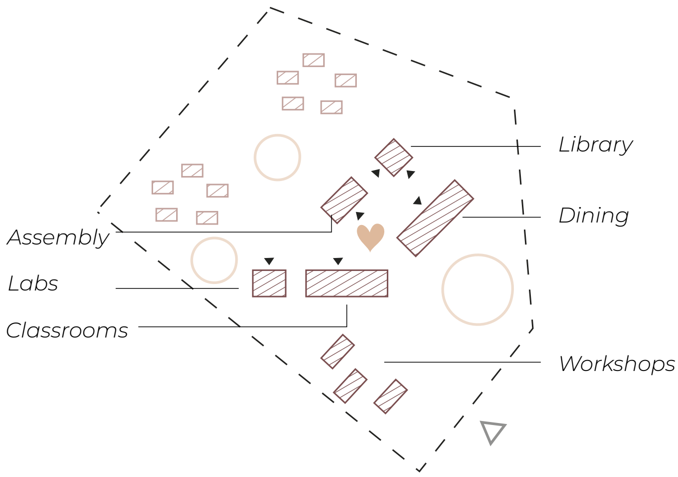


Fig. 84: Function diagram

Functions

The two new workshop buildings are positioned near the existing one (see ill. 84) and maintain consistency by resembling the same shape and size. The centralized school functions all have entrances oriented towards the social heart in order to activate the space between the buildings. These functions are divided into a library, assembly hall, dining, classrooms and laboratories. The private dormitories are placed behind the library and assembly hall, providing a sheltered environment while ensuring easy access to the school facilities.

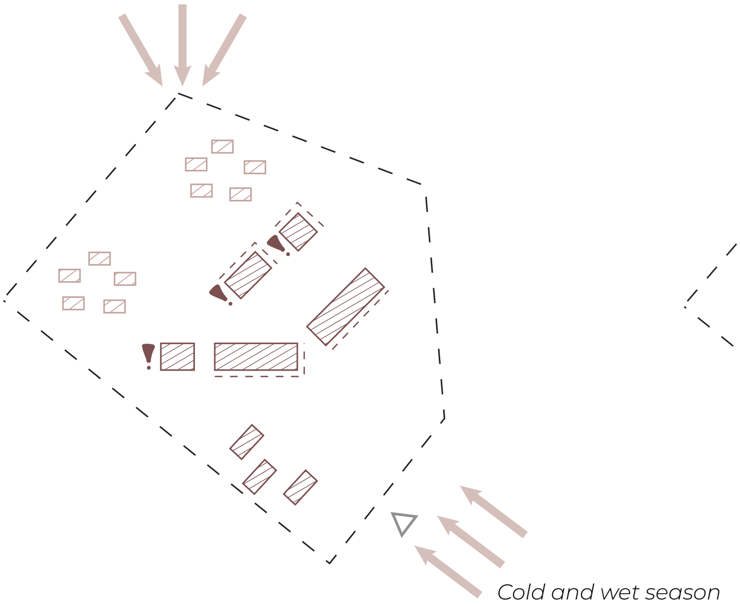


Fig. 85: Climate strategies on masterplan

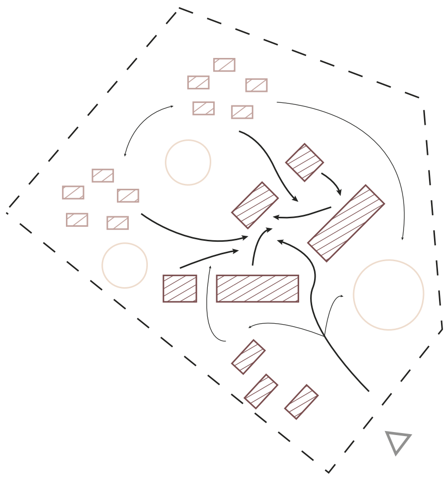


Fig. 86: Flow

Climate

As indicated in the temperature graph (see page 33), the highest temperatures occur in the afternoon, making west facades the most prone to overheating. The buildings are therefore positioned with their longest facades oriented north and south (see fig. 85). Additionally, minimizing windows on the west-facing facades, combined with strategic building placement, can reduce the risk of overheating.

Flow

As shown in figure 86, the social heart serves as the central space where most people pass through or gather while moving between different functions. Considering both the rainy season and high temperatures, this space is designed with the intention of having a sheltered structure. To achieve this, an overhang is envisioned, providing protected paths for movement between buildings.

School campus

Since the primary focus of this project is the school environment, the further development of the design has centered around the school campus. When shaping the functional layout and programming of the campus, it is essential to respect the traditional character of the local environment, as outlined in design criteria 4.2: Traditional architecture. In this context, a brief study has been conducted on a traditional Zambian home in a rural setting, providing insights into vernacular design principles that inform the approach to spatial organization as well as material use.

Reference study
Traditional Zambian layout

In traditional Zambian architecture, household functions are physically separated into distinct structures, each serving a dedicated purpose. The toilet, kitchen, and bedroom are typically housed in separate buildings on the same land plot, designed for their specific function and used at different times throughout the day. (Kashitu High School, 2022) This spatial arrangement accommodates their typical daily routines and reflects Zambian cultural practices.

An essential communal element in traditional Zambian design is the insaka (see fig. 88), an open, circular structure typically used as a how social gathering space for the family and meeting place for visitors while sheltering in the rainy seasons (Zebron, 2011).

An example of this spatial and functional layout is the case of The Kunda Compund (see fig. 87), home to a big family located in a rural area in the Central Province. The main buildings on the compound are the insaka and the master bedroom, where the outdoor space in between serves as an entrance area welcoming guests and visitors. The remaining functions are placed further away, secluded in its own private area. (Zebron, 2011)

Integrating the principles of the insaka into the school design can create a welcoming and familiar environment, which respects the rural context and traditional building practices as stated in design criteria 4.2. It is important to recognize and incorporate these local architectural traditions in order to develop a school design that aligns with the community expectations.

Integrating the principles of the insaka into the school design can create a welcoming and familiar environment, which respects the rural context and traditional building practices as stated in design criteria 4.2. It is important to recognize and incorporate these local architectural traditio

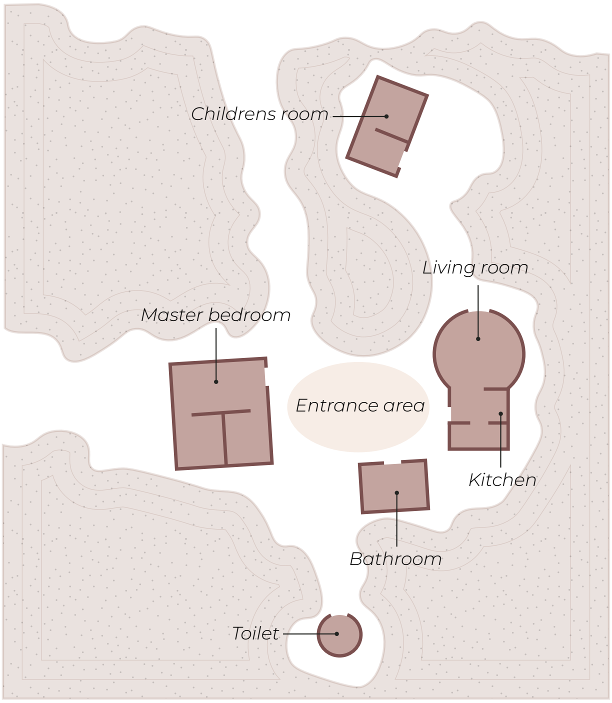


Fig. 87: The Kunda Compund, remake based on (Zebron, 2011)

Fig. 88: A traditional Insaka, (Kashitu High School, 2024)

Functional layout

The function layout presents a zoomed in view of the school campus. The placement of the functions is based on the function diagram from the project outline, which provides an understanding of the connections between the different functions, whether physical or visual. Building upon the initial masterplan proposal, this layout (see fig. 90) translates the conceptual framework from a masterplan scale into a more resolved spatial arrangement at a closer level.

The classrooms and laboratories are housed in separate buildings on the western side of the site closest to the workshop area. These educational facilities are equipped with nearby staff areas, toilets, and a break area, providing convenience for both students and teachers in between classes. The administration area is positioned near the main entrance to the school campus, serving as a reception while maintaining management and overview of the entire facility.

The dining area is equipped with an open kitchen, located in a separate building away from the academic zones. The purpose of this placement is to minimize noise disturbances during mealtimes, as the area is expected to accommodate a large number of students and remain active in the designated eating times.

These primary buildings are connected with a continuous floor deck and overhang in order to ensure a sheltered movement between the buildings, especially during Zambia's long rainy season.

Placed in the northeast corner with its own toilets and staff area, the library offers a quiet space separate from the active zones. The nearby building consists of an assembly hall, which provides space for gatherings or large meetings. It is located close to the dormitories as this function is a part of the daily school routine (see page 22) typically used every morning for a common assembly of the students.

All buildings are oriented toward the gathering point, which acts as the primary circulation area making it the most frequented space on campus.

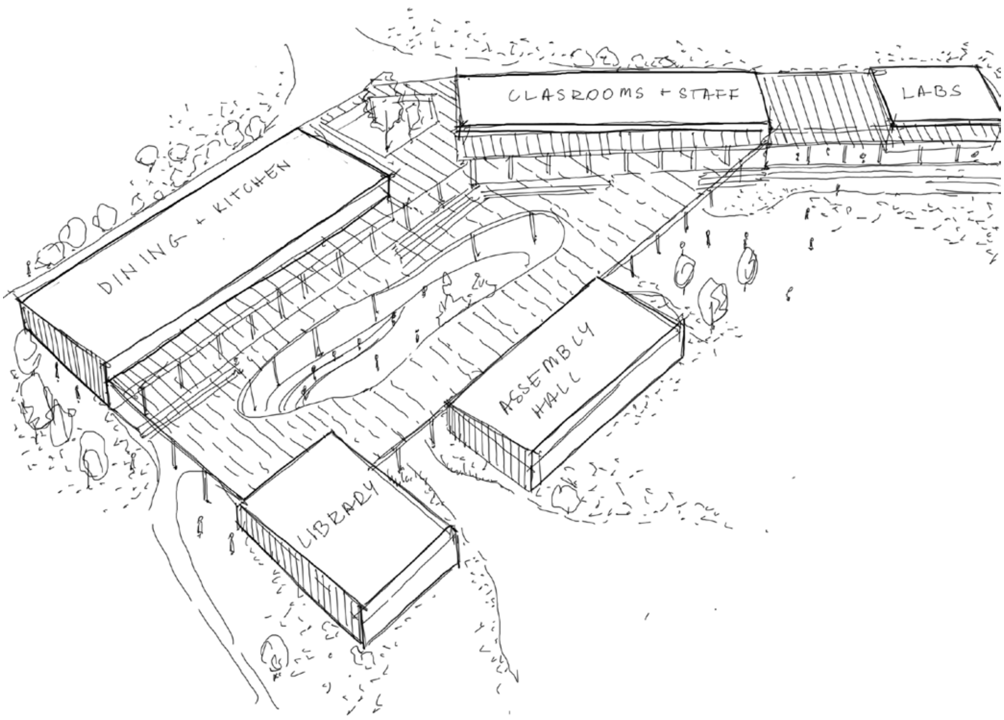


Fig. 89: Overhang sketch

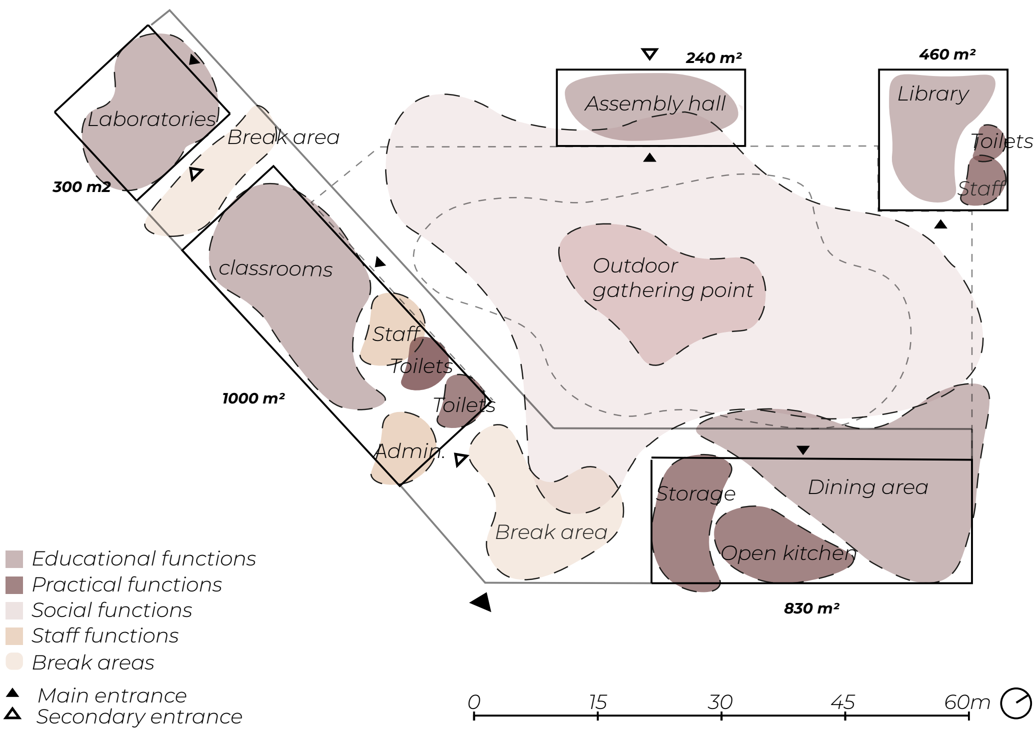


Fig. 90: Functional layout

Gathering point

Designing these buildings in relation to the outside space they create is a critical part in order for this area to work as the intended purpose. The functions are envisioned to expand beyond their building volume, allowing the gathering space to become a dynamic, multifunctional area where activities from various directions overlap and interact at the same time.

The physical character of the social heart can take several shapes; the most important aspect however is to provide an overhang or structure, where people can come together and be protected from uncomfortable climatic conditions (see previous fig. 89). A place where there is an opportunity to sit and talk, while feeling safe.

A way to introduce spatial variety and define zones within the gathering point, is to make changes in ground level (see fig. 91). The circular shape of the space encourages inclusive interaction from all sides and references the traditional Zambian insaka, reflecting the communal meeting space.

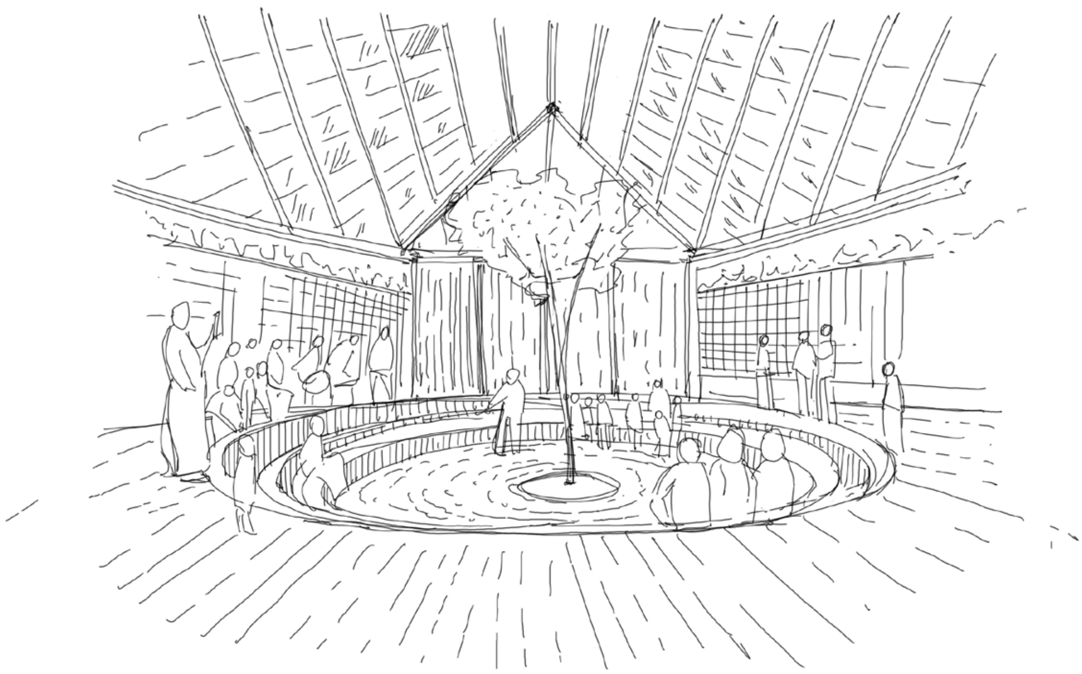


Fig. 91: Circular social space

Design proposals

Introducing a central circular shape can be an effective way of creating a social heart, and a space that brings people together at the core of the campus. Its placement however must be carefully considered to avoid disrupting the primary circulation flows between buildings.

To distinguish the buildings from the gathering space, variations in ground level are explored through integrated steps in all iterations. This change in elevation not only enhances spatial definition, but also contributes as water retention pond, controlling the risk of flooding in the area, meanwhile also providing a recreational element to the space and atmosphere.

Three different proposals were sketched in regard to the design of the circular geometry.

The first proposal (see fig. 92) presents a single circular shape in the middle of the gathering point surrounded by steps. This creates the same slope from all sides leading to the lowest point in the centre. This option creates a harsh outline, limiting the intended multipurpose character of the space.

The second proposal showcases half a circle lining up to the main building. Although this option creates a cohesiveness by integrating the buildings, it does not accommodate water retention, which is an important purpose of including this circular element.

The final proposal distributes multiple smaller circular shapes across the area in order to maintain uninterrupted flow while supporting a multifunctional purpose. By breaking up the large area in this way, it creates a more dynamic spaces by offering these smaller niches, which are also convenient in case of heavy rain or flooding.

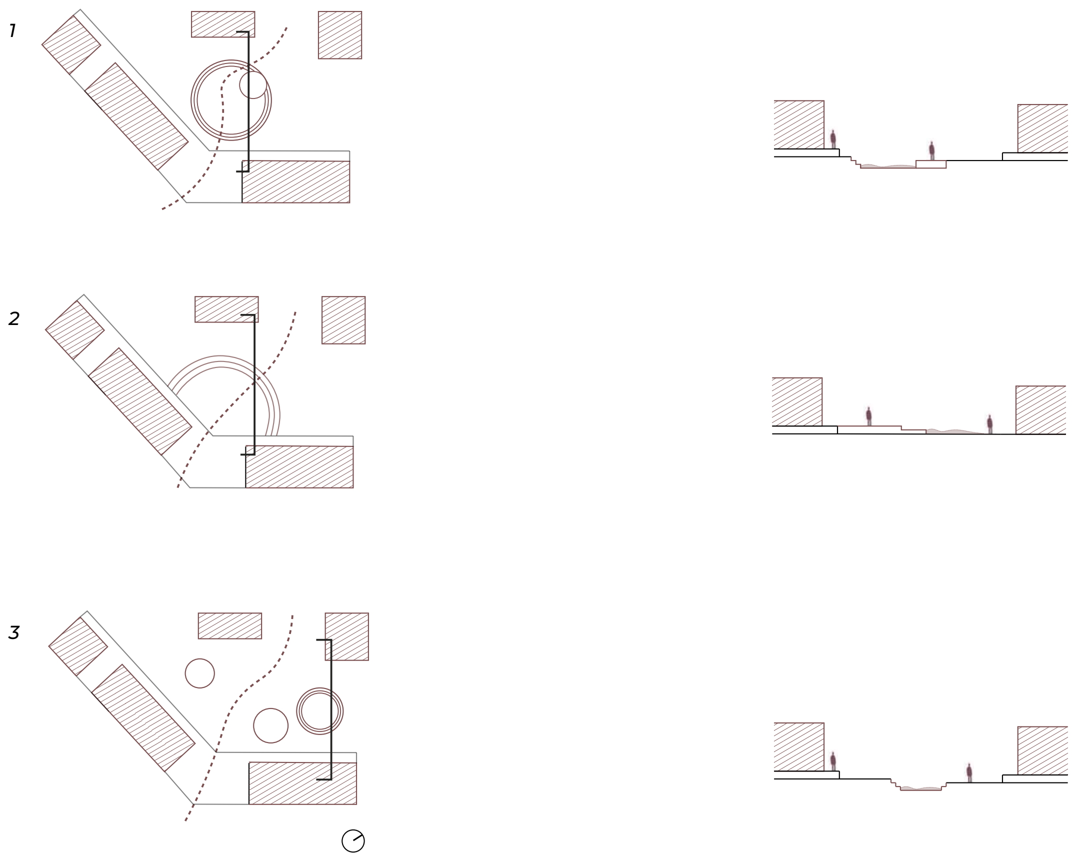


Fig. 92: Gathering point, circular design proposals

School building

Following the allocation of functions within the simplified building volumes, the next step involves a more detailed take to establish a conceptual room arrangement. At this stage, the layout of individual rooms undergoes an iterative process, balancing qualitative aspects such as spatial connections and architectural expression with practical and technical considerations, including daylight access, ventilation, and “easy to build”, as defined in the design criteria.

Conceptual room arrangement

The following options showcases the iterative process behind the arrangement of specifically the classrooms, as this is where the students will spend majority of their time.

In the initial arrangement (see fig. 93), the classrooms are physically separated in different building volumes as a reference to the traditional Zambian functional layout (see page 86). The break areas are placed in between these rooms as a space dedicated to the students in between classes. This arrangement however stimulates a disorienting flow and increases the use of materials as opposed to gathering the rooms together.

This leads to the second iteration, where the rooms are connected but consistently shifting to create enclosed safe spaces for the break areas. This arrangement is however not easy to build with the increased number of building corners.

This leads to the third and most simple arrangement of gathering all classrooms in the same building envelope. Although this option is easy to build, it does not have a varying architectural expression, with the long continuous facades.

These iterations lead to the final room arrangement, where a couple of classrooms are clustered together, still referring to the Zambian tradition while reducing material use, being easy to build and avoiding long facades. The two main flow paths follow along the building volumes for easy acecs and leads to the break areas adjacent to the clusters.

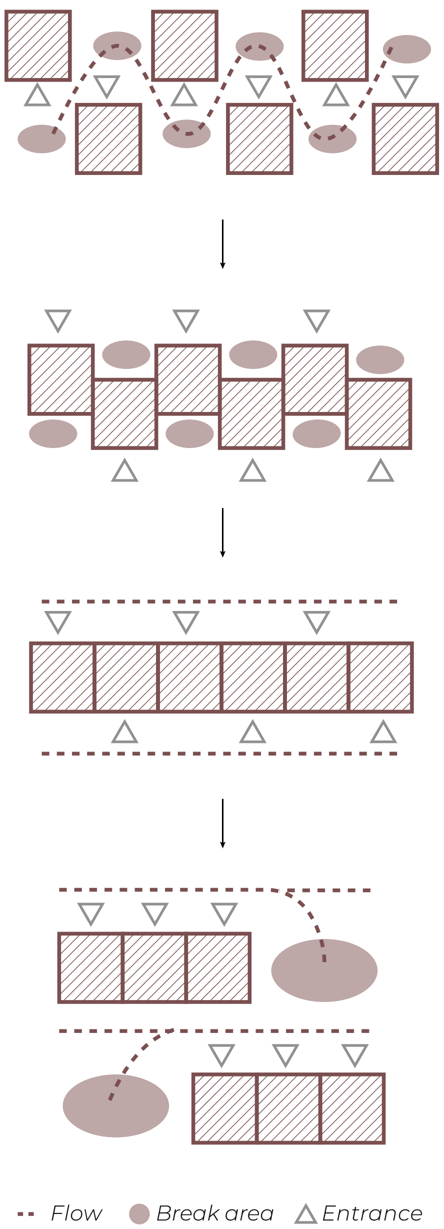


Fig. 93: Process of conceptual room arrangement

Design principles

This room arrangement has not only been optimized in terms of flow and break areas but also consider daylight access and natural ventilation.

The classroom clusters and break spaces are placed so every classroom has access to a break area (see fig. 94). In order to protect the break room and circulation from climate conditions, an overhang is added that creates a cohesive building expression.

Placing the classrooms according to this arrangement, allows for the wind to flow in between the volumes, ensuring a comfortable and cooler outdoor space in the warm seasons. Following this arrangement, every classroom are able to have windows on opposite sides for the purpose of cross ventilation, as well as natural daylight from both sides. The effectiveness of these windows depends on the size and transparency of the overhang, which will be further investigated in the daylight study (see page 101).

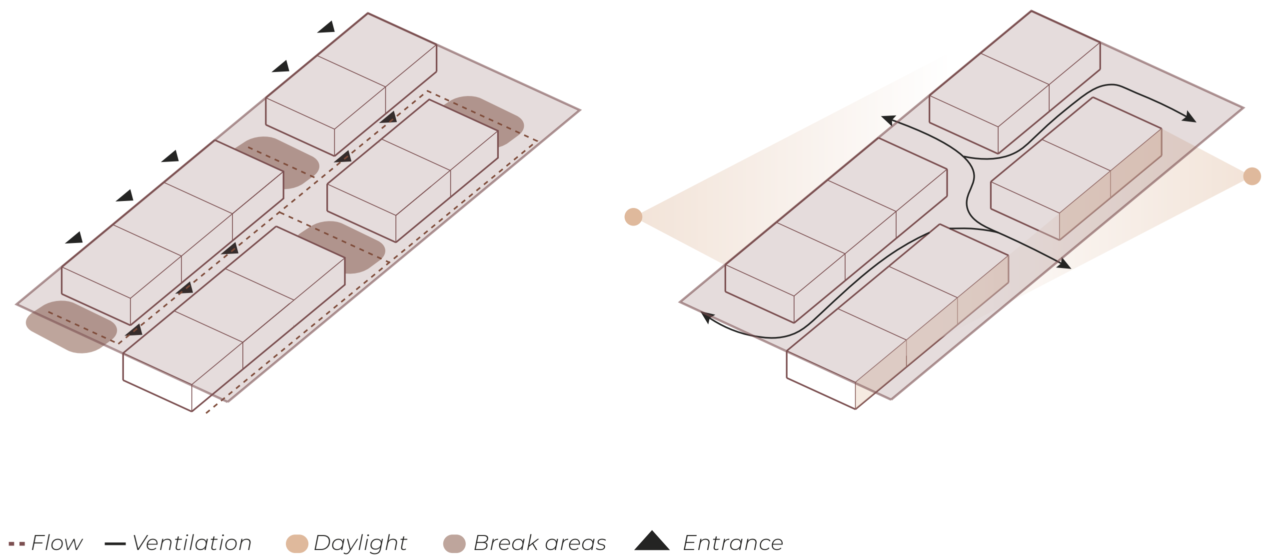


Fig. 94: Detailing the school layout

Initial floor plan proposal

The previous considerations of the functional layout and room arrangement lead to an initial floor plan proposal of the building volumes (see fig. 95), in which the room program also has been taken into account considering the number of functions and their sizes.

The separate buildings arrangement to each other follow the conceptual room arrangement from the previous process, with functions being clustered in multiple building volumes, a concept which was derived from the traditional Zambian layout. This concept is also applied throughout the main educational wing in south, where the buildings are placed parallel to each other enclosing the circulation hallways and creating in between spaces for the break areas.

The educational functions such as the classrooms and laboratories are placed in extension of each other, with multiple toilet cores spread among them. The functions belonging to the staff are centrally placed in order to keep an overview of the school, remaining close to the main south entrance foyer with a reception area.

In the north wing, what previously was a separate assembly hall and dining area have now been combined to one big multipurpose area equipped to use as dining and as an assembly hall for large gatherings. This change happened to the reason of reducing material use and avoid large spaces not being used to their full potential.

The library is located next to the dining and assembly hall with a cohesive roof structure, but in closer proximity to the educational functions. The library provides a secluded and quieter atmosphere for when the students are performing concentrated work for instance during extra-curricular and supervised study, as listed in their daily school routine (see fig. 12).

This proposed floor plan establishes a cohesive and functional school environment, integrating traditional inspirations with practical considerations to create an engaging educational space for the users.

Fig. 95: From functional layout to initial floor plan

Spatial qualities

Circulation

An investigation regarding the height and width of the circulation space in between the buildings has been made (see fig. 97) to visually evaluate the qualities of the created space. The illustration shows that having a height of three meters creates a low, small feeling space, even when the width extends to five meters.

Having a circulation space that is four meters wide, already gives the appearance to be more spacious, where the greater widths allow for more different things to happen at the same time.

The iterations with a height of five meters seem to have a great spatial quality. However, when thinking about material use and the ease of building, this option can be too demanding.

On this basis, the circulation hallways will be five meters wide with a height of four meters, finding a balance between spatial quality and practicality. space it creates, which will be detailed further in the next section.

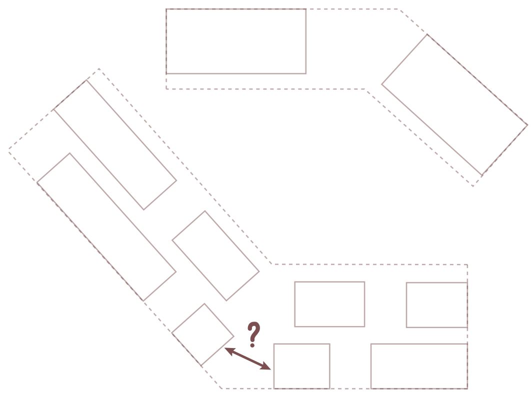


Fig. 96: Spatial quality study, indication of circulation

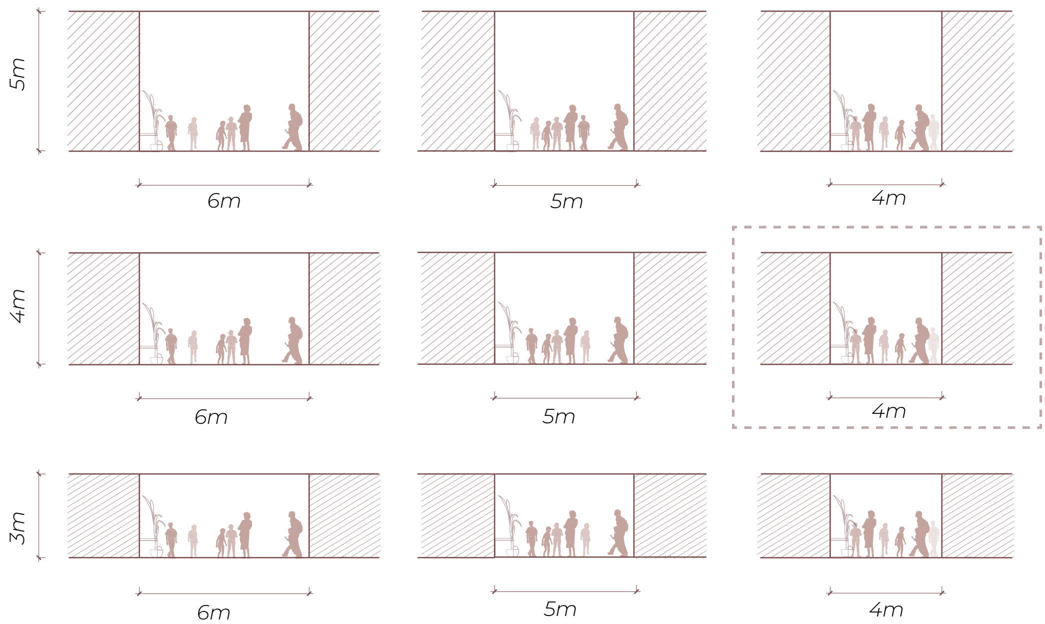


Fig. 97: Spatial quality sections of circulation

Entrance

The entrance of the school buildings has a different spatial quality than the circulation hallways due to its purpose of having a welcoming and inviting character. It is intended to be a space where people enter the school facilities as well as a big common break area.

A width of ten as well as fifteen meters has been investigated (see fig. 99), where both of them are illustrated with three different heights. The different widths illustrate a clear difference between the entrances capacity to gather people and having several activities going on at the same time. However, the school buildings should still appear as one connecting function, which can be lost when having a span of fifteen meter in between.

The design will therefore opt for a solution in between. Spatially, it would be qualitative to have a higher roof in this area, but since the construction will be connected to the circulation hallways overhang, a height of four meters is the most practical solution. Adding a cut out opening in this overhang, allowing greenery to grow through, opens up creates an open atmosphere in the entrance area, even when having a height of four meters.

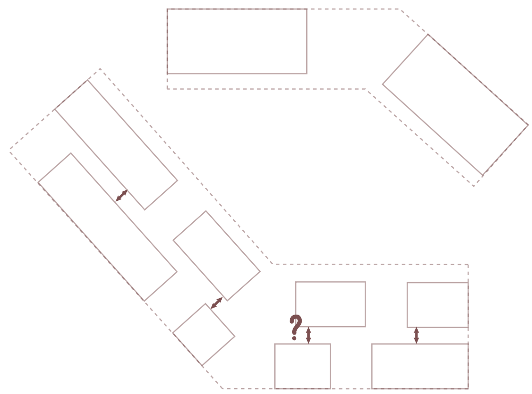


Fig. 98: Spatial quality study, indication of entrance

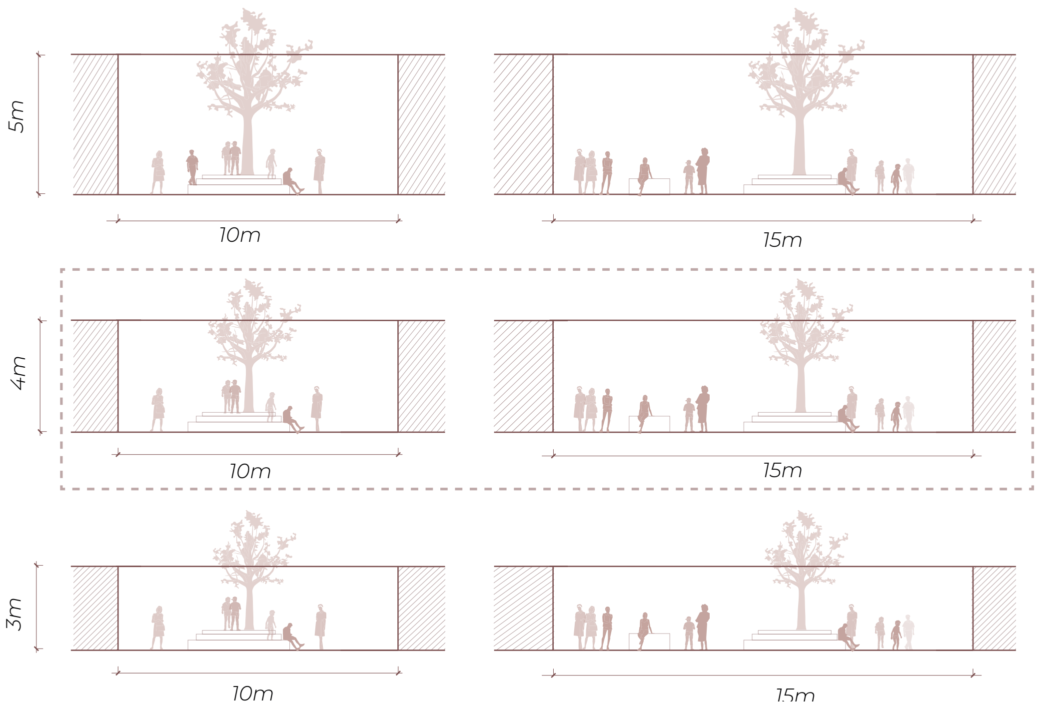


Fig. 99: Spatial quality sections of entrance

Roof study

It is important to not only conduct research on plans and section, but to also consider the building in a three-dimensional perspective. The shape of the roof influences not only the building expression, but also thermal comfort, daylighting, and rainwater management, which all are key factors in achieving a climate-responsive design.

This study evaluates multiple options of gable roofs and flat roofs on how easy they are to build as well as thermal comfort, daylight and rainwater management. The evaluation is based on informed assumptions, where the exact calculations including the roof will be provided in a later section of the report.

Gable roofs

Although the gable roofs (see fig. 100) offer a visually distinctive architectural expression, their geometry and multiple slope directions make them more challenging to construct when compared to a flat roof. These types of roofs typically require more material, increasing the environmental footprint, but however have the advantage of improving natural stack ventilation due to the height. Additionally, the steep slope helps leading rainwater away, minimizing pooling and leaks forming on the roof, which is particularly favorable in heavy rain climates like Zambia.

Flat roofs

Flat angled roofs present a more minimal expression, with cleaner lines and simpler construction techniques. Their lower profile results in a more cohesive design in regard to the overhang, and can help visually unify multiple building volumes.

This typology also allows for more control over roof orientation, which is important when opting to reduce solar heat gain. For example, large roof surfaces facing east and west, as seen in the third option, are likely to contribute to overheating due to direct solar exposure during peak hours, which was informed by the theoretical background (see page 32). Additionally, roofs sloping inward toward the circulation hallways, like in the second and fourth option, may lead to drainage issues during heavy rainfall.

Among the flat roof variations, the second option combines simple construction with limited east-west exposure and effective water runoff. This option also allows for the integration of integrating upper windows to improve daylight levels and natural ventilation strategies without compromising thermal comfort.

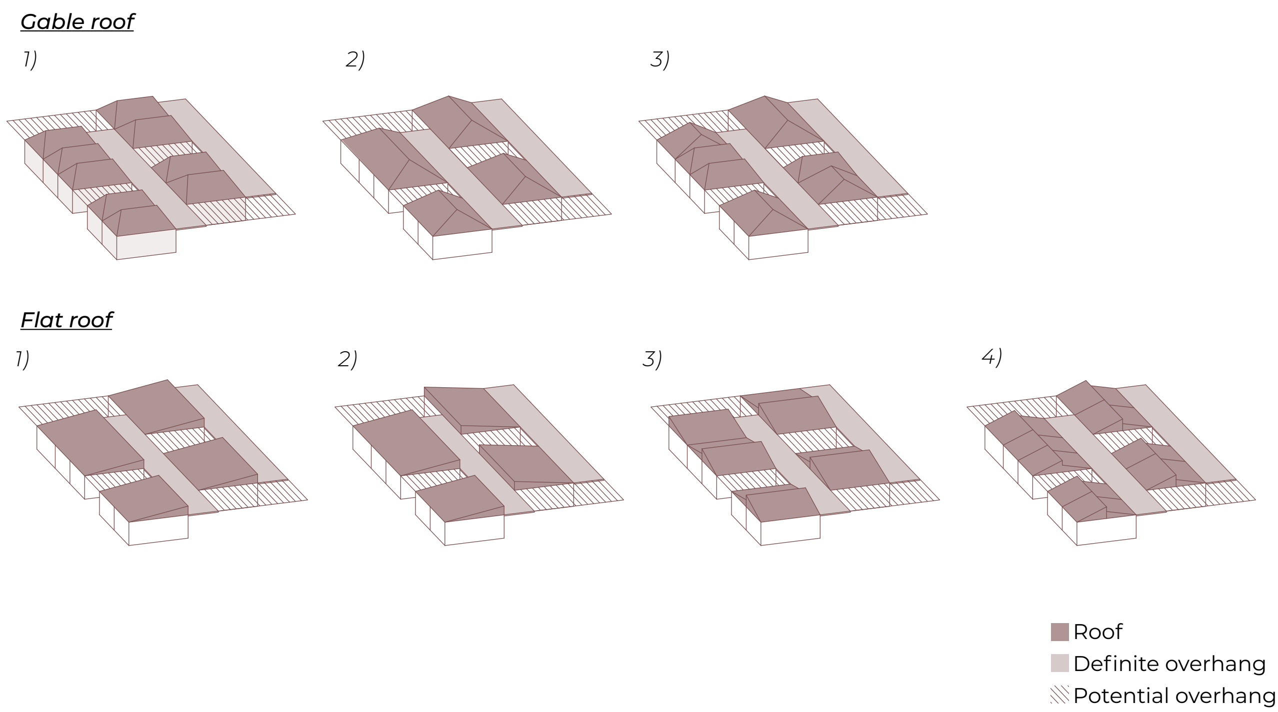


Fig. 100: Roof study

Overhang

In all previous iterations, the overhang has been considered as a separate flat structure from the roofs, which does not give a cohesive expression and is also unfavourable in terms of rainwater management.

After deciding on the flat sloped roof, the overhang can be constructed to align with the roof by extending it in both directions to cover the circulation hallways and the break areas (see fig. 101).

The hallway in between the building volumes is covered with a flat overhang, which is placed lower than the roofs in order to make room for windows above the overhang in consideration of daylight levels.

The break areas are differentiated from the roof in terms of construction and material use to visually stand out as a separate outdoor function.

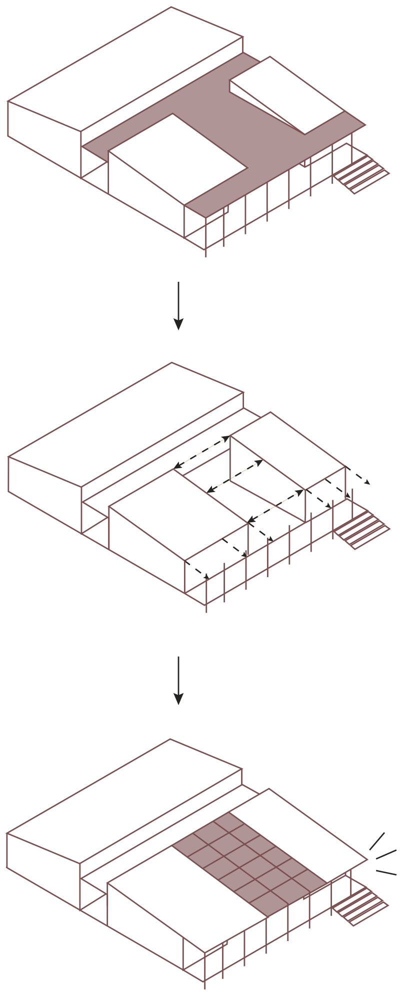


Fig. 101: Overhang

Daylight study

In this study, a color-coded diagram is used to illustrate daylight factor percentages across classroom spaces. According to research by the Chartered Institution of Building Services Engineers and the Society of Light and Lighting (2002), a daylight factor between two and five percent is considered acceptable. In contexts where electric lighting is not typically used, a daylight factor above five percent is recommended.

As this study serves as a principle-based exploration, a simplified building volume is used. To streamline the model, all windows are represented as fully glazed facades, allowing for more consistent and comparable daylight analysis. The objective is not to evaluate detailed design elements but to identify general daylighting principles applicable to classroom environments. Window placement is consistently on the north and south facades.

1. Single-sided windows

In the first daylight study (see fig. 102), the simulation model is designed without overhangs, and each classroom features single-sided windows, either on the north or south façade. The results indicate that daylight does not reach deeply enough into the classrooms. This suggests that windows on both sides are necessary to achieve sufficient daylight distribution.

This would not only improve daylight levels but also enable cross ventilation, which can improve indoor thermal comfort through passive cooling. Additionally, the study reveals that in areas adjacent to the windows, the daylight factor exceeds twenty percent, making the classrooms vulnerable to glare, which could negatively impact visual comfort in the learning environment.

2. Dual-sided windows and shaded hallway

In the second study (see fig. 103), an overhang is introduced to reduce the risk of glare, and windows are placed on both the north and south facades of each classroom. The results show a clear improvement in daylight distribution, with a noticeable reduction of the darker areas. However, the daylight results are less significant in the classrooms that have a facade towards the inner hallway because of the overhang.

These findings suggest that the shape and placement of the overhang should be reconsidered to improve daylight levels in both the underlit and overlit areas. Across all classrooms, the middle ones remain the most critical, where daylight levels are still insufficient.

3. Extended semi-translucent overhang

In the third study (see fig. 104), the overhang is extended to span the full length of both the north and south façades with a projection of four meters. The overhang is constructed from bamboo, creating a semi-translucent structure that allows filtered light to pass through. As a result, the overall daylight conditions show clear improvement, with even the central zones of the classrooms experiencing higher daylight levels.

4. Upper windows

In the fourth study (see fig. 105), the facades are extended above the overhang, so upper windows can be implemented, allowing additional daylight to enter the classroom from above. This can also enhance natural ventilation by enabling the stack effect principle. To isolate the impact of the high-level windows, the standard windows on the north and south façades were removed in this iteration.

The results indicate that the upper windows effectively provide supplementary daylight, with a performance that is independent of the overhangs material choice and translucency. This makes it an effective strategy for improving daylight conditions.

Conclusion

The study indicates that incorporating windows on both the north and south facades is essential to reduce areas with daylight factor values below two percent. Windows located beneath the overhang between buildings have minimal impact when the overhang is fully opaque. However, using a semi-translucent material for the overhang allows more light through the windows. Despite this, such a solution may not be ideal given the long rainy season which requires durable and weather-resistant materials. Additionally, the study shows that implementing upper windows above the overhang is an effective strategy for bringing additional daylight into the classroom.

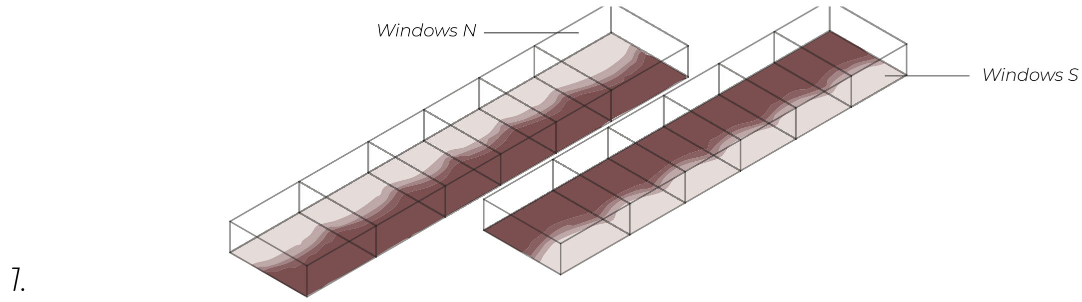


Fig. 102: Single sided windows, datlight study

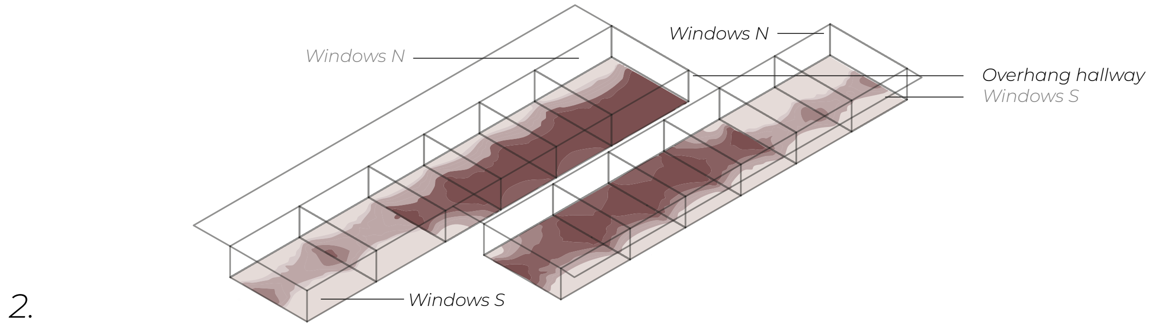


Fig. 103: Dual-sided windows and shaded hallway, daylight study

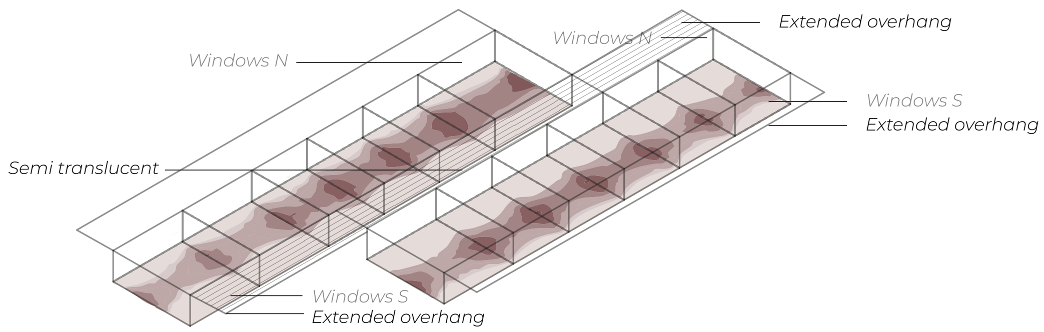


Fig. 104: Extended semi-translucent overhang, daylight study

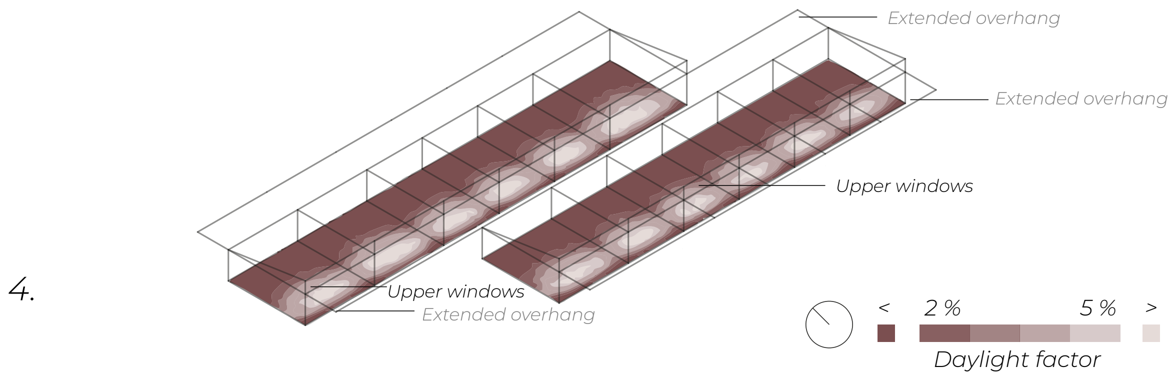


Fig. 105: Upper windows, daylight study

Fig. 106: Close up on ICEB blocks, (INSPIRELI Awards 2024)

Conclusion

The first design phase culminates in a design proposal built on all previous iterations and considerations, ranging from big to small scale.

The design (see fig. 107) consists of functions gathered in separate building clusters as a reference to the traditional Zambian building layout and are connected with a continuous raised deck and overhang. The school campus is mainly accessed by the southern entrance leading to the main road to accommodate non-boarding student, while the boarding students use the opposite entrance in north leading to the private dormitories.

The enclosed central gathering point is an outdoor area offering spaces of varying character and is equipped with round structures inspired by the Zambian insaka structure. These structures provide a space sheltered from rainfall, while the circular steps act as a multipurpose social area and a water retention pond in case of flooding or heavy rainfall. This central gathering space is also the most frequented space in terms of circulation, giving easy and close access to the surrounding social and educational facilities. As the core and heart of the project site, the gathering space is where the community can be experienced, providing space for intimate social interaction and larger group gatherings.

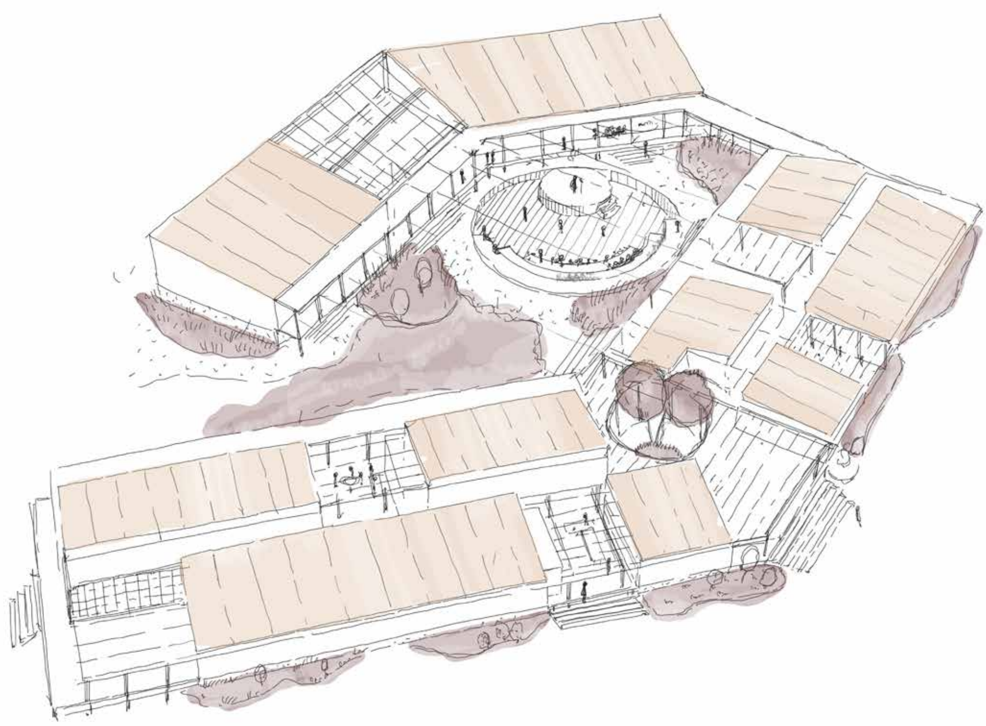


Fig. 107: Initial design proposal sketch

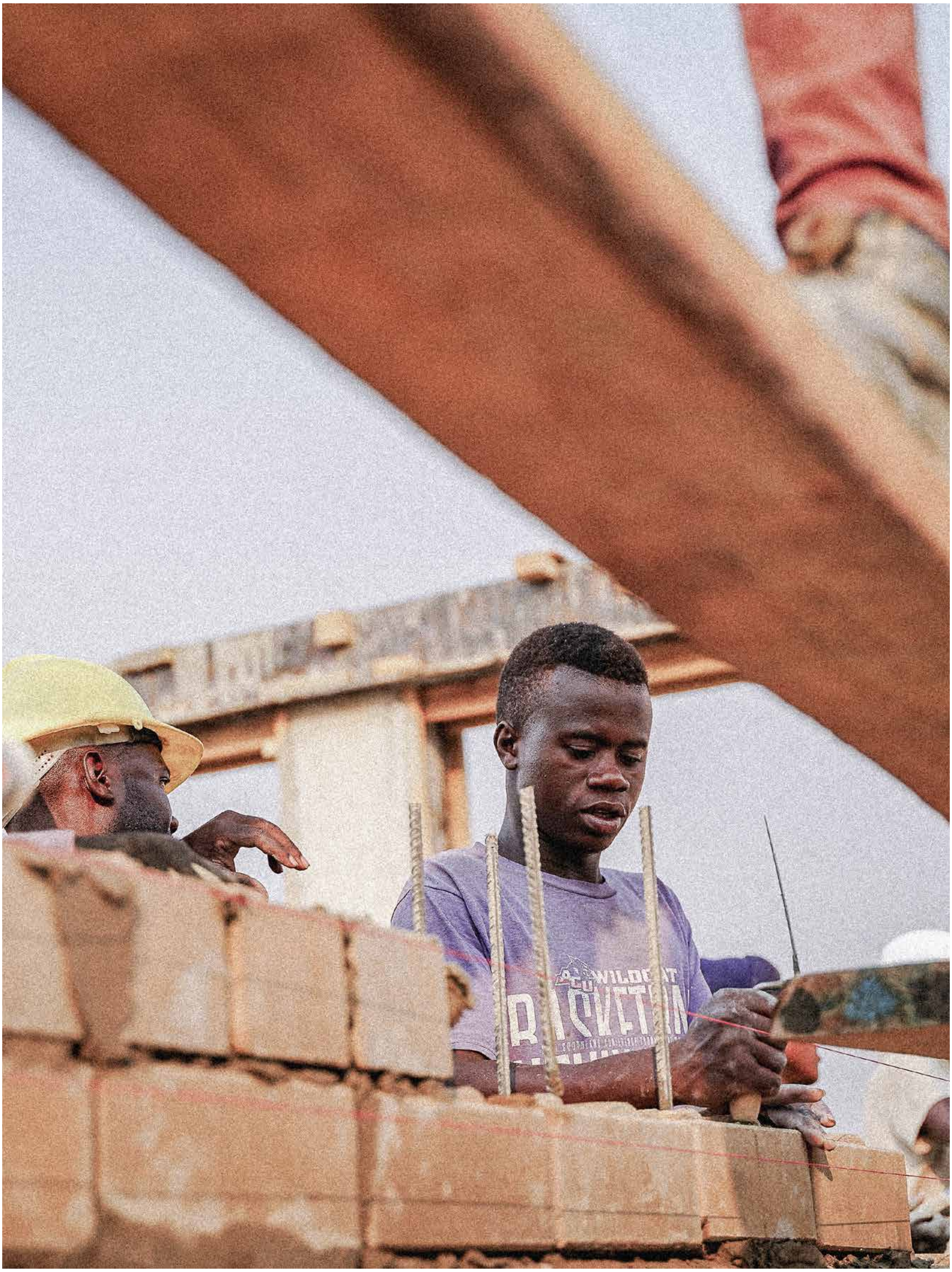


Fig. 108: Stacking ICEB blocks, (INSPIRELI Awards 2024)

06 Design process

phase 2

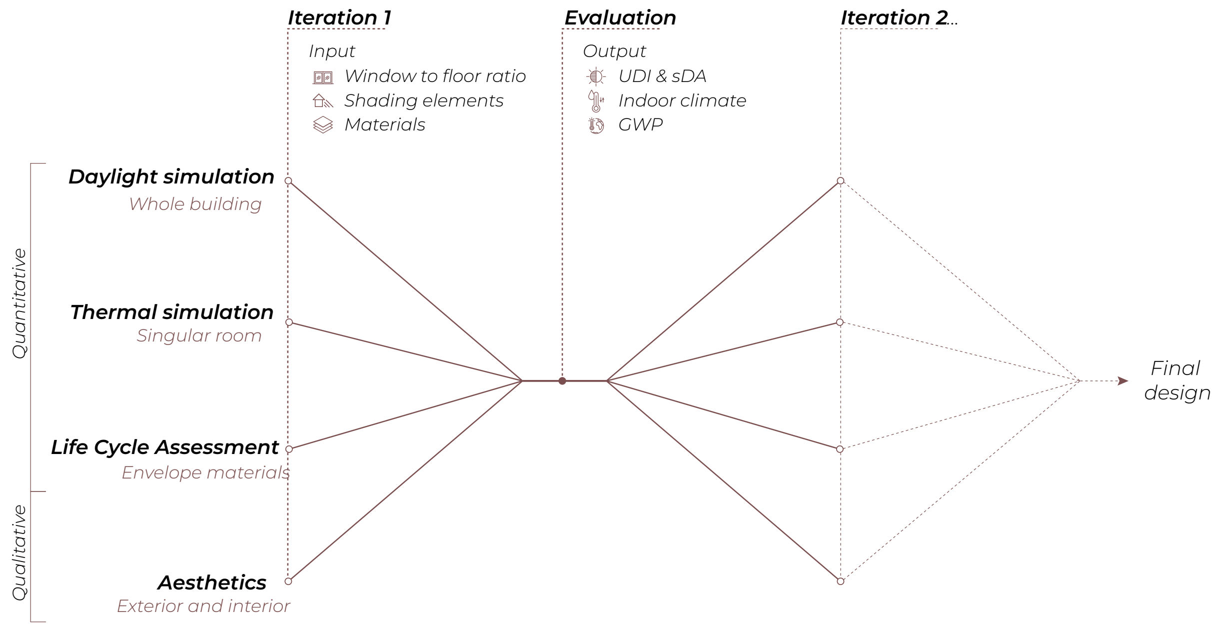


Fig. 109: Design process phase 2 approach

Design Iterations: Simulations and Material LCA

Approach

The following chapter presents the iterative design process, focusing on four parallel tracks being conducted simultaneously (see fig. 109). These include simplified daylight simulations for the entire school building, thermal simulations for a single classroom, a life cycle assessment of the building envelope materials and aesthetics for interior and exterior. The inputs leading to the results are simplified in order for them to be comprehensive and comparable.

The iterative process begins with an initial set of input parameters for the first iteration round, such as window-to-floor ratio, shading elements, and material selection. Each of these aspects is evaluated through quantitative metrics such as spatial daylight autonomy (sDA), useful daylight illuminance (UDI), adaptive thermal comfort (ATC), and global warming potential (GWP). Apart from the numerical simulation results, the iterations will also be evaluated on a qualitative level based on the design criteria of easy to build, traditional architecture, durability as well as practicality and aesthetics.

During this process, the design evolves iteratively where insights gained from one round of simulation will inform the next set of design inputs, leading to subsequent iterations. This approach ensures that design decisions are continuously refined based on the performance feedback after each iteration.

Constant variables

When running the simplified simulations, certain variables remain constant across all iterations to be able to accurately compare the results. All simulation outputs are extracted for the same fixed periods: the most humid and driest week, as well as the coldest and warmest week of the year (see fig. 110, 111).

Occupancy patterns directly influence thermal performance. In the classroom environment, occupancy is set at 100 percent from 08:00 to 16:00 throughout the whole school year, excluding weekends and the summer break (see fig. 112). This reflects realistic usage conditions, impacting internal heat loads and energy use.

Due to the mild and stable climate in East Africa, well-designed buildings in the region can operate efficiently with minimal reliance on active heating or cooling systems by adopting passive design strategies. Given the economic and infrastructural constraints in the East Africa region, connecting to the national grid can be a costly option. Additionally, the region frequently experiences power disruptions, often requiring expensive backup generators to maintain a continuous energy supply. (Clegg and Collin, 2024) These conditions further underscore the importance of designing passive bioclimatic buildings independent of unreliable energy sources.

To reflect these conditions, no dedicated heating or cooling system has been defined for the simulation model. Remaining factors such as lighting and equipment are constant inputs (see fig. 113) given by default based on the 90.1 - 2019 ASHRAE Standard for secondary schools.

Since the operational energy use is limited to lighting and equipment, it is not included in the calculation of the building's Global Warming Potential. As for the Life Cycle Assessment, a simplified approach is adopted with only the embodied impacts of construction materials and their transportation being considered. A detailed list of the specific inputs is provided in appendix B. During all iterations, the use of ICEB remains constant as well as a raised floor deck around the buildings with a bamboo overhang.

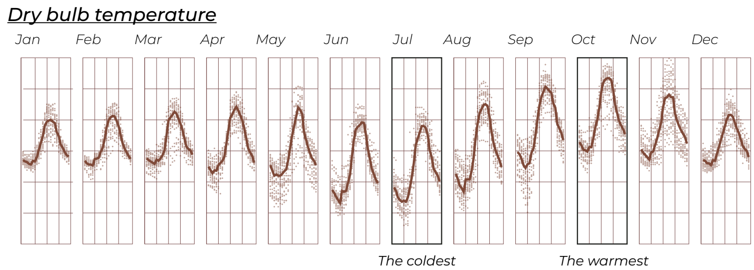


Fig. 110: Simulation period: Warmest and coldest week of the year

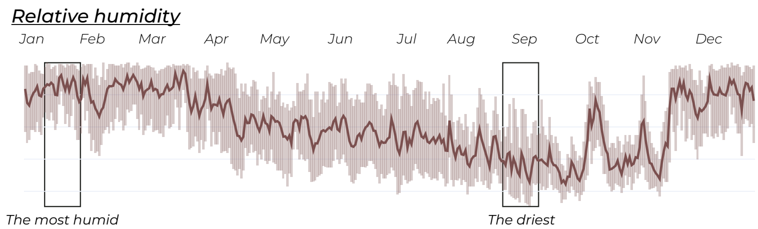


Fig. 111: Simulation period: Driest and most humid week of the year

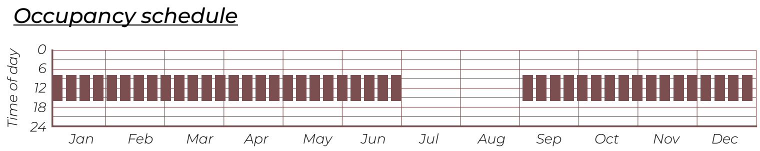


Fig. 112: Simulation input: Occupancy schedule

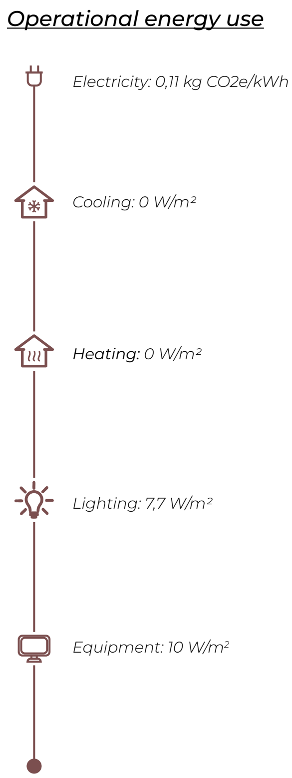


Fig. 113: Simulation input: Energy use

Fig. 114: Construction site process, (INSPIRELI Awards 2024)

Base model - Local materials

Daylight availablity

In order to assess daylight levels inside the building, a base model is built upon a simple extrusion of the floor plan in the shape of basic geometric volumes with flat roofs (see fig. 115). Daylight levels in the educational building are assessed using UDI and sDA.

The window area follows South African Regulations SANS 10400-O:2011, requiring openings to be at least 5% of the room's floor area. In the simulation model, windows are sized accordingly and symmetrically placed on the north and south facades.

To improve environmental protection and comfort, overhangs are incorporated due to Zambia's long rainy season. Circulation hallways and break areas are fully sheltered, while a 60-centimeter overhang covers remaining facades, helping to regulate indoor temperatures by reducing heat gain.

Toilet cores and storage rooms have been excluded from all daylight simulations due to their limited occupancy and the lack of daylight requirements for these spaces.

Results

The average UDI of 9,6 percent shows that daylight levels rarely fall within the optimal range of 300 to 3000 lux during occupied hours, while an sDA of 7,8 percent indicates that only a small portion of the regularly occupied floor area receives adequate daylight.

The maps (see fig. 116, 117) clearly illustrate how the daylight levels within the analysed spaces are significantly diminished. As a result, the indoor spaces experience reduced daylight levels, impacting the learning environment and overall lighting quality, which can be improved by increasing the window area or adjusting the overhang.

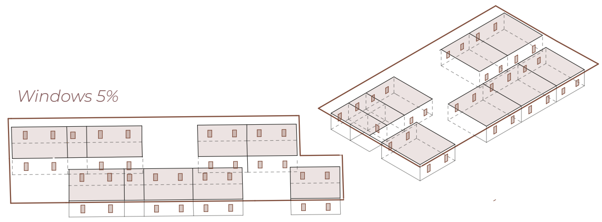


Fig. 115: Daylight availability - base model isometric

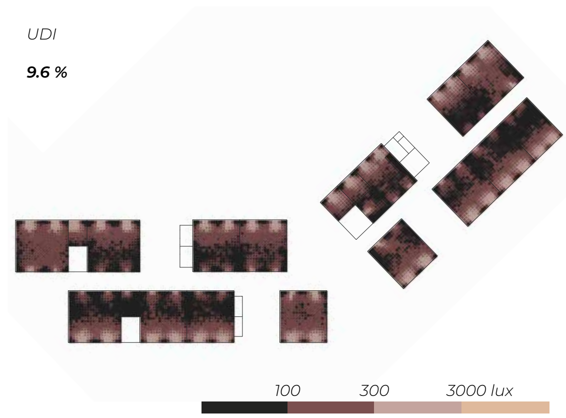


Fig. 116: UDI results- base model

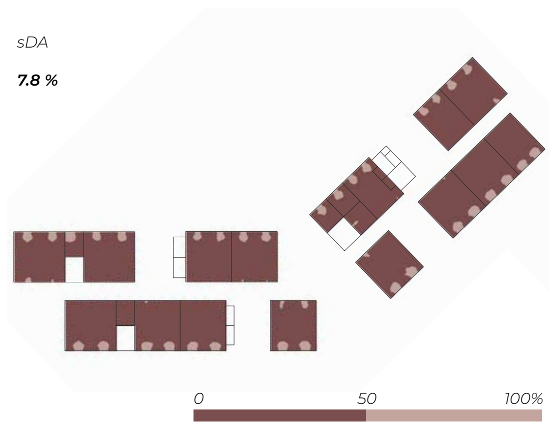


Fig. 117: sDA results - base model

Indoor climate and LCA

To streamline the simulation process, a laboratory in the left wing (see fig. 118) has been selected as assumed to be the most critical room for potential overheating and will be analysed for indoor climate performance.

Materials

The starting point of the construction is to work with the five locally available materials; earth, stone, bamboo straw and wood to reduce transportation emissions and encourage local businesses, while also respecting the local architectural identity as stated in design criteria 4.2.

For the base model, the construction will follow the current building practices in the rural areas of Zambia. The wall construction therefore consists of a single layer of ICEB, while the roof is constructed with wood beams covered by thatched straw (see fig. 119). It is noted that when building a thatched roof, it must have an incline to ensure water drainage and durability, even though the simulation model is simplified with a flat roof. The foundation is a thick layer of rammed earth (Auroville Earth Institiute, n.d.) covered by a thin layer of earth tiles as the floor. To identify the specific U-values of these traditional construction elements, detailed construction sections were defined in Ubakus (see appendix C).

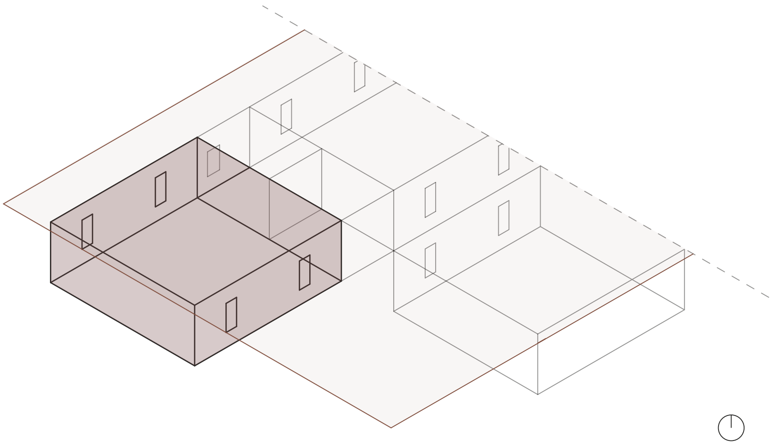


Fig. 118: Thermal analysis zone- base model

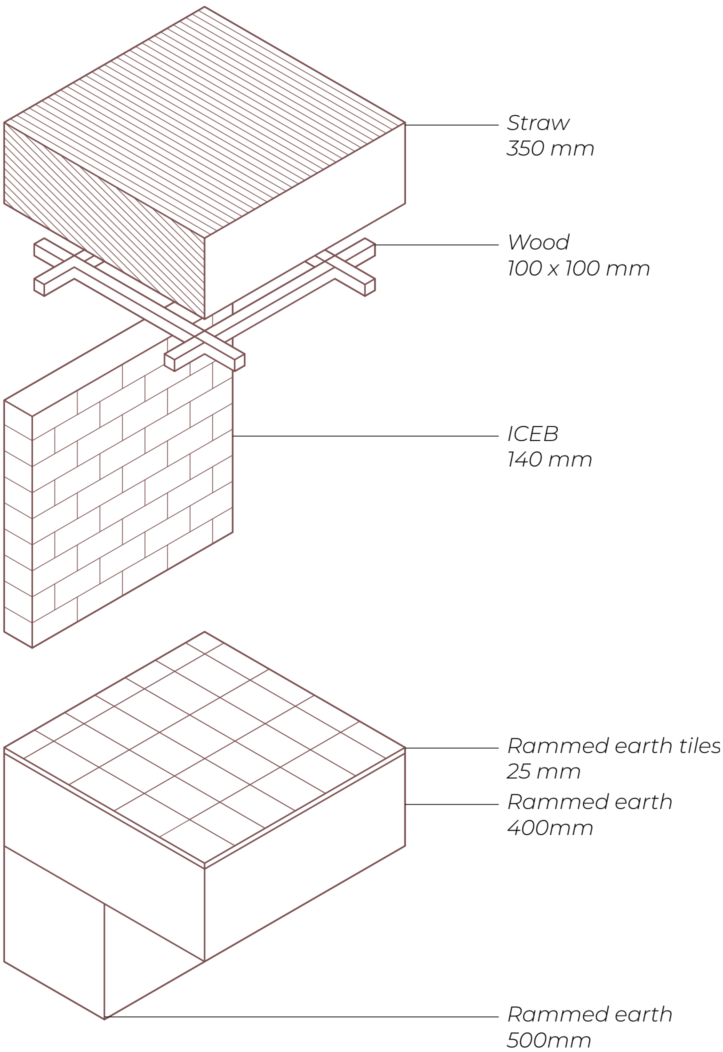


Fig. 119: Exploded diagram of materials - base model

Aesthetic

Overall aesthetics

Having a thatched roof for the base model as seen on figure 120, directly refers to the vernacular architecture which gives a more natural look, harmonizing with the colour palette of the other materials. It however visually dominates the design, resulting in an unbalanced and somewhat overwhelming overall expression. Additionally, the windows seem to be too small, making the facade appear long.

Rammed earth floor tiles as the floor (see fig. 121) make the interior warmer in appearance. Since each tile is unique, it can create an individual character to each classroom.

Practicality

The base model has been made to prove that building a school out of local materials is possible. However, practically seen, having a thatched, gable roof and lightweight bamboo overhang can lead to water damage. Furthermore, the high risk of fire regarding straw is a significant disadvantage when designing a safe space for children.

Easy to build

Building only from what is local and available enables the local community to build the school by themselves since the construction methods are known and traditional, ensuring the school to be easy to build.

Durability

The risk of fire and need for special maintenance which requires replacing the straw every ten to fifteen years (The Thatch Advice Centre, n.d.), makes it a more costly option even though the raw materials are harvested locally. This makes the base model less durable regarding the roof.

Fig. 120: Facade visualization - base model

Fig. 121: Clasroom visualization - base model

LCA

The first graph (see fig. 122) shows the results of the GWP of materials used in different construction elements. The foundation shows lower GWP compared to the floor and walls, primarily because it uses less earth, being constructed only beneath the walls. Despite the cement making up just five percent of the wall material mix, its high impact is clearly reflected in the wall's total GWP, highlighting the environmental cost of even small amounts of high-emission materials.

The second graph (see fig. 123) indicates that transportation has a minimal environmental impact compared to the materials themselves. Overall, the total GWP remains low, largely due to the use of local, sustainable materials. Detailed figures and calculations are provided in the appendix.

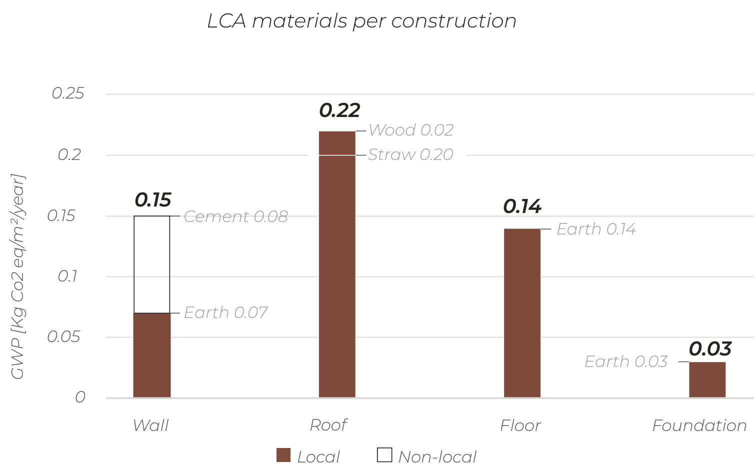


Fig. 122: LCA results - base model

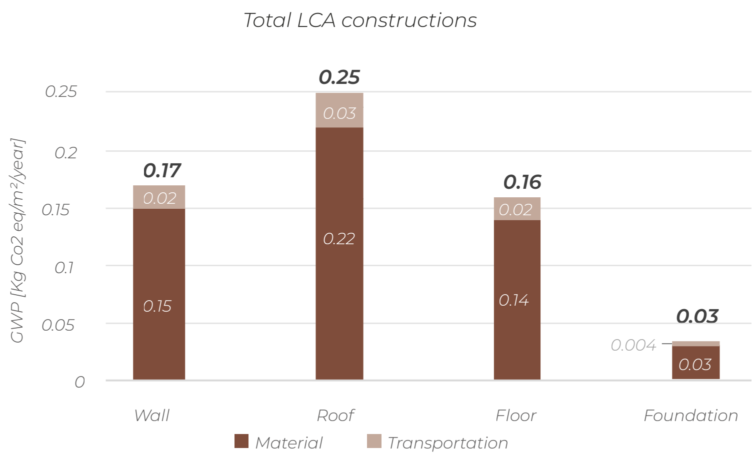


Fig. 123: LCA results - base model

Indoor climate

Extremes

The base model indicates that the highest and lowest values of humidity is 86.1 and 19.2 percent (see fig. 124), and for temperature is 31.7 and 16.1 degrees (see fig. 125). It is seen in the graphs that the highest values inside the occupancy hours are not the most extreme when considering the whole week. However, since this is the timeframe where users are assured to be inside, these values are the most representative.

ATC

The adaptive thermal comfort graph (see fig. 126) illustrates the number of occupancy hours within the comfort range, with darker areas indicating higher values. For example, when the outdoor temperature is 28 degrees Celsius, all operative temperature hours are within the comfort zone. Overall, 60 percent of the hours fall within the category three comfort range.

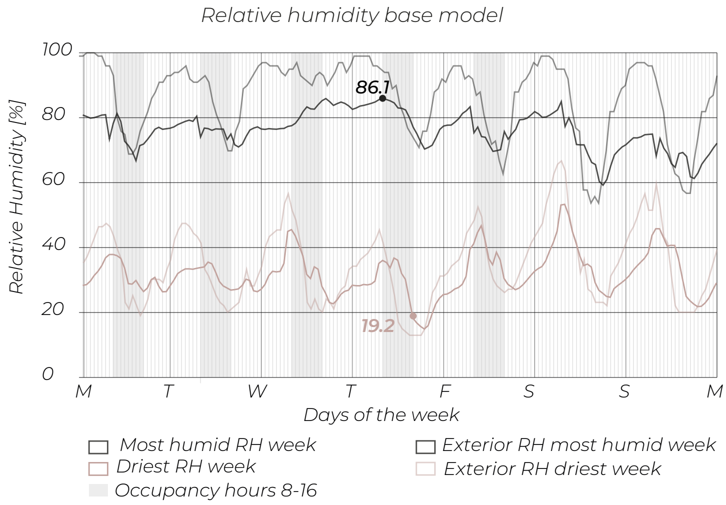


Fig. 124: Relative humidity graph - base model

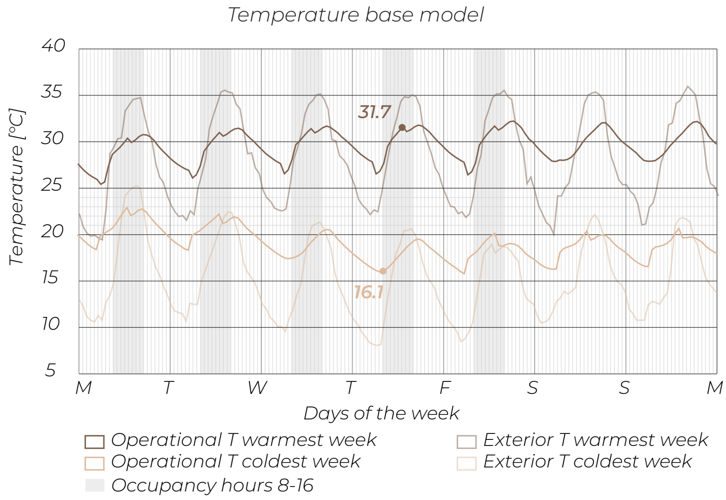


Fig. 125: Temperature graph - base model

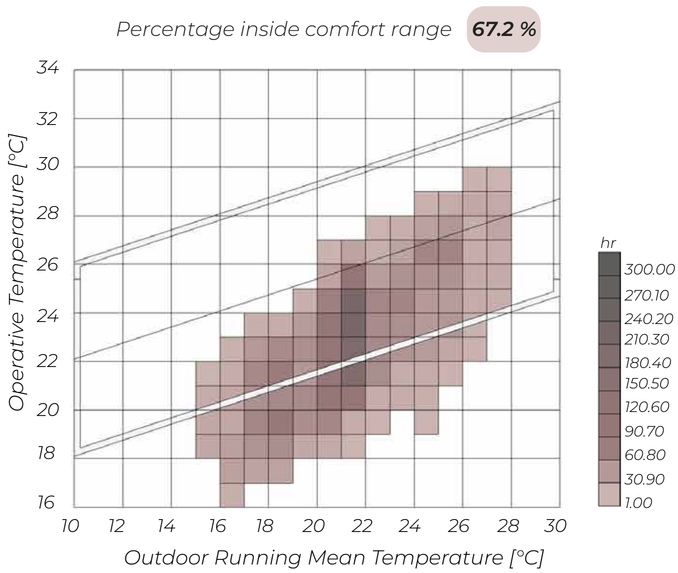


Fig. 126: Adaptive thermal comfort graph - base model

Summary

Base model

Input

Window to floor ratio

North and south facades	*5 %*

Shading elements

Overhang west	*60 cm*
Overhang north	*300 cm*
Overhang south	*1550 cm*

Materials

Wall	*2.70 W/m²K*
Floor	*1.20 W/m²K*
Roof	*0.14 W/m²K*
Foundation	*1.08 W/m²K*

Output

UDI & sDA

UDI	*7.8%*
sDA	*9.6%*

Indoor climate

Highest T	*31.7 °C*
Lowest T	*16.1°C*
Highest RH	*86.1 %*
Lowest RH	*19.2 %*
ATC	*67.2%*

GWP

Wall	*0.17 KgCO2eq/m²/year*
Floor	*0.16 KgCO2eq/m²/year*
Roof	*0.25 KgCO2eq/m²/year*
Foundation	*0.03 KgCO2eq/m²/year*
Total	*0.61 KgCo2eq/m²/year*

Fig. 127: Fact box - base model

Iteration 1 - Optimised local

Daylight availablity

The building's design has evolved from a simple box to a more dynamic form with a sloped roof (see fig. 128), optimizing rainwater management during the long rainy seasons. To further enhance indoor daylight levels, the window-to-floor ratio has been increased to 10 percent. Additional upper windows have been implemented above the overhangs in order to create a well-lit and comfortable indoor environment.

Results

To assess the impact of the upper windows on indoor daylight levels, two simulations have been conducted; one including the upper windows and one without them. These simulations provide a comparative result to determine how significantly the upper windows contribute to natural illumination within the space.

The average numerical results of UDI and sDA clearly demonstrate the significant impact of the upper windows on indoor daylight levels. Without the upper windows, the UDI increases from 7.8 to 27.4 percent and the sDA from 9.6 to 27.3 percent compared to the base model.

However, when adding these upper windows, the UDI increases to 62.3 percent and the sDA reaches 72.1 percent. It is seen that upper windows are therefore very beneficial when opting to create a sufficient learning environment regarding daylight. This means that the goal of reaching at least 50 percent daylight autonomy has been achieved. However, the 80 percent target of UDI has still not been reached.

A closer look at the radiation maps (see fig. 129, 130) indicates, that the majority of the floor area receives an acceptable amount of daylight. Rooms such as the offices and meeting room along with the north classrooms however experience lower daylight levels, suggesting a need for improvement in these areas.

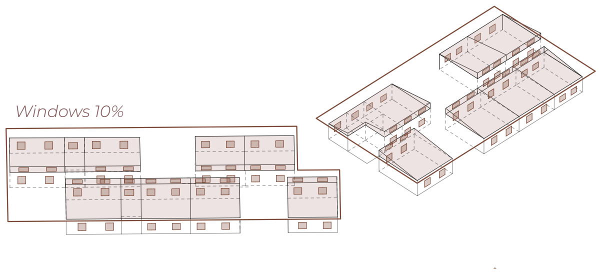


Fig. 128: Daylight availability - iteration 1 isometric

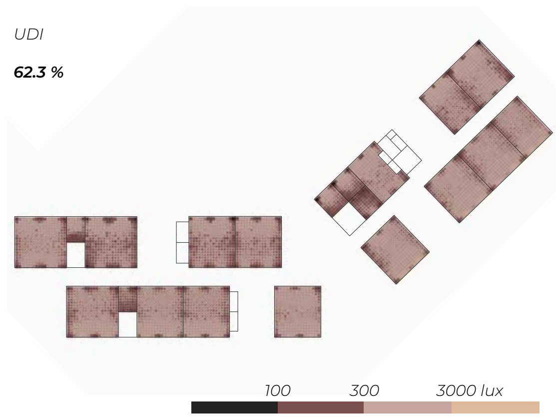


Fig. 129: UDI results- iteration 1

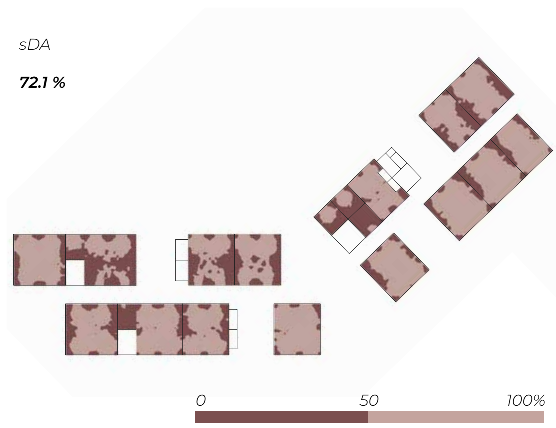


Fig. 130: sDA results - iteration 1

Indoor climate and LCA

In the following iteration, the base model will be optimized for U-values while using only the same five locally available materials to improve the indoor climate. Zambia lacks building codes, but in hot, humid climates, recommended U-values are below 1 W/m²K for walls and below 0.85 W/m²K for roofs (Unhabitat.org, 2015). A maximum U-value of 1 W/m²K for floors and foundations is recommended (TIPSASA Technical Committee, 2022).

Adding straw insulation reduces the walls U-value from 2.7 W/m²K to 0.39 W/m²K, while increasing its thickness from 140 millimetres to 380 millimetres (see fig. 132). Floor optimization includes straw insulation in a wooden frame (TIPSASA Technical Committee, 2022, pp.17), lowering the U-value from 1.2 W/m²K to 0.48 W/m²K while reducing thickness from 425 millimetres to 170 millimetres.

For foundations, rammed earth offers a better thickness-to-U-value performance, while stone provides a better water resistance considering the areas risk of flooding. Just as the wall construction, these stones need cement to be built. Bamboo will be integrated into the roof as a ceiling without increasing the thickness, slightly lowering the U-value from 0.14 W/m²K to 0.13 W/m²K while improving acoustic and thermal properties (Clegg and Collin, 2024, pp.108).

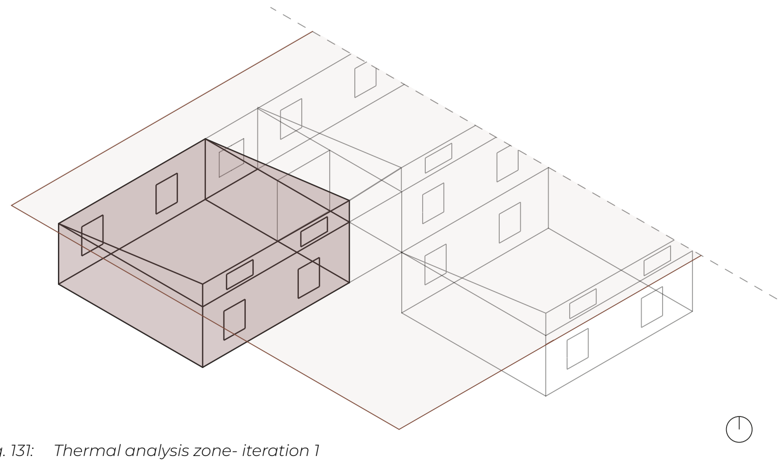


Fig. 131: Thermal analysis zone- iteration 1

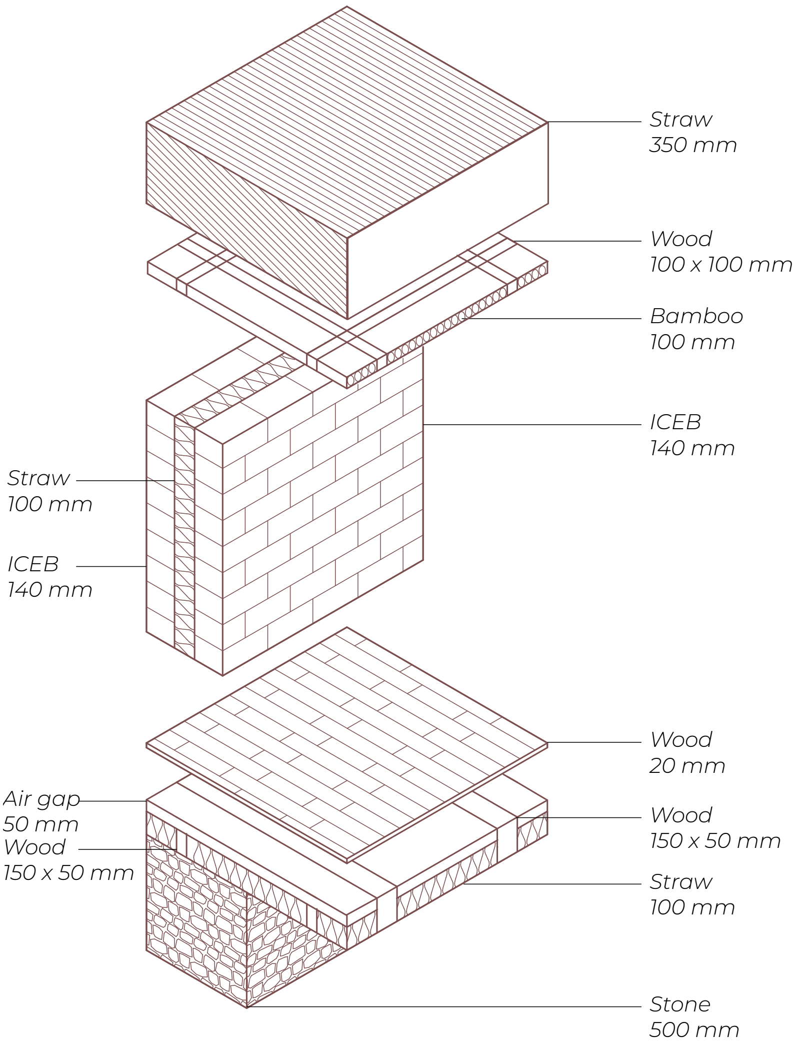


Fig. 132: Exploded diagram of materials - iteration 1

Aesthetic

Overall aesthetics

The sloped thatched roof has the same issue as the base model. However, it is seen that the bamboo ceiling attached to its construction compliments the ICEB, making the interior more cohesive (see fig. 134).

Practicality

Replacing rammed earth tiles with wooden floor makes the classroom more child friendly since they can walk on the warm floor without shoes or play on it.

Easy to build

This iteration has the same roof challenges as the base model, appearing too dominating (see fig. 133). Using a stone foundation might need more qualified people on the construction site, which would exclude the locals from this process.

Durability

Stone foundation has a larger durability, which can help withstanding heavy rains and is considered a significant advantage. Wooden floors used for this iteration can be hard to maintain and can be a questionable solution when it comes to flooding risks.

Fig. 133: Facade visualization - iteration 1

Fig. 134: Clasroom visualization - iteration 1

LCA

The overall GWP of the constructions increased due to the addition of materials for insulation, structural, and acoustic purposes. Notably, the GWP of the floor decreased when switching from rammed earth to a wooden floor with straw insulation (see fig. 135). This is mainly due to a reduction in thickness by 300 millimetres.

In contrast, the foundation's GWP rose significantly, primarily due to the use of stone and its high transportation impact (see fig. 136), influenced by both distance and material density (see appendix B for detailed figures).

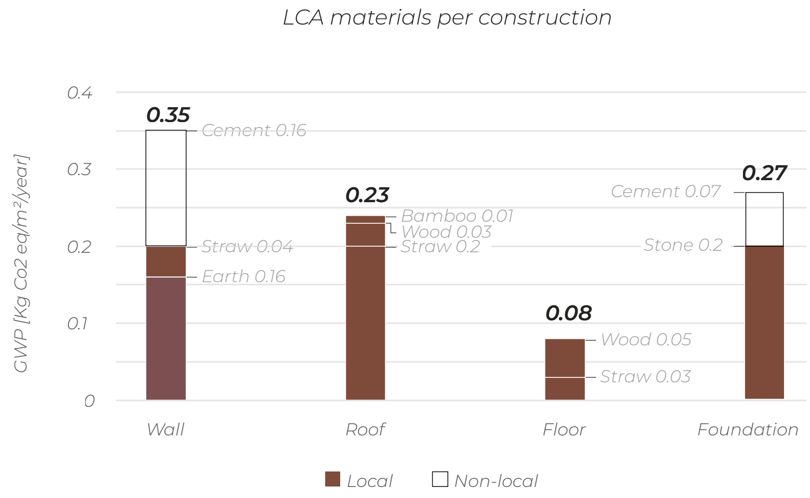


Fig. 135: LCA, materials per construction comparison of iteration 1

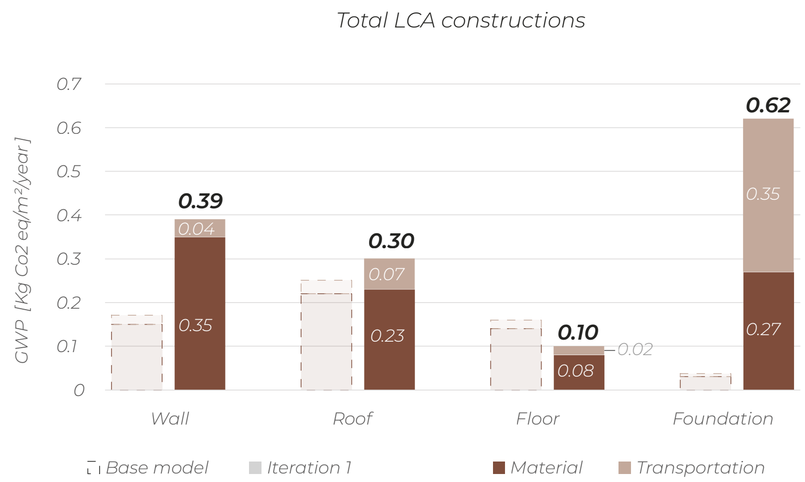


Fig. 136: LCA, total constructon comparison of iteration 1

Indoor climate

Extremes

The first iteration shows a significant decrease in most humid percentage and a smaller, yet noticeable improvement of the coldest degree (see fig. 137, 138). The lowest relative humidity and highest temperature show minimal to no change. As expected from the preceding theoretical research, the highest temperature occurs in both cases in the afternoon.

ATC

The adaptive thermal comfort graph (see fig. 139) shows that there are more hours inside the range compared to the base model, especially considering the lower temperatures. This also corresponds with extreme temperatures shown above (see fig. 138). The total percentage inside the range improved from 67.2 to 83.5 percent.

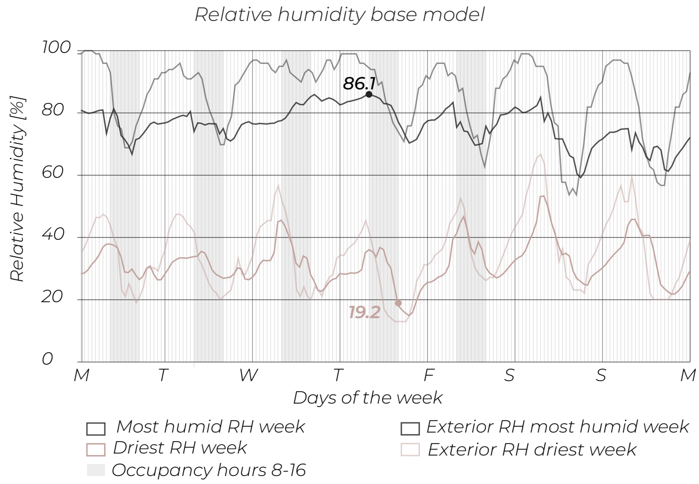


Fig. 137: Relative humidity graph - iteration 1

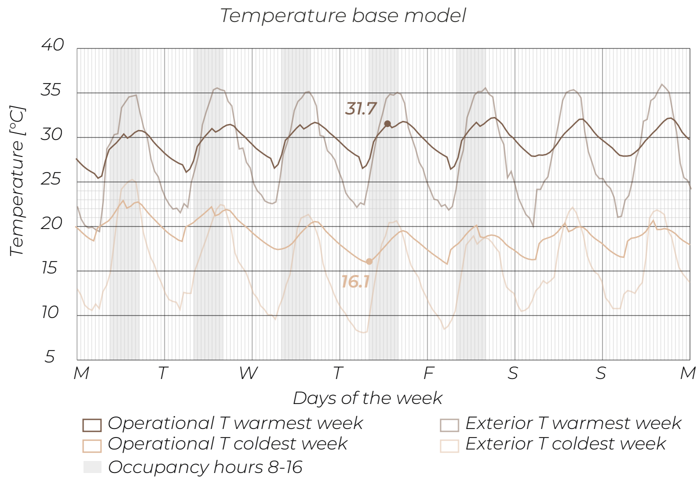


Fig. 138: Temperature graph - iteration 2

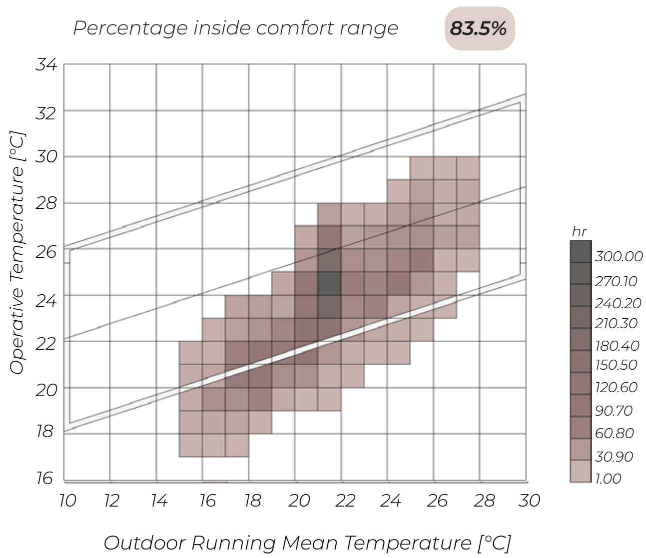


Fig. 139: Adaptive thermal comfort graph - iteration 1

Summary

Iteration 1

Comparison to base model

Input

Window to floor ratio

*North and south facades + **upper windows*** △ **10** %

Shading elements

Overhang west	= 60 cm
Overhang north	= 300 cm
Overhang south	= 1550 cm

Materials

Wall	▽ **0.39** W/m²K
Floor	▽ **0.48** W/m²K
Roof	▽ **0.13** W/m²K
Foundation	△ **2.60** W/m²K

Output

UDI & sDA

UDI	△ **62.3 %**
sDA	△ **72.1 %**

Indoor climate

Highest T	= 31.7 °C
Lowest T	△ **18.3** °C
Highest RH	▽ **78.8** %
Lowest RH	△ **19.9** %
ATC	△ **83.5** %

GWP

Wall	△ **0.39** KgCO2eq/m²/year
Floor	▽ **0.10** KgCO2eq/m²/year
Roof	△ **0.30** KgCO2eq/m²/year
Foundation	△ **0.62** KgCO2eq/m²/year
Total	△ **1.41** KgCo2eq/m²/year

Fig. 140: Fact box - iteration 1

Iteration 2 - Bio based

Daylight availablity

While the building volume remains unchanged from the previous iteration, the window-to-floor ratio was increased to fifteen percent due to insufficient UDI performance (see fig. 142). In spaces with the lowest sDA values, such as offices and meeting room, the ratio was raised further to twenty percent to improve daylight conditions.

Results

Based on the results, it is seen that the UDI has increased from 62.3 to 80 percent, reaching the target value. The sDA has also increased and is well above the set goal of 50 percent. The radiation maps (see fig. 142, 143) indicate that daylight levels are sufficient and within an acceptable range during occupancy hours.

However, the results also show that the sDA value in some areas is above the maximum desirable value of 3000 lux. To address this, shading elements and shutters will be explored in the next iteration to reduce excessive daylight levels. These additions may also impact indoor temperature and humidity, which will be evaluated accordingly.

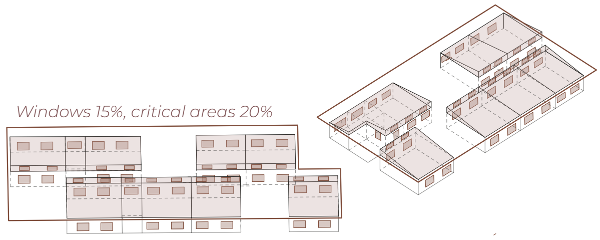


Fig. 141: Daylight availability - iteration 2 isometric

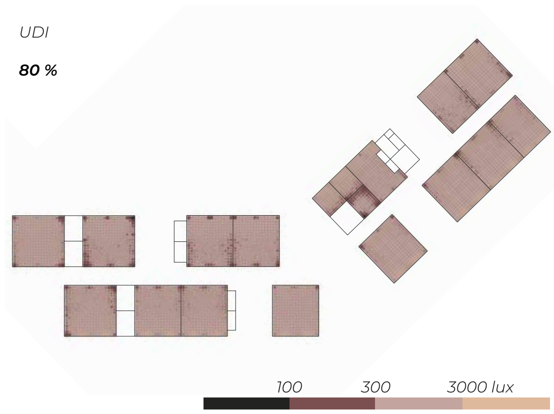


Fig. 142: UDI results- iteration 2

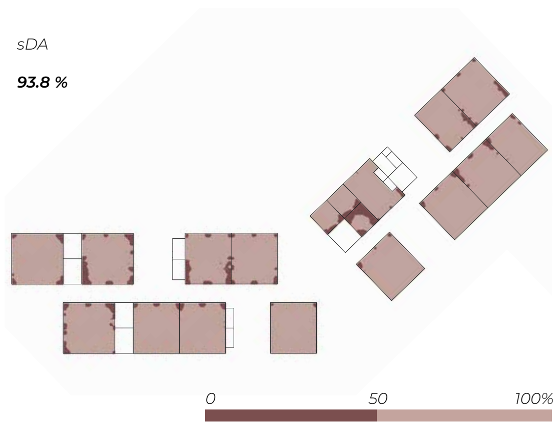


Fig. 143: sDA results - iteration 2

Indoor climate and LCA

Materials

In the following iteration, the base model will be further optimized for U-values while using bio-based materials as an addition or replacement of the five local materials used in the previous iterations (see fig. 145)

Apart from straw bales, there are other bio-based insulation materials which can be harvested with low emission. One of those materials is kenaf fibre, which is a carbon-negative insulation material with better thermal conductivity than straw (Westerholm, 2023). This kenaf insulation is used for the floor construction which changes the U-value respectively from 0.48 to 0.33 w/m²K. Kenaf fibre is also used in the walls and makes the walls 70 millimetres thicker, which translates into a U-value decrease from 0.39 to 0.22 W/m²K.

An alternative environmentally friendly option for the roof cladding, which can be used instead of straw, is wood roof shingles. This, in combination with kenaf fibre insulation and an increased thickness of 30 millimetres only increased the U-value with 0,008 W/m²K. This is a very small difference in terms of thermal performance, but a large difference in architectural expression.

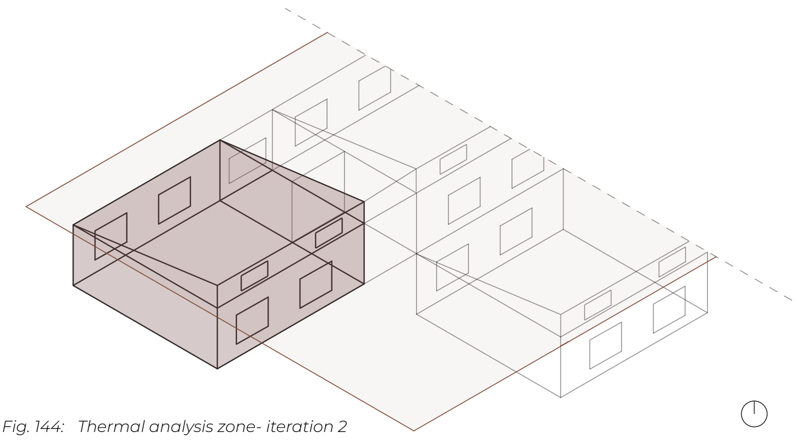


Fig. 144: Thermal analysis zone- iteration 2

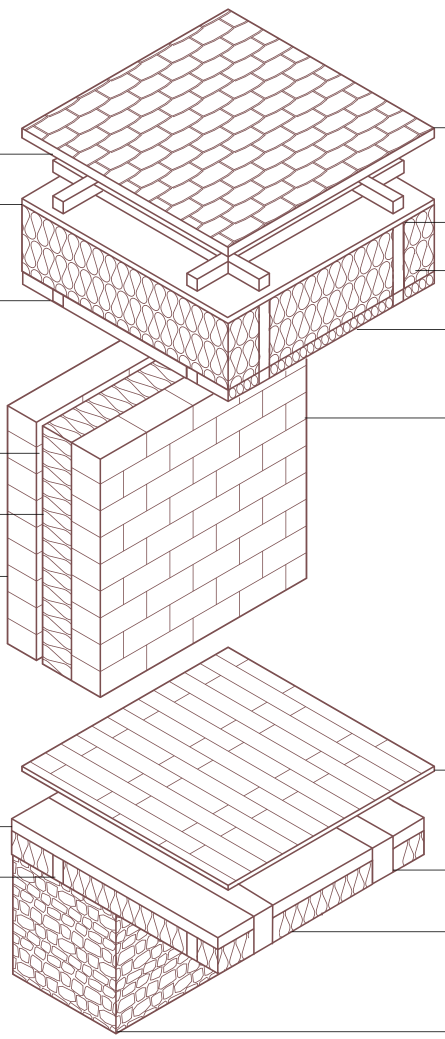


Fig. 145: Exploded diagram of materials - iteration 2

Aesthetic

Overall aesthetics

Wooden shingles create a cohesive look with other wooden elements of the building since they have the same colour tones (see fig. 146). Its construction also allows to keep the bamboo ceiling (see fig. 147). Bigger windows break the facade into smaller parts, which increases the transparency between indoor and outdoor.

Practicality

Replacing the thatched roof with wooden shingles may introduce maintenance challenges. Given the long rainy season and high humidity levels, it can be difficult to maintain the roof as the cedar wood performs the best with relative humidity around 40-60 percent (Treatex Limited, 2023).

Easy to build

This iteration struggles with the same roof issues as the previous one., where wooden shingles possibly need qualified people on the construction site.

Durability

Choosing cedar wood for a roof exposed continuously to rain and harsh climate conditions can lead to moisture damage and deterioration, especially if humidity levels are high and the assembly process is not properly executed.

Fig. 146: Facade visualization - iteration 2

Fig. 147: Clasroom visualization - iteration 2

LCA

In the second iteration, the most notable change in GWP occurs in the roof construction (see fig. 148). The insulation's GWP decreases due to kenaf's extended lifespan and reduced need for replacement. However, the overall roof GWP remains higher because of the impact of the shingles. Other construction elements show minimal changes in GWP.

The transportation impact (see fig. 49) of the roof is also higher due to the longer distances involved in transporting kenaf fibre and wooden shingles (see appendix C for detailed figures).

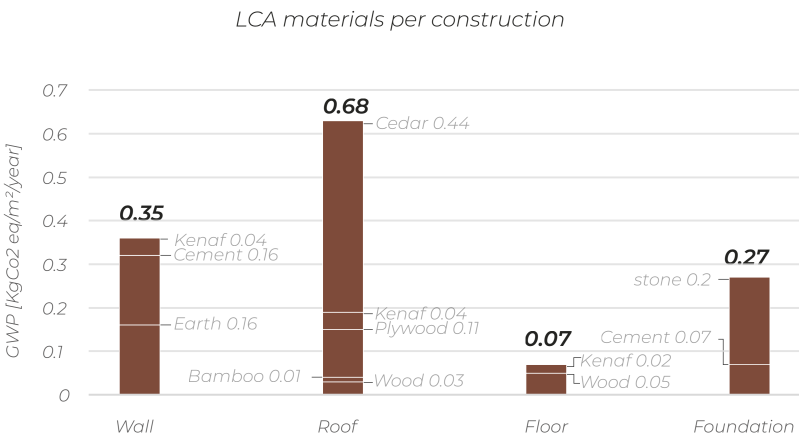


Fig. 148: LCA, materials per construction comparison of iteration 2

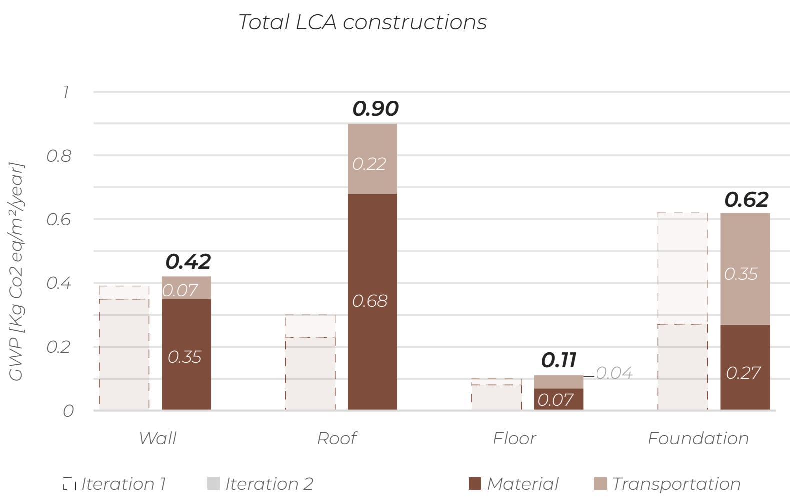


Fig. 149: LCA, total constructon comparison of iteration 2

Indoor climate

Extremes

When comparing iteration 1 to iteration 2 based on their extreme values, it is seen that only the coldest temperature improved while the other values show a small negative change (see fig. 150, 151). The changes are less significant and can be explained by the smaller change in u-value, while at the same time increasing the windows to reach sufficient daylight levels

ATC

The adaptive thermal graph (see fig. 152) also follows this logic and shows a smaller change, compared to the difference between the base model and iteration 1. The graph however does show change regarding the upper indoor temperatures, which corresponds to the highest temperatures increasing, as seen in figure x. The number of hours inside the range however still improves from 83.5 to 83.8 percent.

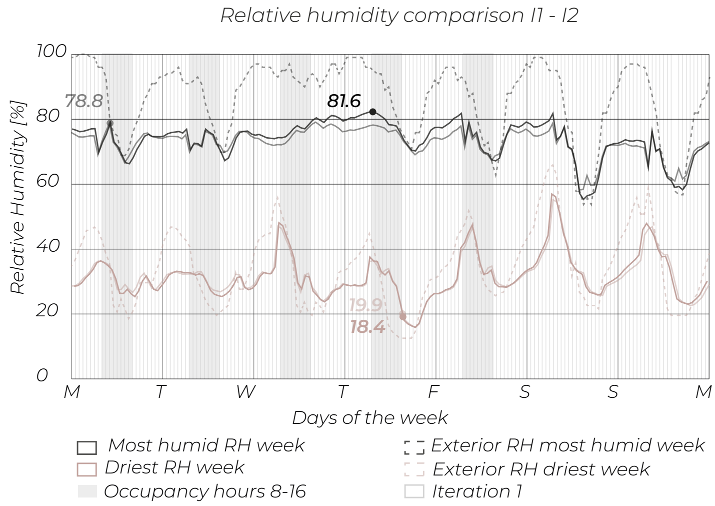


Fig. 150: Relative humidity graph - iteration 2

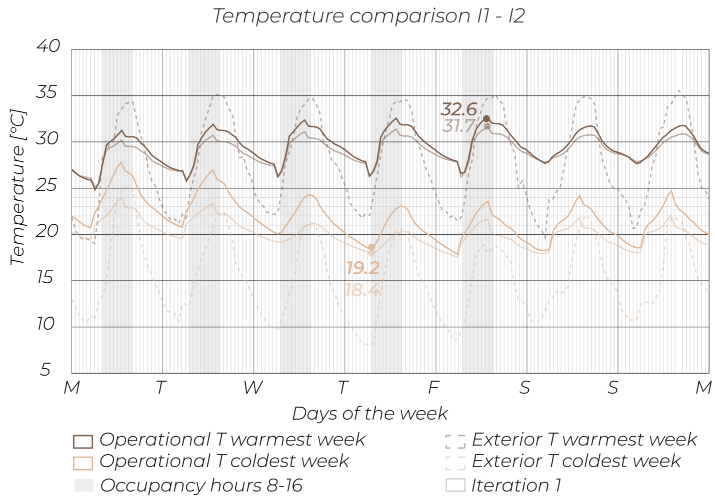


Fig. 151: Temperature graph - iteration 2

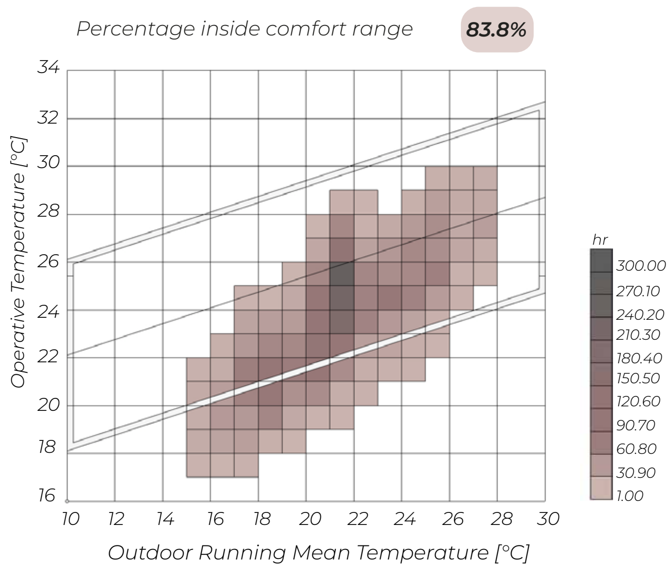


Fig. 152: Adaptive thermal comfort graph - iteration 2

Summary

Iteration 2

Comparison to iteration 1

Input

Window to floor ratio

North and south facades + upper windows	△ ***15 %***
Office and meeting rooms	△ ***20 %***

Shading elements

Overhang west	= *60 cm*
Overhang north	= *300 cm*
Overhang south	= *1550 cm*

Materials

Wall	▽ ***0.22*** ***W/m^2K***
Floor	▽ ***0.33*** ***W/m^2K***
Roof	= *0.13 W/m^2K*
Foundation	= *2.60 W/m^2K*

Output

UDI & sDA

UDI	△ ***80.0*** *%*
sDA	△ ***93.8*** *%*

Indoor climate

Highest T	△ ***32.6***°C
Lowest T	△ ***19.2*** °C
Highest RH	△ ***81.6*** *%*
Lowest RH	▽ ***18.4*** *%*
ATC	△ ***83.8*** *%*

GWP

Wall	△ ***0.42*** *KgCO2eq/m²/year*
Floor	△ ***0.11*** *KgCO2eq/m²/year*
Roof	△ ***0.90*** *KgCO2eq/m²/year*
Foundation	= *0.62 KgCO2eq/m²/year*
Total	△ ***2.05*** *KgCo2eq/m²/year*

Fig. 153: Fact box - iteration 2

Iteration 3 - Non biobased

Daylight availablity

The model has now been provided with shutters on all windows except the upper windows to decrease indoor temperature (see fig. 154). The shutters have a transmittance of 50% and are operated manually by the users during the occupancy hours.

For the daylight simulations, the shutters have been closed where excessive daylight levels have been experienced in previous simulation, which is the south side of the south buildings.

Results

The addition of shutters to the windows has expectedly led to a decrease in both sDA and UDI daylight levels when they are closed (see fig. 155, 156). However, these shading elements are manually operated by the users during the classroom occupancy period, allowing them to regulate daylight levels and indoor temperatures as needed.

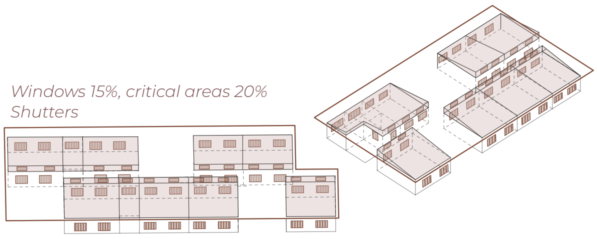


Fig. 154: Daylight availability - iteration 3 isometric

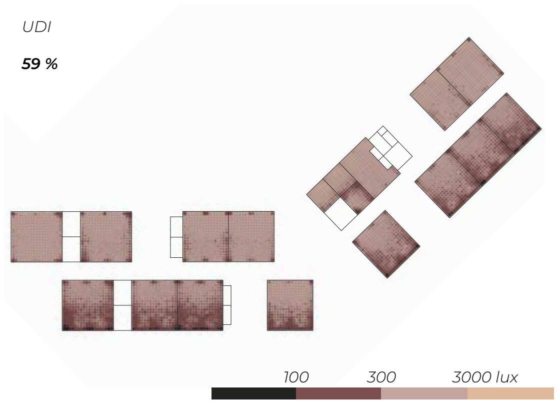


Fig. 155: UDI results- iteration 3

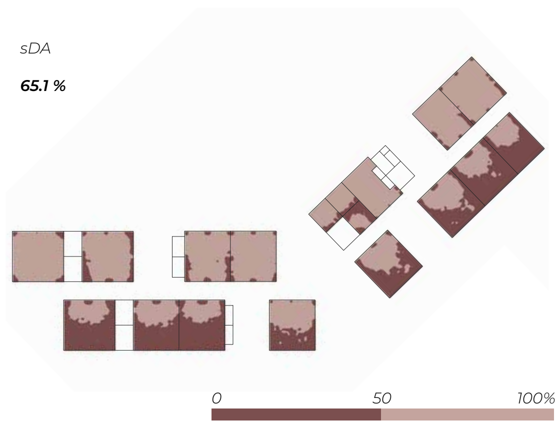


Fig. 156: sDA results - iteration 3

Indoor climate and LCA

Materials

The final iteration further optimizes U-values, either by adding to or replacing previous construction elements. This phase prioritizes improving the indoor climate above the consideration of environmental impacts.

The insulation in the roof, as well as the floor and walls are changed from kenaf fibre to mineral wool (see fig. 158). The wooden shingles in the roof have been replaced by an aluminium roofing to be more climate resilient as well as to reflect sunlight. This however did not change the U-value, so it remains at 0.13 W/m²K. The floor has a higher thickness of 80 millimetres and changes in U-value from 0.33 to 0.19 W/m²K. The wall has also increased in thickness by 50 millimetres with a decreased U-value from 0.22 to 0.16 W/m²K. The foundation made of stone remains the same as in iteration 1 and 2.

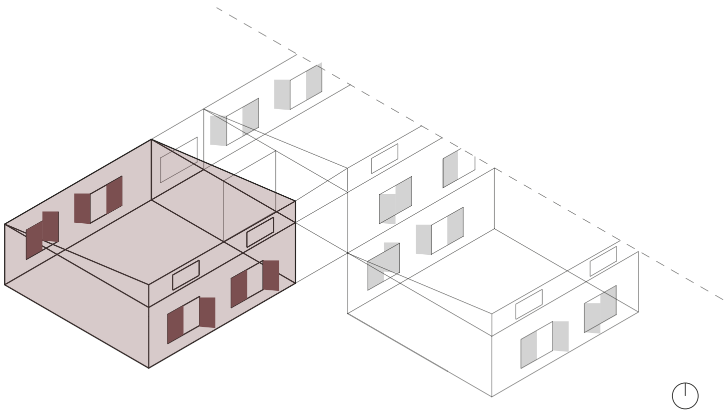


Fig. 157: Thermal analysis zone- iteration 3

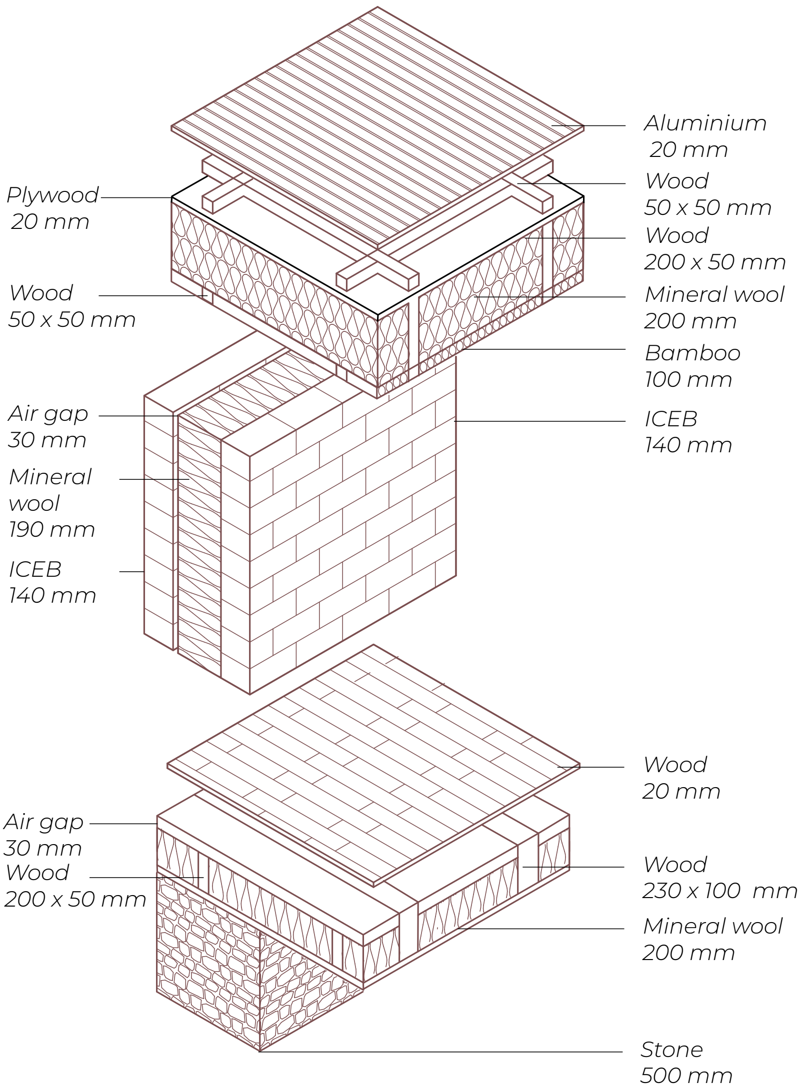


Fig. 158: Exploded diagram of materials - iteration 3

Aesthetic

Overall aesthetics

As seen in figure 159, aluminium roofing makes the building volume brighter with a lighter architectural appearance. The Interior hasn't been changed in terms of materials. However, shutters have been added, creating a play of shadow inside when the sun is low on the horizon. From the exterior, the facade appears more dynamic as the shutters differentiate from open to closed during the day.

Practicality

Replacing wooden shingle roof with aluminium roofing plates (see fig. 160) solves the problem of maintenance during the rainy season. However, aluminium performs poorly in terms of acoustic, therefore any insulation with a bamboo ceiling is needed.

Easy to build

Aluminium roofing can be easily constructed on the site by locals, since existing workshop building on the project site has been built the same way.

Durability

Aluminum has a great durability of almost 50 years (JJRoofing Supplies, 2025), which makes it the best solution of all proposed roofing iterations.

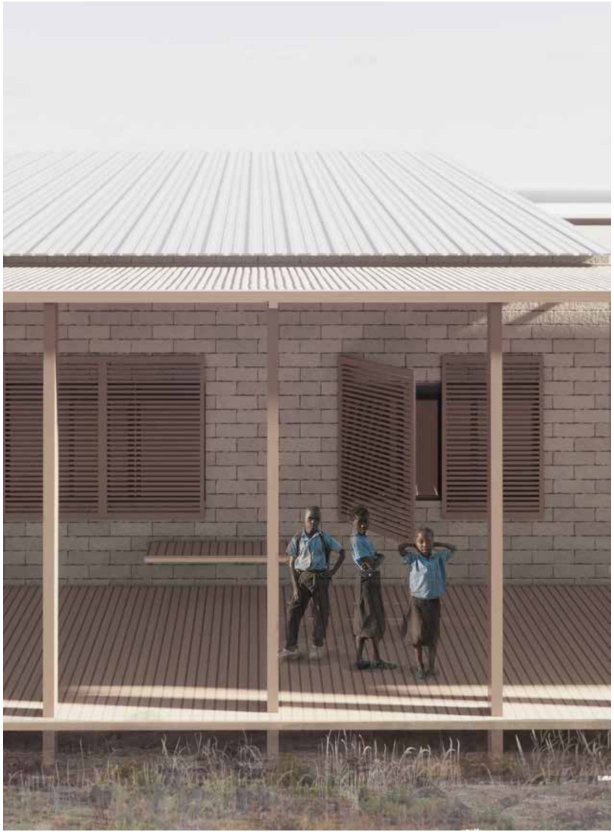


Fig. 159: Facade visualization - iteration 3

Fig. 160: Classroom visualizarion - iteration 3

LCA

In the third iteration, non-sustainable materials are imported to improve the indoor climate as much as possible. The use of mineral wool makes the GWP of the total construction of the wall, roof and floor significantly higher than the previous iterations (see fig. 161).

The second graph (see fig. 162) shows that despite a decrease in transportation impact, the total GWP remains higher than previous iterations. However, this impact is minor compared to the GWP of the materials themselves. Detailed data and calculations are provided in the appendix.

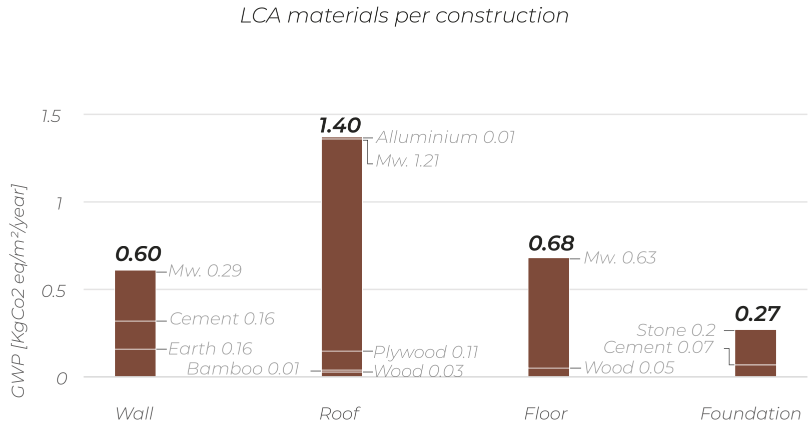


Fig. 161: LCA, materials per construction comparison of iteration 3

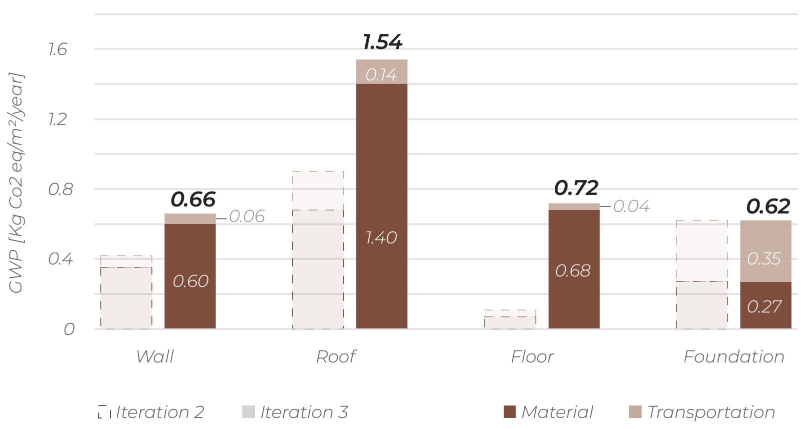


Fig. 162: LCA, total constructon comparison of iteration 3

Indoor climate

Extremes

The graphs (see fig. 163, 164) show that the coldest temperature as well as the driest month has improved in iteration 3. The other values remain unchanged or improved with a value as small as 0.1. While adding shutters had minimal effect on room temperatures in the thermal analysis, they significantly impacted daylight levels. This raises the question of whether shutters should be included in the final design.

ATC

The adaptive thermal comfort graph (see fig. 165) shows a broader range of values outside both the upper and lower limits. However, these represent fewer hours, resulting in an overall increase in hours within the comfort range from 83.8 percent to 85.6 percent.

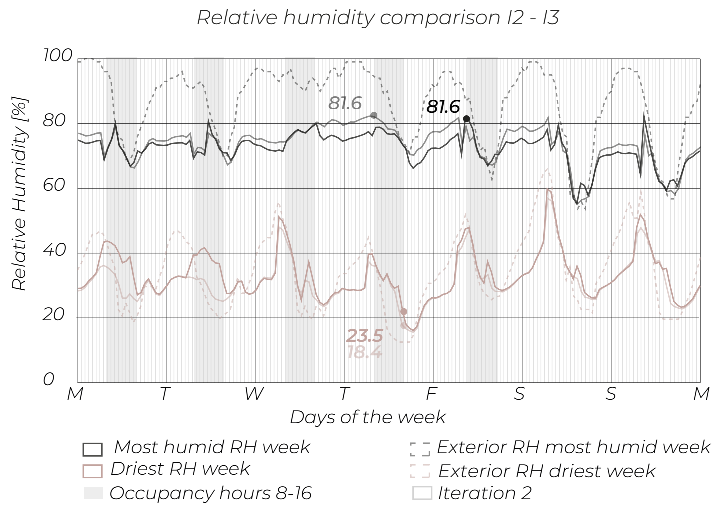


Fig. 163: Relative humidity graph - iteration 3

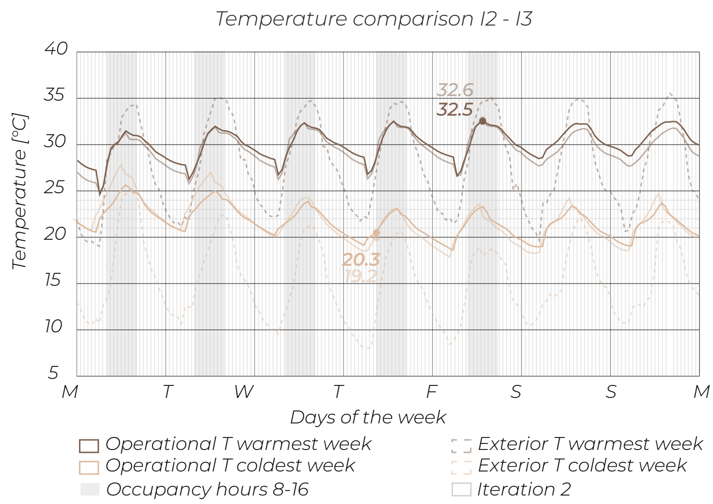


Fig. 164: Temperature graph - iteration 3

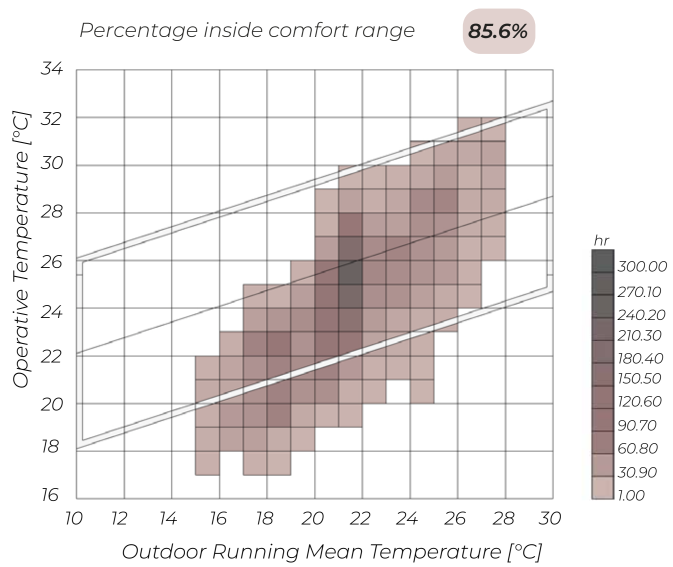


Fig. 165: Adaptive thermal comfort graph - iteration 3

Summary

Iteration 3

Comparison to iteration 2

Input

Window to floor ratio

North and south facades + upper windows	*15 %*
Office and meeting rooms	*20 %*
Glazing on upper windows	***No***

Shading elements

Overhang west	= *60 cm*
Overhang north	= *300 cm*
Overhang south	= *1550 cm*

Materials

Wall	▽ ***0.16 W/m²K***
Floor	▽ ***0.19 W/m²K***
Roof	= *0.13 W/m²K*
Foundation	= *2.60 W/m²K*

Output

UDI & sDA

UDI	▽ ***59.0*** *%*
sDA	▽ ***65.1*** *%*

Indoor climate

Highest T	▽ ***32.5*** *°C*
Lowest T	△ ***20.3*** *°C*
Highest RH	= ***81.6*** *%*
Lowest RH	△ ***23.5*** *%*
ATC	△ ***85.6*** *%*

GWP

Wall	△ ***0.66*** *KgCO2eq/m²/year*
Floor	△ ***0.72*** *KgCO2eq/m²/year*
Roof	△ ***1.54*** *KgCO2eq/m²/year*
Foundation	= *0.62 KgCO2eq/m²/year*
Total	△ ***3.54*** *KgCo2eq/m²/year*

Fig. 166: Fact box - iteration 3

Final comparison

Daylight availability

The graph (see fig. 167) illustrates the comparison of daylight performance across the design iterations, focusing on UDI and (sDA. The base model, with a window to floor ratio (WFR) of just 5 percent, shows minimal daylight performance. Iteration 1 improves significantly with a WFR of 10 percent, but it is in Iteration 2, where both daylight benchmarks are met with achieving 80 percent UDI and 94 percent sDA. Iteration 3 introduces shutters, which lowers daylight access, reducing UDI to 59 percent and sDA to 65 percent. This highlights the trade-off between daylight levels and shading strategies, making Iteration 2 the most effective in terms of daylight optimization.

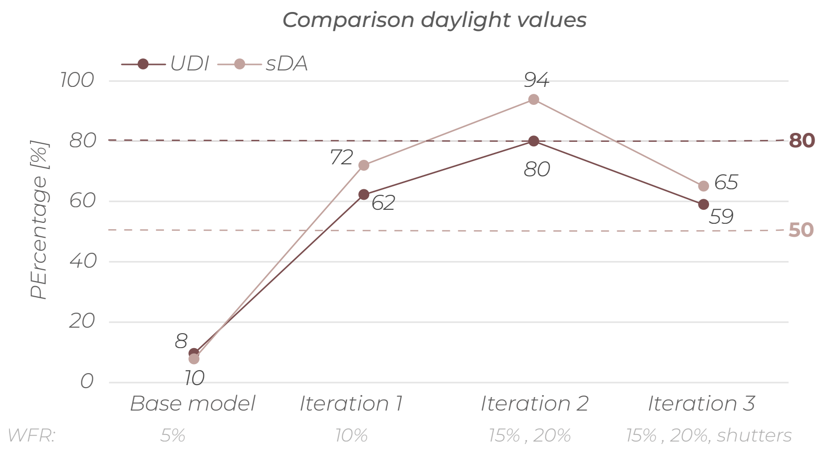


Fig. 167: Comparison of daylight values

Extreme

The two graphs (see fig. 168, 169) illustrate the progression of extreme temperature and humidity values across all iterations. Notably, the driest, coldest, and most humid conditions all improve from improving the thermal performance of the construction element, which is especially beneficial during cooler periods. The highest RH decreases from 86.1 percent in the base model to around 81.6 percent in later iterations, indicating better moisture control due to improved natural ventilation. While the highest temperature slightly increases in the last two iterations, it is no drastic change. Overall, the results show a consistent improvement in thermal comfort, particularly during colder and more humid periods.

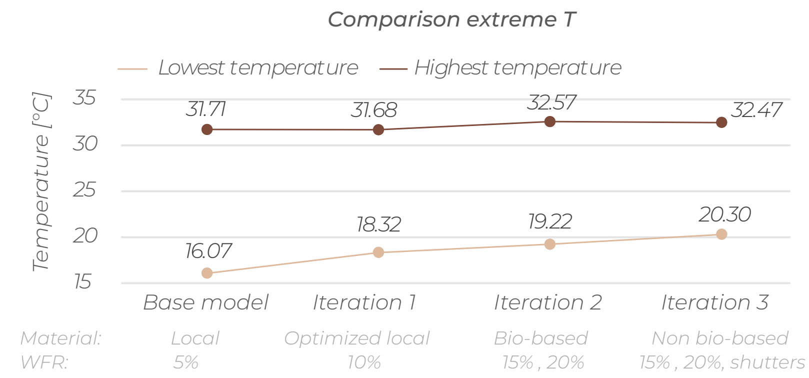


Fig. 168: Comparison of extreme temperatures

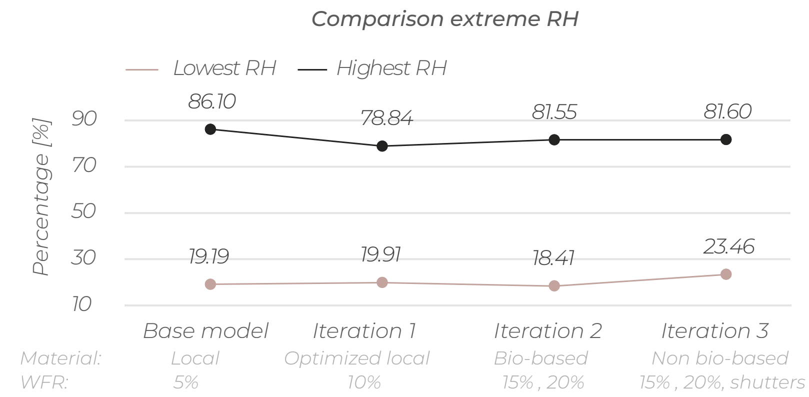


Fig. 169: Comparison of extreme relative humidity

ATC

While the extreme values reflect only the peak weeks of the year, the adaptive thermal comfort (ATC) graph evaluates comfort across the entire year. The graph (see fig. 170) highlights a significant improvement in indoor climate between the base model and iteration 1. The following iterations show only marginal gains, indicating that most of the thermal comfort improvement is achieved early on through the use of optimized local construction elements.

LCA

Figure 171 clearly shows a steady increase in GWP across the iterations, which is driven by several factors. Firstly, as the design moves away from local materials, transportation distances grow, raising the GWP from logistics, especially when material quantities also increase to improve indoor climate performance.

However, the most significant contributor to the rising GWP is the embodied impact of the materials themselves. This is affected by both the quantity used and each material's individual environmental impact. Iteration 3, which introduces non-sustainable imported materials, illustrates the sharpest rise. While shorter material lifespans in earlier iterations, such as the base model and iteration 1, contribute to the GWP, their impact remains lower than that of durable, non-local alternatives.

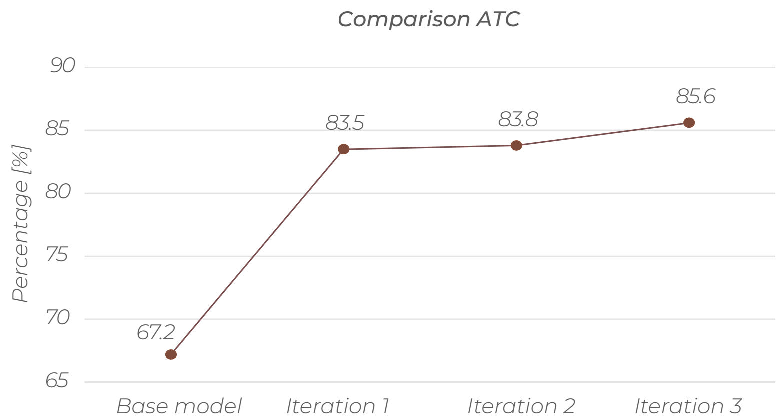


Fig. 170: Comparison of adaptive thermal comfort

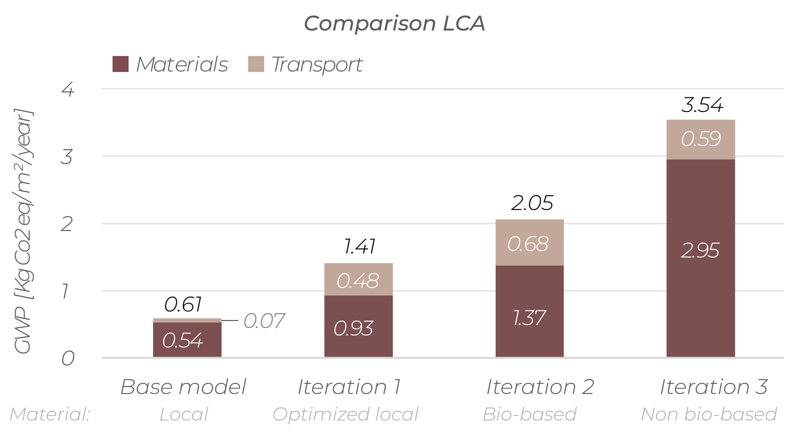


Fig. 171: Comparson of LCA

Conclusion

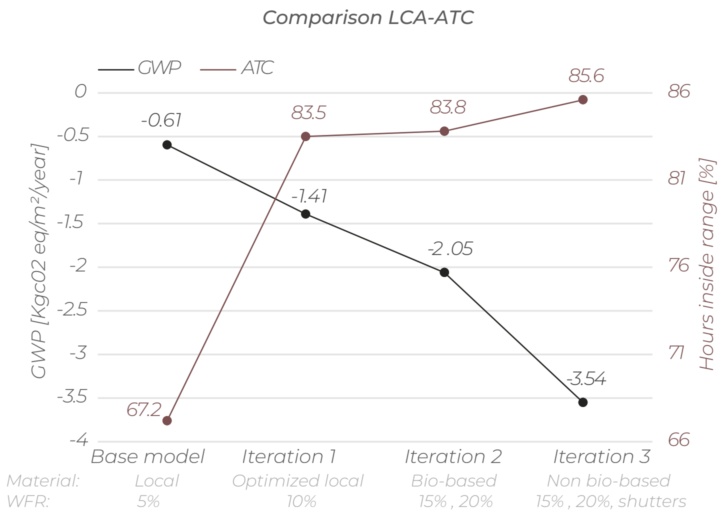


Fig. 172: Evaluarion of quantitatives

Quantitative

Figure 172 presents a combined analysis of environmental impact and indoor thermal comfort across the design iterations. The environmental impact is expressed as GWP in kg CO_2 eq/m²/year and shown as negative values, where a more negative value indicates a higher environmental impact. In contrast, adaptive thermal comfort is shown as the percentage of hours indoor temperatures fall within a comfortable range, with higher percentages representing better performance.

The base model, using local material and building practices as well as a window to floor ratio (WTF) of 5 percent, results in the lowest environmental impact, but also delivers the poorest indoor comfort.

Moving to iteration 1, which employs optimized local materials by improving the thermal construction properties and an increase in WFR, a substantial jump in comfort is seen at the cost of a higher GWP. This represents the steepest improvement in comfort, indicating that small, strategic design changes, such as enlarging window areas and improving local material use, can result in significant comfort gains at a relatively low environmental cost.

Iterations 2 and 3 maintain the same WFR but differ in material use and design strategies. Iteration 2, using bio-based materials, achieves a slight improvement in ATC, while the environmental impact rises. In Iteration 3, non bio-based materials and external shutters are introduced, further increasing ATC to 85.6 percent, which is the highest among all iterations, alongside the steepest increase in GWP. The marginal comfort gains in both cases, despite the significantly higher environmental impact, suggest that the benefits of these strategies may be limited.

Among all iterations, iteration 1 presents the most favourable balance between thermal comfort and environmental impact. It demonstrates a substantial increase in ATC with a relatively moderate increase in GWP. The comparison of the two metrics across the graph indicates that design strategies involving early-stage optimization such as adjustments in WFR and use of local materials offer the most efficient improvement in performance.

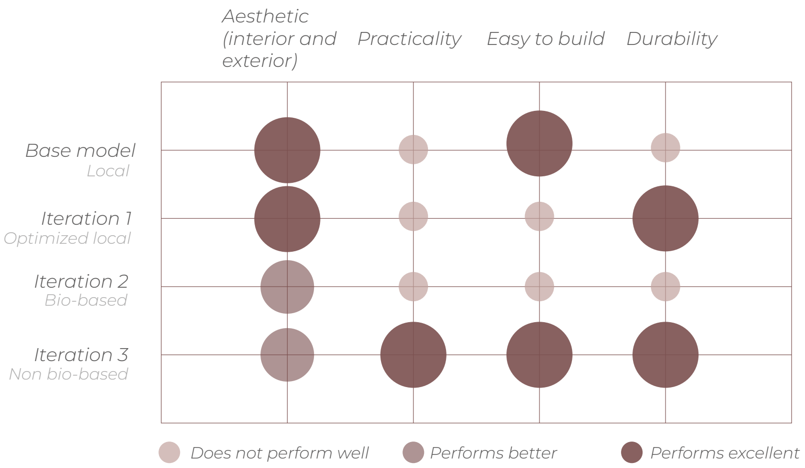


Fig. 173: Evaluation of qualitatives

Qualitative

To support the final proposal with a qualitative assessment, a comparison tool has been developed (see fig. 173) to evaluate the overall quality of each design iteration. This tool aids in identifying the most effective combination of design elements based on qualitative performance. The iterative approach allows for adjustments within each version, contributing to the refinement of the final proposal. As shown in the figure, iteration 4 demonstrates the strongest performance across most qualitative criteria.

The final proposal will combine the most effective elements from the iterations, drawing on conclusions from both the quantitative and qualitative analyses to achieve a balanced and optimized design outcome.

Fig. 174: Visualization of main entrance

07 Presentation

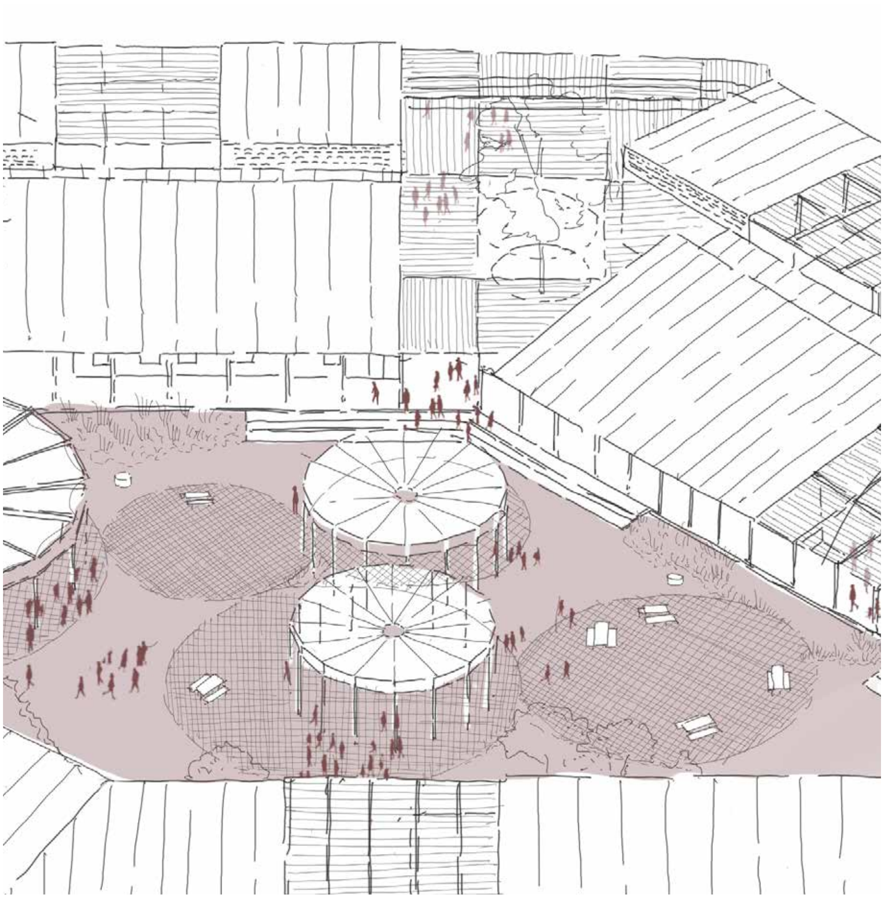


Fig. 175: Final sketch of main entrance

The presentation of the final design follows the same structure as the initial phase of the design process. It begins at the masterplan level, providing an overview of the overall project site. This is followed by a more detailed exploration of the school campus and the individual school buildings. The chapter concludes with a summary of the quantitative design aspects, presenting the final proposal through data and performance metrics.

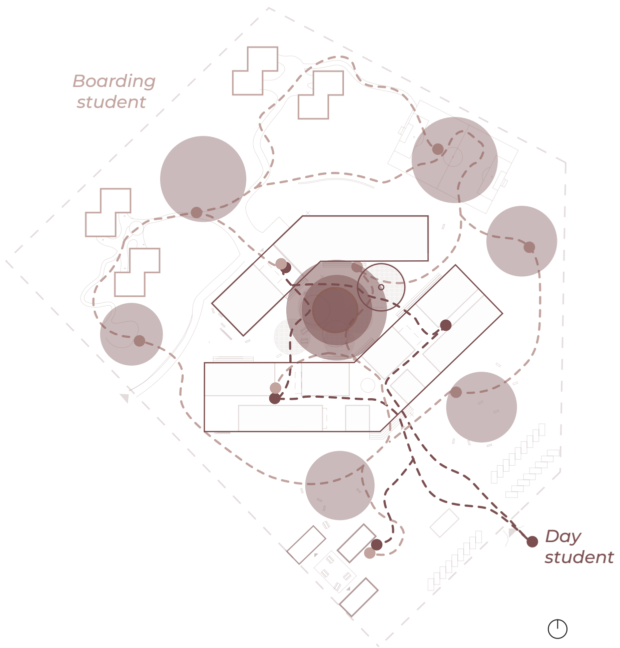


Fig. 176: Flow of boarding and day students on a masterplan level

Masterplan

The final masterplan layout, as shown in figure 177, is organized around a central space known as the 'gathering point', which forms the heart of the design enclosed by the school buildings. These volumes have been placed strategically, not only based on climate considerations but also on architectural expression.

The main entrance is located near the watchman's building and is equipped with parking spaces for visitors, staff, and non-boarding students of Kashitu School. To create a smooth transition between the parking area and the school buildings, tall greenery and water retention ponds to not only provide water management but also contribute to the recreational quality of the area.

Close to the watchman's building, an existing workshop has been expanded with two additional facilities: a cooking area and a fabrication unit. Together, these structures form a cohesive functional space with designated outdoor break areas and sheltered spaces that encourage social interaction. All of these facilities are oriented toward the facades of the school building to integrate with the school campus.

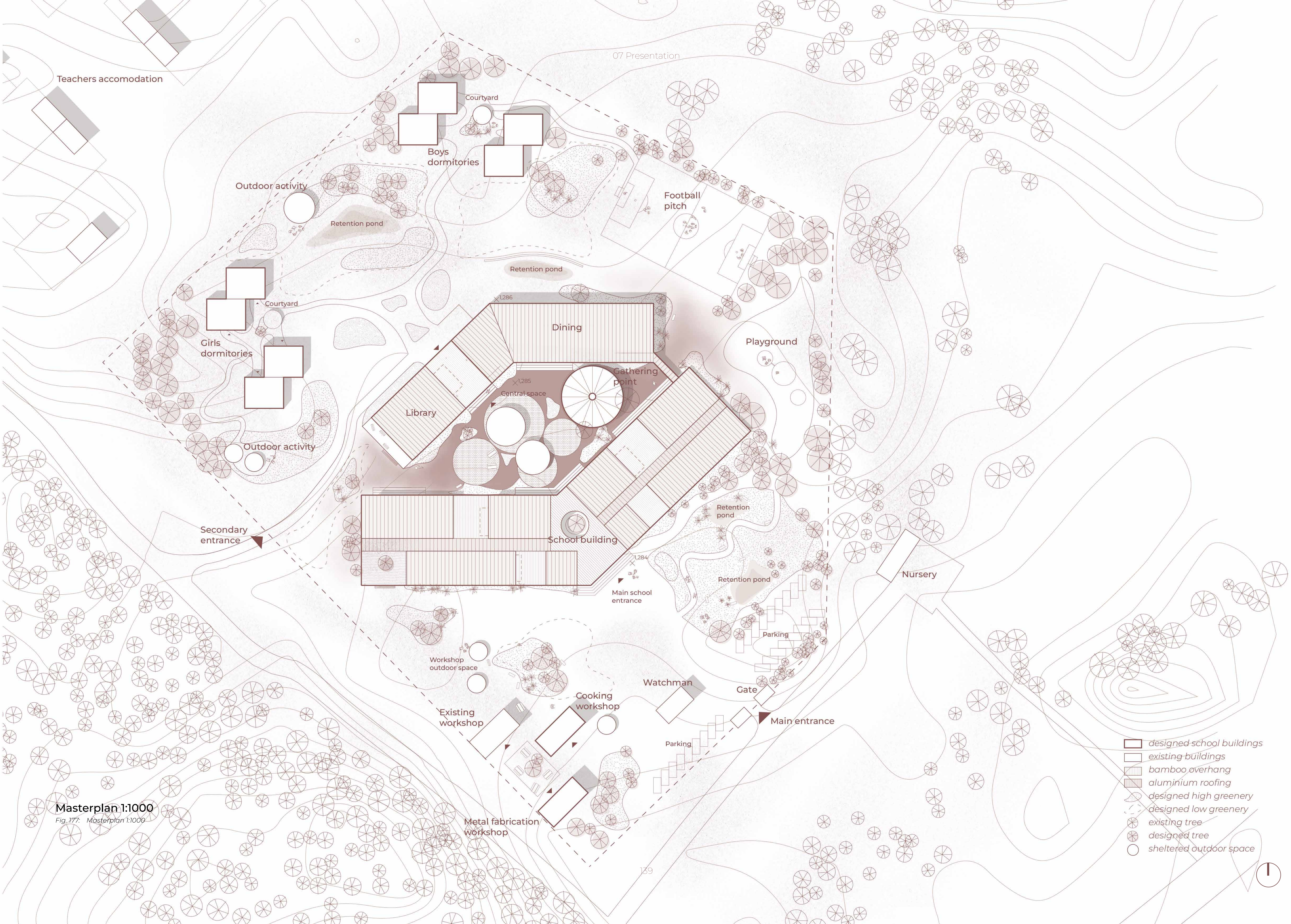
The school building features a prominent facade facing the main entrance from the road, offering a clear visual connection to the central gathering space and serving as a representative front of the campus. Upon entering the school grounds, the building volume splits into two wings, where the school facilities are distributed across the left and right wings in a way that maintains a smooth circulation flow without disrupting the main pathway.

As one moves toward the central gathering point, the space comes to life, filled with students during breaks or moving between classes, making it the most active and socially vibrant area within the design.

The central gathering point is enclosed by a second volume housing the library and dining area. The circulation flow continues through this building (see fig. 176), creating a smooth transition toward the dormitory area located in the upper part of the site. This route is also connected to a secondary entrance to the dining area, which has been added to facilitate truck deliveries.

As the main circulation path progresses, it gradually transitions into more private zones where the girls' and boys' dormitories are situated. Each dormitory features an outdoor central space and access to designated outdoor activity areas, enhancing the quality of the environment. The retention ponds create a natural and calming passage for the users on the way to school.

Additionally, the site is provided with a football pitch, playground and sheltered outdoor spaces in circular shapes to enhance social interactions during and after a day at school. The rest of the plot area has been covered with designed low and high greenery with new trees to fill the void of deforestation and enhance the ecological value of the site while creating a pleasant environment.



Masterplan 1:1000

Fig. 177: Masterplan 1:1000

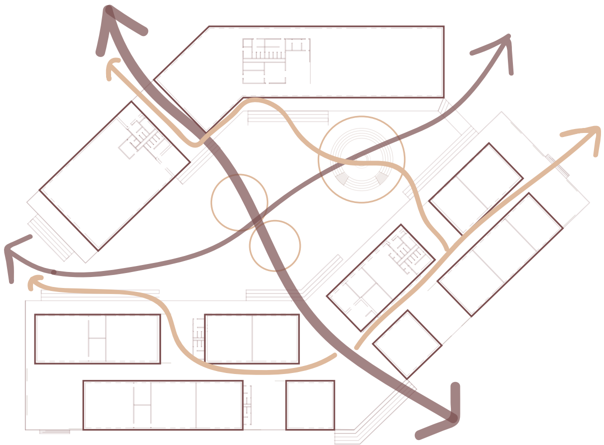


Fig. 178: School campus flow

School campus

The school campus plan (see fig. 179) illustrates the functional distribution of the school building, dining area, and library, while highlighting internal circulation, gathering points, and outdoor spaces that are carefully integrated with designed high and low greenery.

A set of steps, guides students, teachers, and visitors into the main entrance space sheltered by a perforated bamboo overhang. At the centre, a circular bench surrounding a newly planted Miombo tree subtly divides the area, suggesting two possible paths, left or right, (see fig. 178) as the entire school building is elevated on the same level.

The left wing of the school building contains classrooms, laboratories, and break rooms, supplied with toilets and connected through a clear hallway circulation path. In the right wing, an open reception area combined with an administrative function has been placed near the entrance as an intentional choice to ensure accessibility for first-time visitors and during school meetings or events. This wing follows the same spatial and circulation principle as in the left wing, leading to outdoor areas including the football pitch and playground east of the site, supporting both educational and recreational activities.

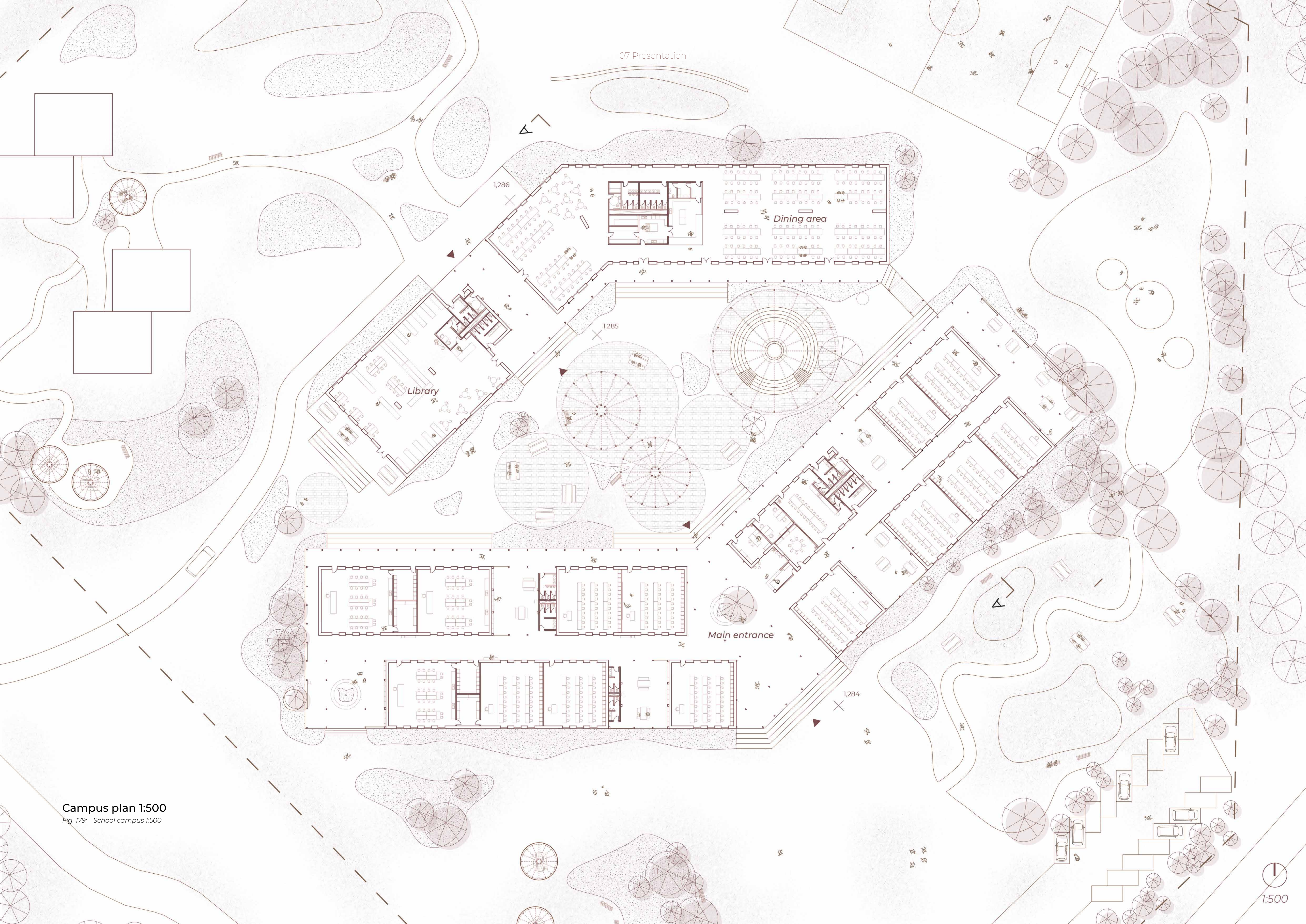
The hallway circulation paths spread out through break rooms to the main gathering point, where one encounters circular shelter structures in reference to the traditional Zambian Insaka. This form has been also applied to the brickwork pavement full of benches and tables to spend time with classmates.

To not disturb the main flow any of the other forms have been designed, and also to underline the importance of the gathering point in the bigger circle. However, since the Kashitu experiences rainy season, stretched fabric has been mounted to provide a shortcut for those who don't want to go through the connector on the northern part of the building.

The hallway circulation paths extend through the break rooms and lead into the main gathering point, where the user encounters a central circular structure inspired by the traditional Zambian Insaka. This circular shape is also reflected in the brickwork pavement, where benches and tables are placed to for outdoor stay.

These structures also provide a sheltered shortcut to the opposite building during the long rainy season, allowing movement between spaces without requiring passage through the northern connector of the building.

The opposite building volume contains the larger communal functions. The library serves as a quiet space for supervised study and is supplied with a terrace with outdoor seating that create a fluid connection between the indoor and outdoor. The dining area is directly accessible from the courtyard, with a facade that opens outward to strengthen the relationship between indoor dining and outdoor activity. Internally, the main kitchen and restrooms are centrally located to divide the space into two zones, helping to reduce noise and prevent an overwhelming atmosphere, while also improving functionality.



Campus plan 1:500

Fig. 179: School campus 1:500

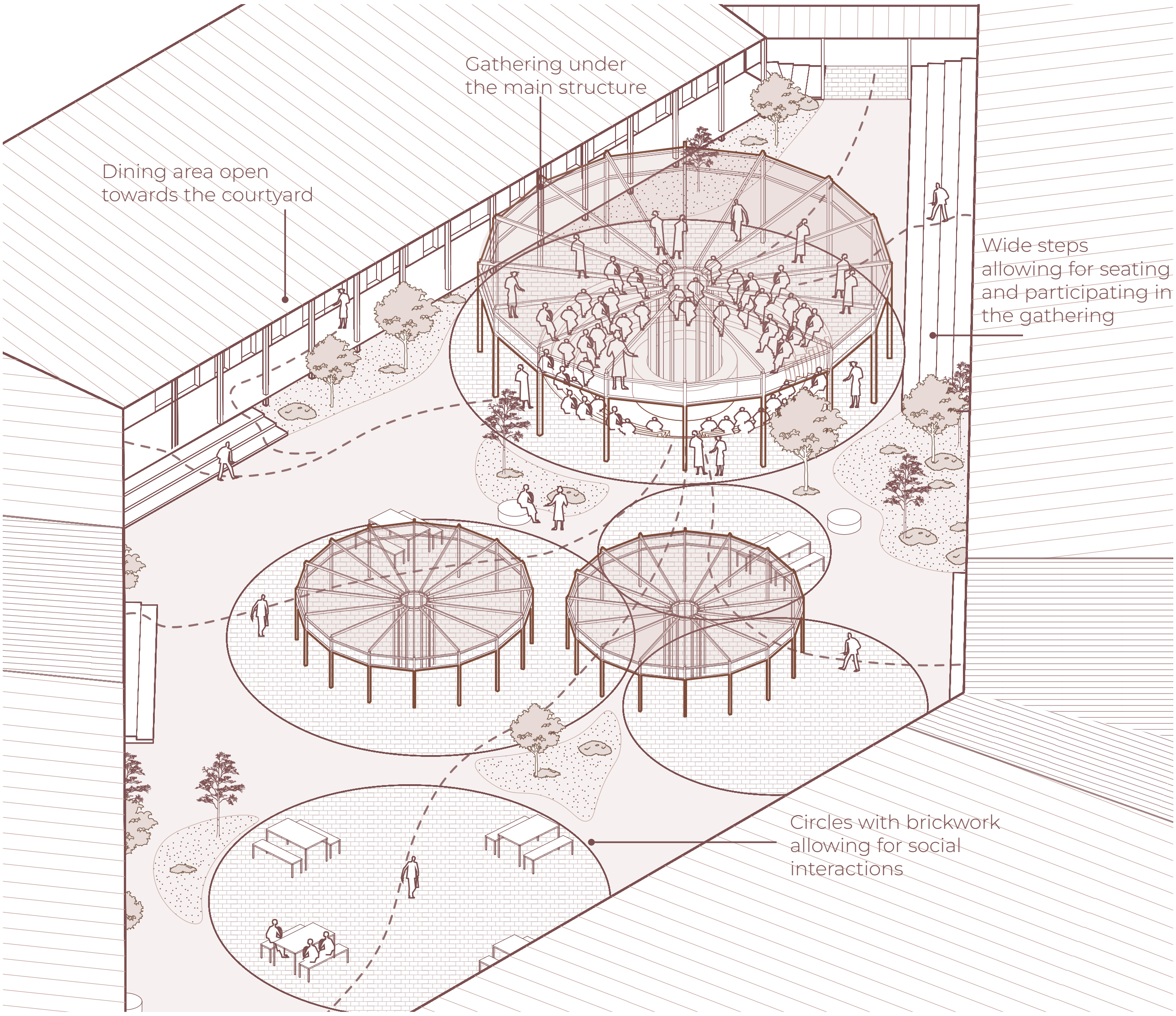


Fig. 180: Isometric of courtyard during gathering

Gathering point

The circular structures at the heart of the school campus are more than just architectural features, they shape the way students interact, move, and gather throughout the day while responding to both climate and community needs.

Figure 180 captures a scenario, where the central circular structure becomes a natural stage. A teacher steps forward to speak, and students gather around, sitting informally on the built-in stepping seats or standing around under the shade. The structure is framed as architecture that supports open dialogue and group gatherings.

The second moment (see fig. 181) unfolds on a rainy day. Movement across the campus naturally shifts toward the circular shelters that connect the two main buildings. Together with the sheltered hallways along the building facades, these smaller structures offer a dry, direct path across the outdoor space. Even in wet weather, the design supports fluid circulation while maintaining the social and communal energy at the heart of the campus.

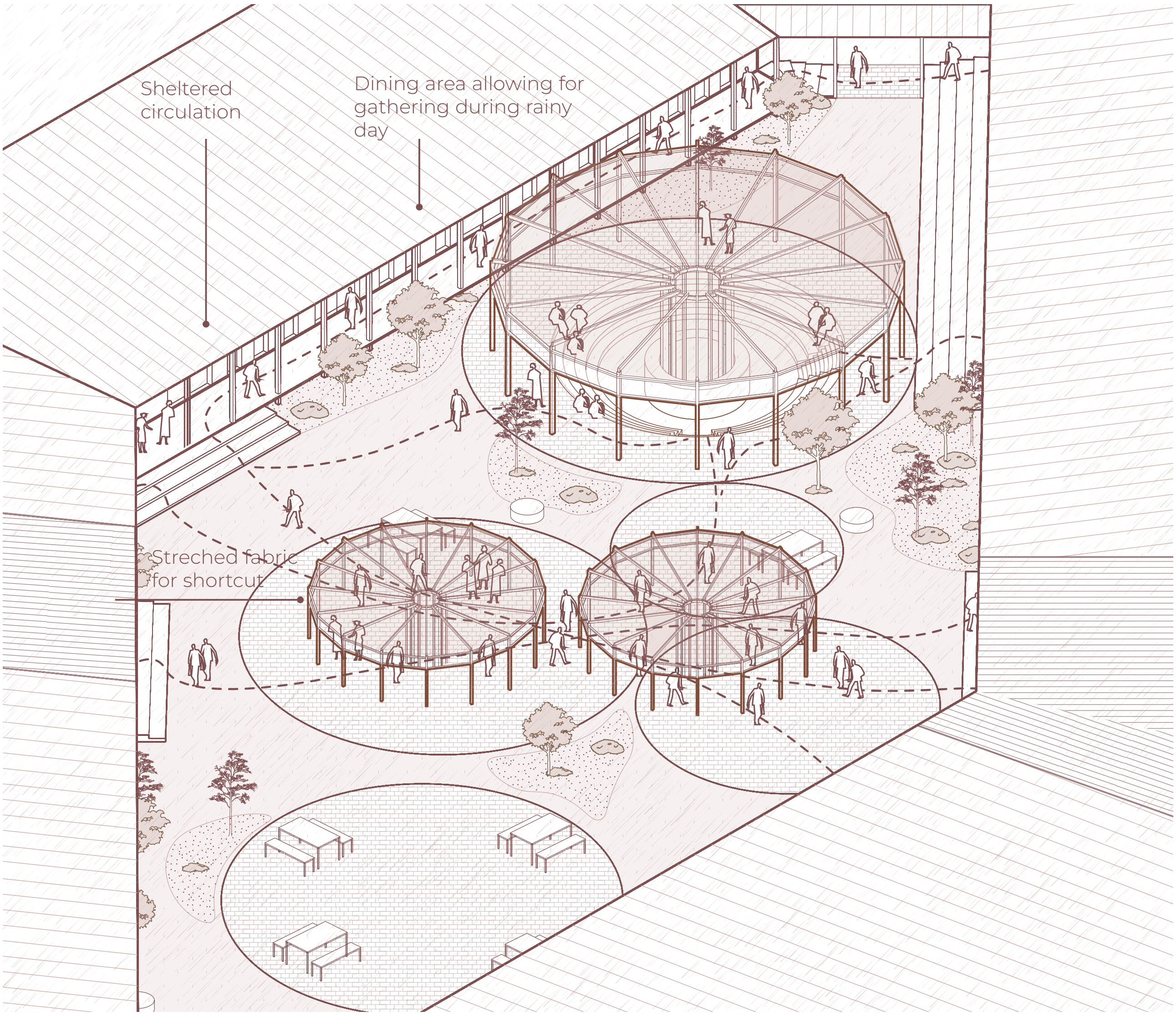


Fig. 181: Isometric of courtyard during rainy day

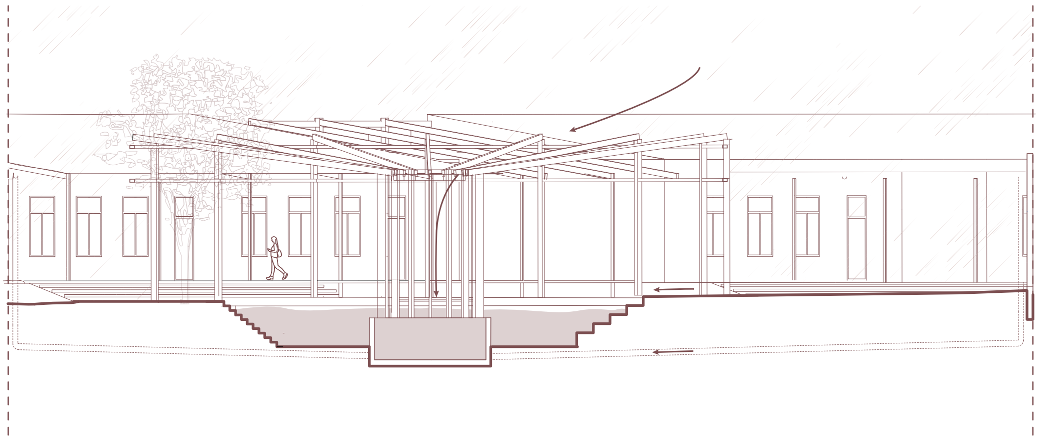


Fig. 182: Detail section of collecting rainwater 1:250

Landscape design

Although the landscape is generally flat, it features subtle variations in elevation. As illustrated in the section (see fig. 183), the terrain begins at its lowest near the workshop area and gradually rises across the site. The main school building is elevated on a floor deck to mitigate potential flooding, which necessitates the use of stairs at its entrances and exits.

At the heart of the campus, the circular gathering structure shelters a sunken area slightly lower than the surrounding landscape. Here, integrated steps not only facilitate access but also serve as informal seating, which is used as the space's social function. As the terrain continues to incline, the building with the dining area aligns with the natural topography which creates a gentle transition toward the dormitories.

The circular structure serves a dual purpose, while functioning as a social gathering space, it is also utilized as a water detention basin (see fig. 182). Its inward-sloping roof is designed to collect and direct rainwater into a recessed central area, which manages runoff during the region's frequent rains. In addition, gutters from the surrounding building roofs are strategically connected to this detention, leading water to the basin when the water tanks next to the buildings fill up, further supporting the site's water management.

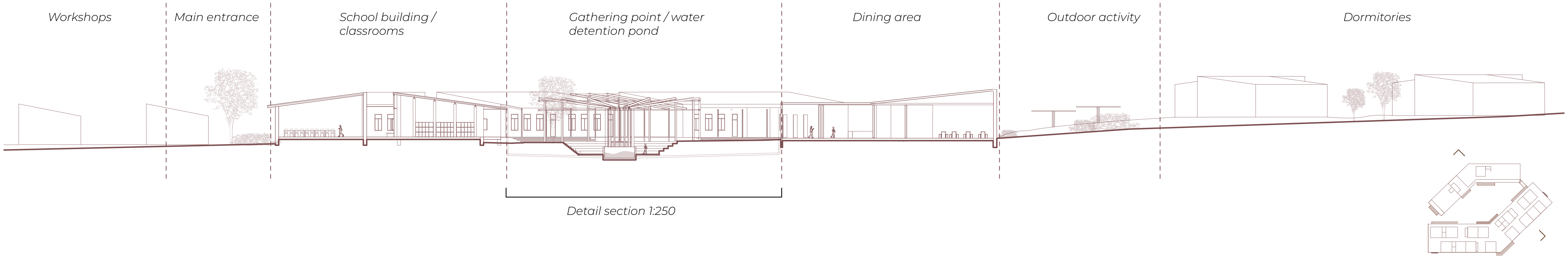


Fig. 183: Section of school campus 1:500

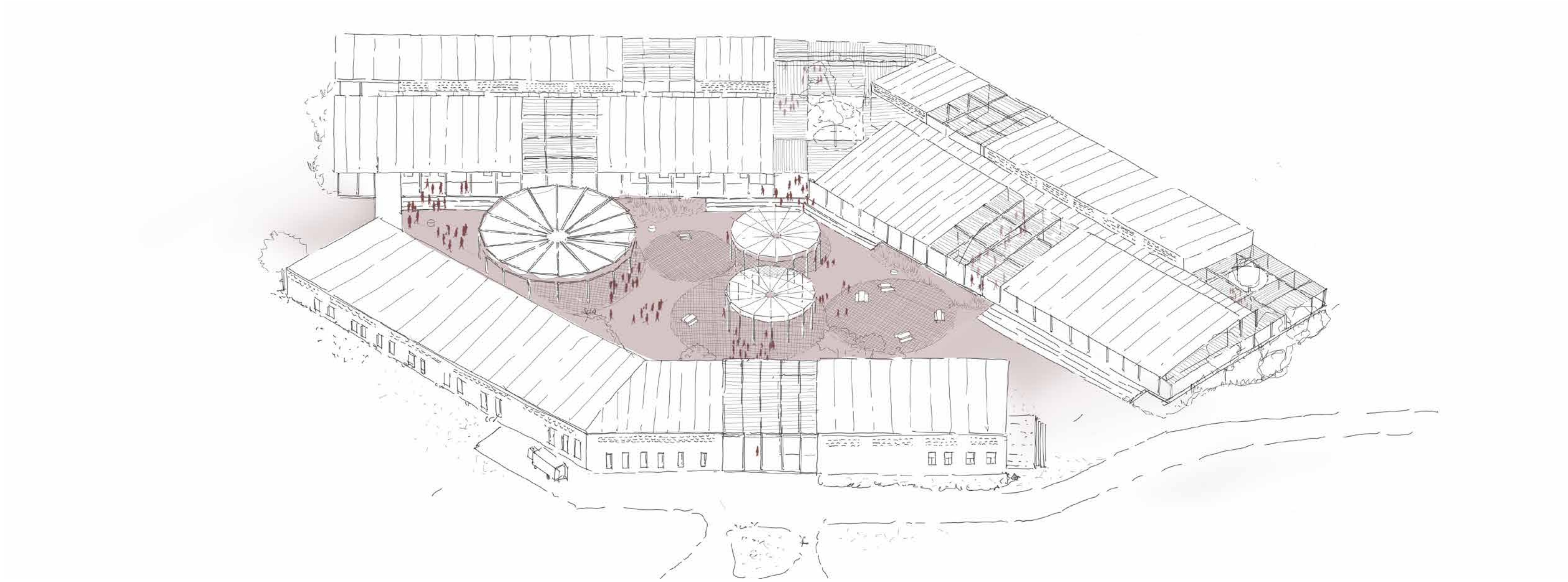


Fig. 184: Sketch of school campus

Fig. 185: *Visualization of gathering point*

Left wing

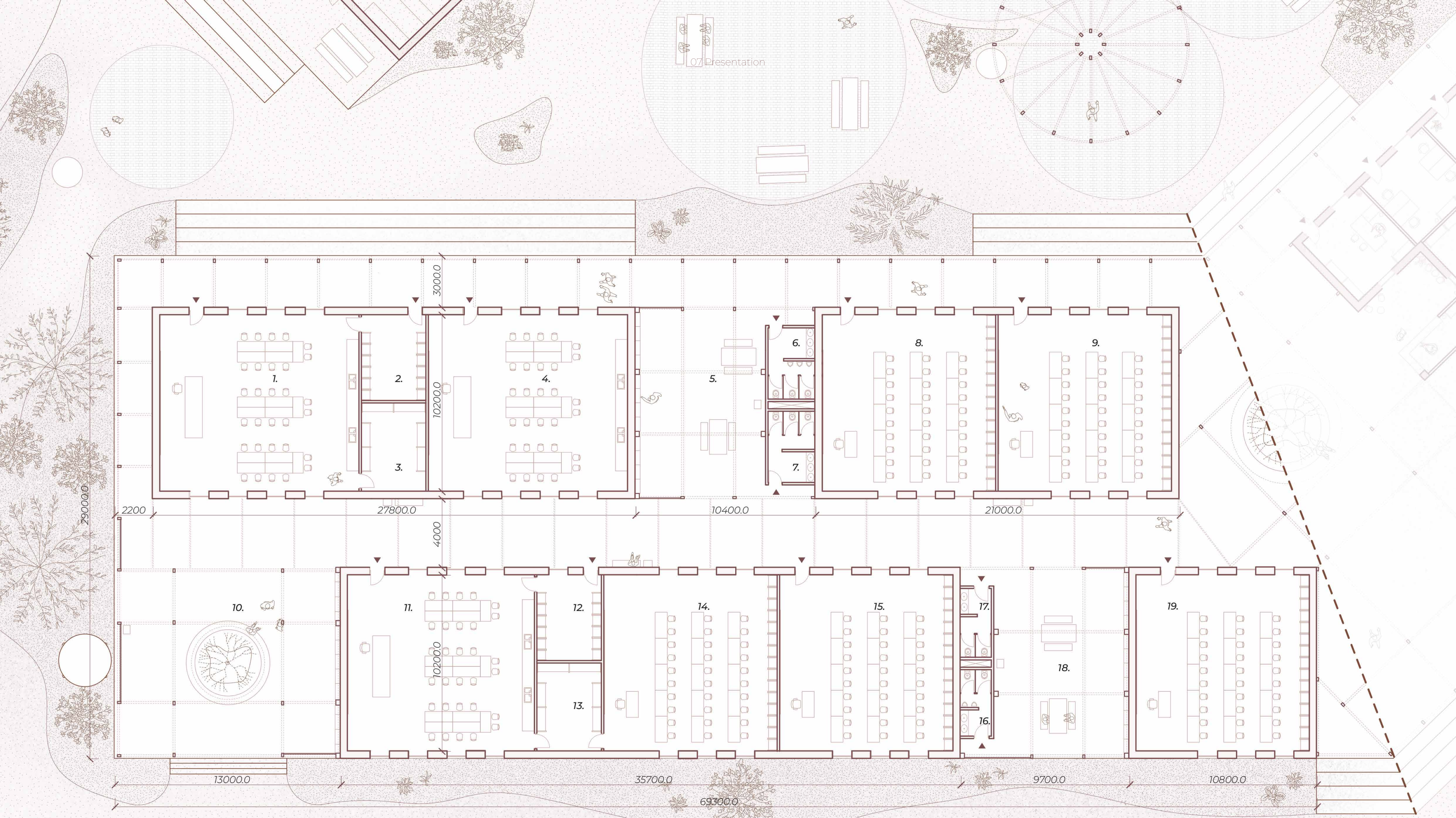
The detailed plan for the left wing (see fig. 187) emphasizes a strong connection between classrooms, internal circulation among them, and a link to the courtyard. As illustrated in figure 187, the main entrance directly leads to the hallway circulation, that connect each break room, classroom and laboratory. An aluminium overhang covers the circulation paths, providing protection from rain and other weather conditions to allow for a smooth flow of movement.

Each classroom and laboratory in the left wing accommodate up to 30 students and includes space for storing personal items in storage lockers. Additionally, laboratories are equipped with preparation rooms for storing personal items and supplies during class.

The design ensures that each classroom has direct access to a break room, preventing overcrowding when students transition between classes. Each break space is covered with a bamboo overhang, creating playful lighting in the space. Furthermore, lockers have been placed for personal belongings in the break areas, as well as benches and tables. Restrooms are strategically located nearby, with access from the circulation to provide privacy. Furthermore, the arrangement of these spaces breaks the building facades into smaller parts, contributing to a more human scale appearance.

The overall design maintains a simple shape while utilizing local materials, encouraging community involvement in the construction process.

Fig. 186: Visualization of classroom



School building 1:200

Fig. 187: Floorplan of school building 1:200

Rooms:

1. Laboratory 123 m²
2. Preparation room 22 m²
3. Storage 22 m²
4. Laboratory 23 m²
5. Break area 93 m²
6. Boys WC 7 m²
7. Girls WC 7 m²
8. Classroom (30 students) 110 m²
9. Classroom (30 students) 110 m²
10. Break area 158 m²

11. Laboratory 23 m²
12. Preparation room 22 m²
13. Storage 22 m²
14. Classroom (30 students) 110 m²
15. Classroom (30 students) 110 m²
16. Boys WC 7 m²
17. Girls WC 7 m²
18. Break area 87 m²
15. Classroom (30 students) 110 m²

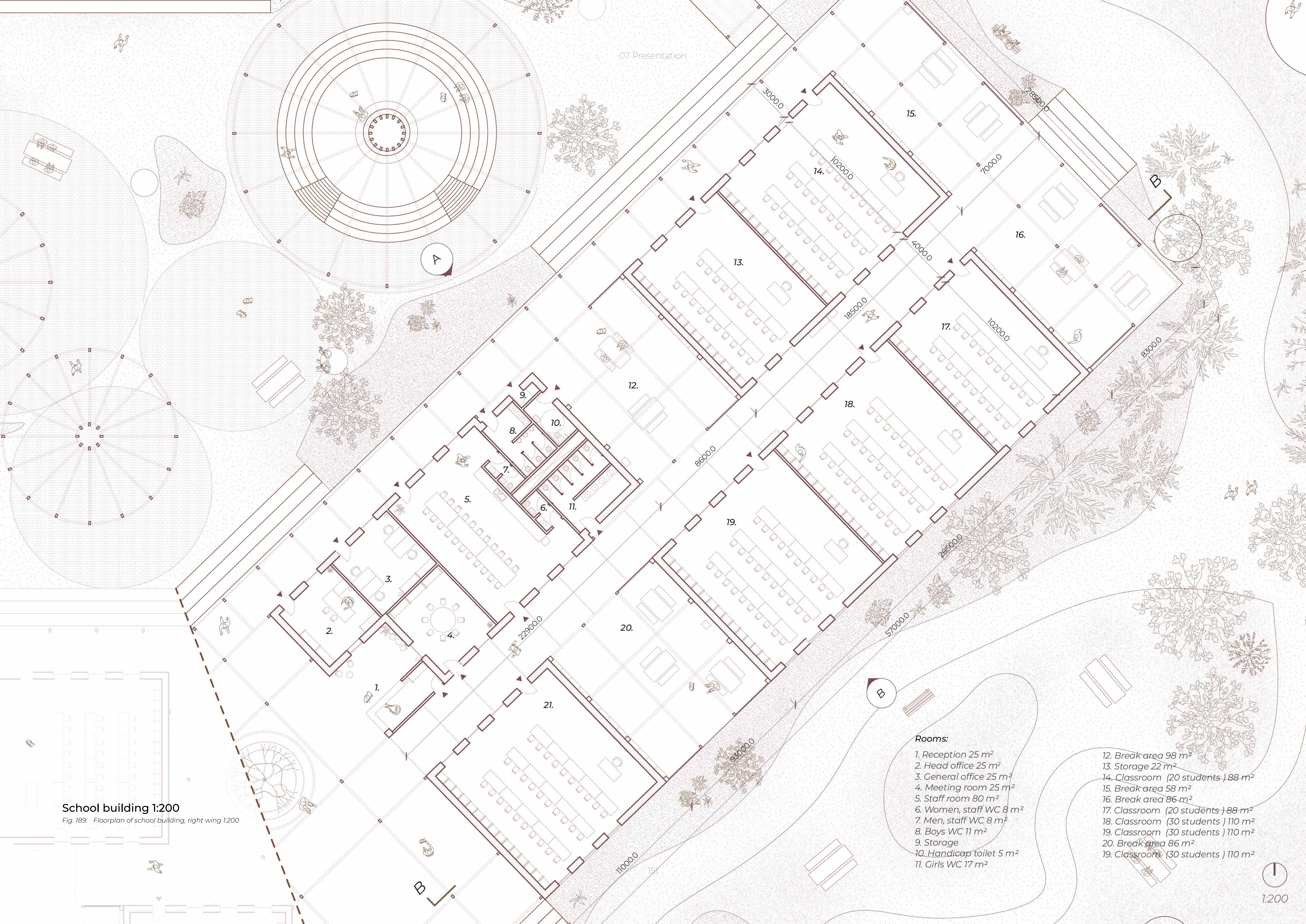
1:200

Right wing

The right wing (see fig. 189) follows the same design principles as the left wing, but includes additional facilities for teachers and staff, as well as a reception area oriented towards the main entrance.

The various administrative functions for teachers have a central placement, allowing them to keep an overview of the site. The hallway circulation (see fig. 188) path leads to a large and open break room, which is covered with aluminium roofing. The bamboo wall elements help reduce glare and enclose the large spaces, creating a more comfortable environment.

Fig. 188: Visualization of hallway



School building 1:200

Fig. 189: Floorplan of school building, right wing 1:200

Fig. 190: Visualization of break room

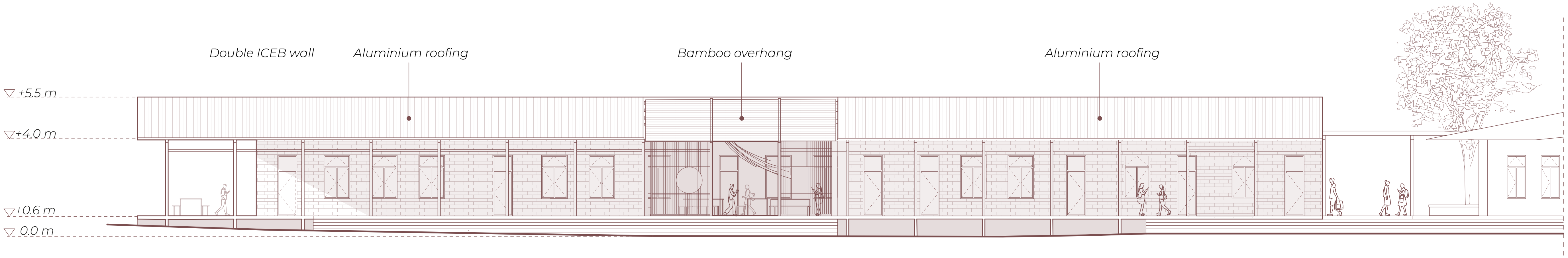


Fig. 191: Elevation B 1:200

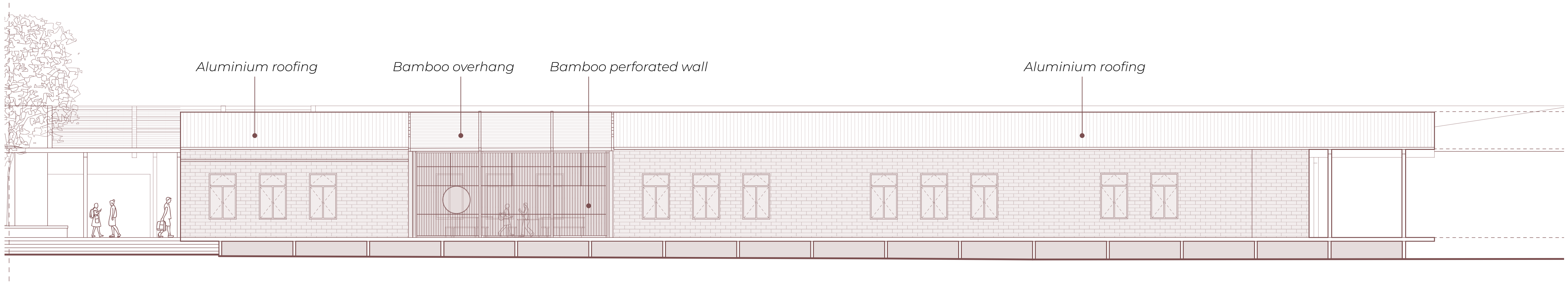


Fig. 192: Elevation A 1:200

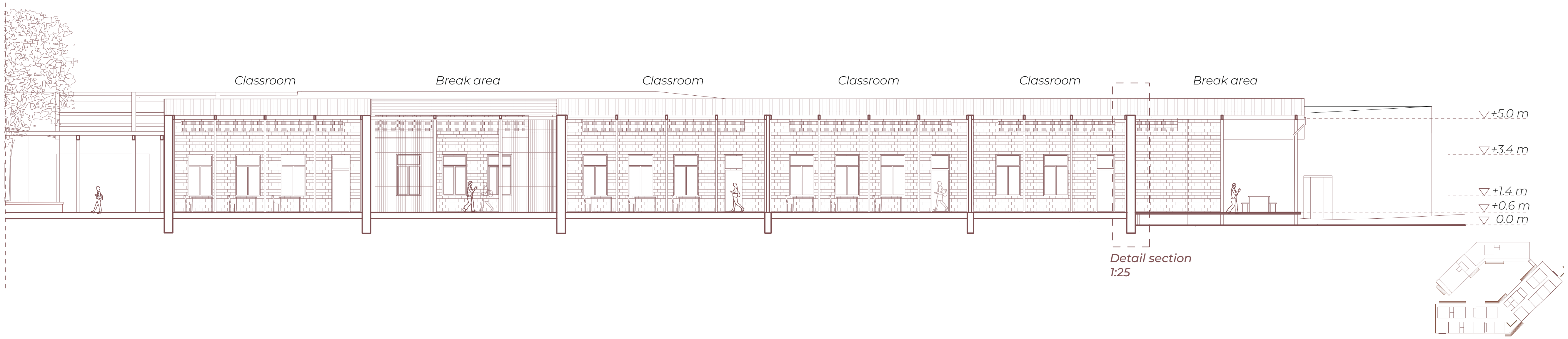


Fig. 193: Section A-A, 1:200

Building performance

Construction

The final construction detail (see fig. 194) illustrates a climate-responsive and resource-efficient building envelope by the use of local and natural materials.

The roof consists of multiple layers that prioritize thermal insulation and resilience against heavy rainfall. It consists of an aluminum corrugated sheet supported by spruce battens and plywood, insulated with 280 millimetres of kenaf fibre, and finished with an interior bamboo layer for improved acoustics and aesthetics.

The outer wall combines ICEB with a 120 millimetres straw bale core as insulation. The raised floor is insulated with 140 millimetres of straw bales and topped with OSB boards, which is supported by a ventilated stone foundation. A capillary barrier and an additional 120 millimetres of kenaf insulation below the foundation enhance thermal performance. These components alltogether create a durable and flood-resilient structure with low environmental impact.

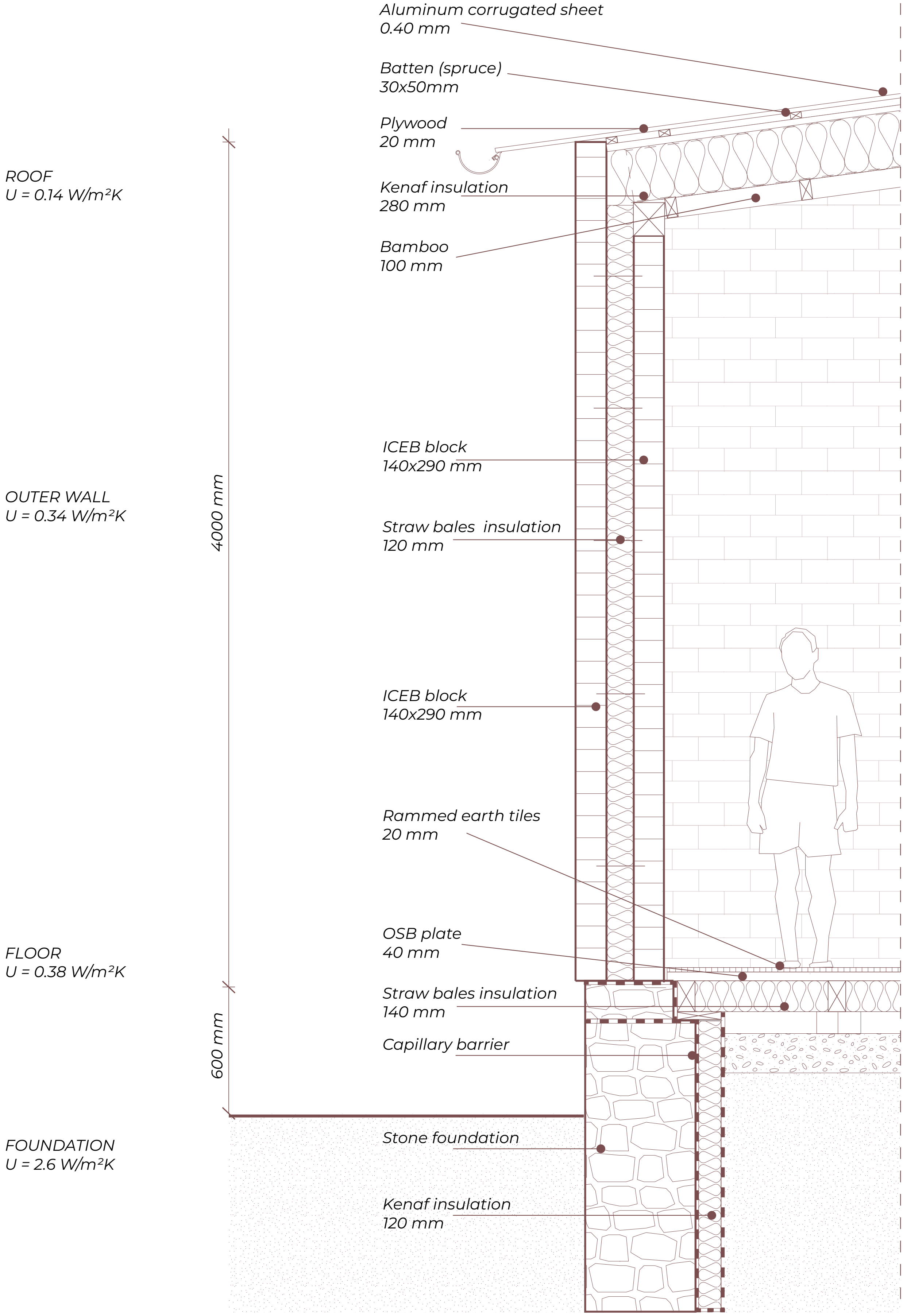


Fig. 194: Detail section of construction 1:25

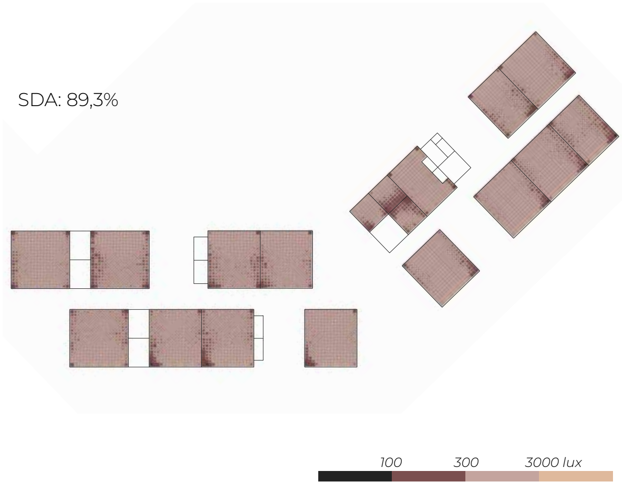


Fig. 195: Final SDA results

Fig. 196: Final uDI results

Daylight

The final window proposal presents a well-balanced solution to daylight access, ventilation, and façade aesthetics. The windows in the final design have a window to floor ratio of at least fifteen percent in all rooms and go up to twenty percent where it is more needed. The final design makes no use of shutters, as this was proven to have a minimal impact on thermal environment with a negative effect on daylight levels. The absence of shutters allows for a more consistent distribution of daylight, as reflected in the radiation maps (see fig. 195, 196). The UDI value of 76% and sDA of 89.3% confirm strong daylight autonomy in the final design, proving sufficient daylight levels for a learning environment.

LCA

The life cycle assessment of the final design reveals how material choices and transportation impact carbon emissions (see fig. 197).

Among the construction element, the stone foundation demonstrates the highest GWP, with a significant portion coming from transportation which is directly related to the distance and material density. Despite being a heavier material option, the stone is locally sourced and resilient to flooding, making it a sustainable and durable choice in the long run.

The wall has the second highest environmental impact, primarily due to the cement content in the

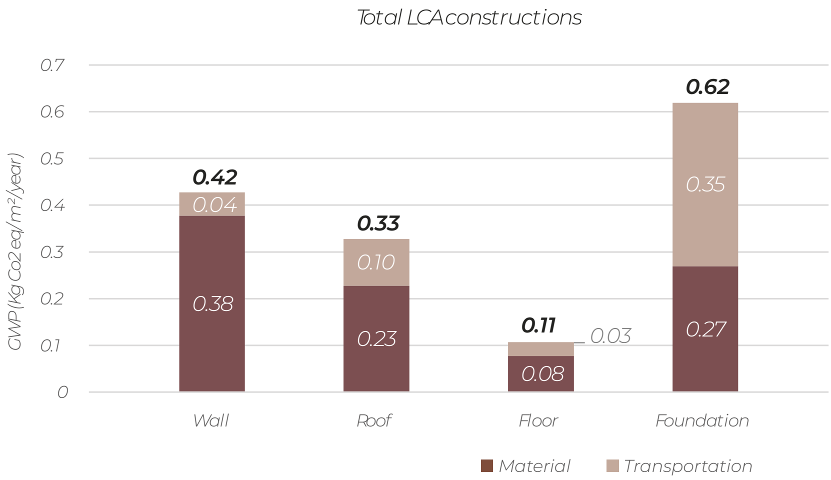


Fig. 197: Final LCA results

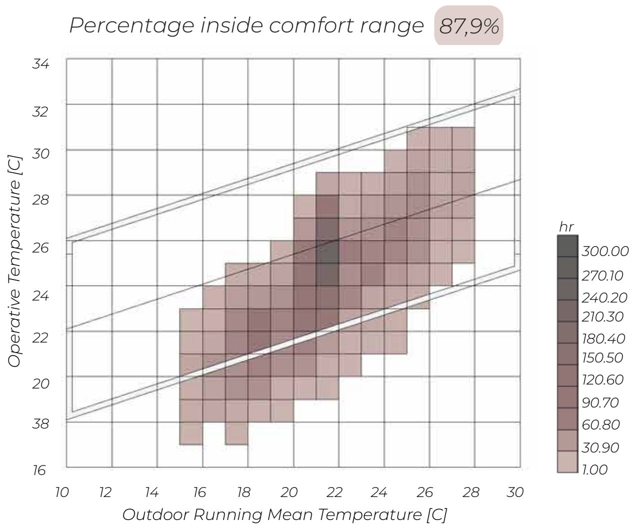


Fig. 198: Final ATC resulrs

ICEB mixture, despite it making up just five percent of the composition. Its presence significantly contributes to the structure's overall GWP.

In contrast, the roof and floor have the lowest GWP. The floor's wooden structure with straw insulation, coupled with earth tiles, minimizes carbon emissions. Similarly, the roof integrates kenaf insulation, bamboo, and aluminium to balance climate resilience and acoustic performance while maintaining a low environmental footprint.

ATC

The graph (see fig. 198) illustrates the percentage of hours within the adaptive thermal comfort (ATC) range, highlighting the improvements made in the final design. The final design achieves 87.9 percent of hours within the comfort range of category three, a significant increase from the base model's 67.2 percent, demonstrating the effectiveness of material and design modifications in optimizing indoor climate conditions.

The rise also reflects the embodied carbon in additional materials used to achieve better comfort levels, but the improvements in ATC justify this trade-off by ensuring a more comfortable indoor environment. Ultimately, the final design prioritizes thermal comfort, significantly enhancing the indoor climate without excessive environmental costs.

Summary

Input	Output

Input

Window to floor ratio

North and south facades + upper windows	15 %
Office and meeting rooms	20 %
PErforated bricks upper windows	Yes

Shading elements

Overhang west	= 60 cm
Overhang north	= 300 cm
Overhang south	= 1550 cm

Materials

Wall	0.34 W/m^{2}K
Floor	0.38 W/m^{2}K
Roof	0.14 W/m^{2}K
Foundation	2.60 W/m^{2}K

Output

UDI & sDA

UDI	76.0 %
sDA	89.3 %

Indoor climate

Highest T	31.0°C
Lowest T	19.4°C
Highest RH	84.6 %
Lowest RH	29.3 %
ATC	87.9%

GWP

Wall	0.42KgCO2eq/m^2/year
Floor	0.11 KgCO2eq/m^2/year
Roof	0.33 KgCO2eq/m^2/year
Foundation	0.62 KgCO2eq/m^2/year
Total	1.48 KgCo2eq/m^2/year

	Base model	Final proposal	Difference
UDI sDA	7.8 % 9.6 %	76.0 % 89.3 %	△ **68.2 %** **79.7 %**
ATC	67.2 %	87.9 %	△ **20.7 %**
Total GWP	0.61 KgCo2eq/m^2/year	1.48 KgCo2eq/m^2/year	△ **0.87 KgCo2eq/m^2/year**

Fig. 199: Fact box of final proposal

Fig. 200: Locals and volunteers after finishing the building (INSPIRELI Awards 2024)

08 Outro

Conclusion

This master thesis aims to answer a problem that is stated as the following:

How can a climate-resilient school building in Zambia, with the use of local materials, be designed with an easy-to-build, community-driven approach to ensure a safe and high-quality learning environment?

This research question encompasses a set of connected design aspects, including climate resilience, material use, 'easy to build', user needs, and architectural quality. To address these, the project began with comprehensive literature research and a contextual site analysis, both of which were critical to understanding the environmental, cultural, and technical conditions necessary for an effective and contextually relevant design.

The user needs, derived from the Inspireli Awards competition brief and additional research, provided a foundation for a community-aware design process. While no direct participatory design process was carried out, the competition served as a platform for translating the needs identified by of the users. As the final project will be built by local labour, of who is partly inexperienced, it highlighted the importance of prioritizing simple construction techniques and the use of locally available materials, ensuring that the resulting design can realistically be implemented by and for the local community.

Beyond practical considerations, the design aims to deliver qualitative architectural spaces that are durable, functional, and create a comfortable indoor climate. This required detailed assessment of thermal comfort, daylighting, ventilation, and humidity through simulation and performance evaluation.

The iterative process

Throughout the design process, it became clear that achieving a balance between different indoor climate factors was inherently challenging. For example, improving daylight availability often had a negative effect on thermal performance, and vice versa. To navigate these competing demands, the design process was structured around three iterations, each seeking to improve the indoor environment.

These iterations were evaluated not only for indoor climate, but also for their environmental impact of global warming potential. Results showed that while indoor climate performance generally improved with each iteration, the associated environmental impact also increased. The most effective balance was found in an iteration that optimized the traditional Zambian building methods using local materials, achieving significant indoor climate gains without excessive environmental cost.

Final design

The final design proposal integrates both quantitative data and qualitative insights. Passive design strategies were employed to enhance the indoor climate, with the majority of materials sourced locally to lower environmental impact and respect the local architectural expression.

The school layout consists of multiple building clusters inspired by traditional Zambian function layout. These clusters are connected by a continuous overhang and raised floor deck, providing sheltered circulation while offering protection against flooding. At the heart of the campus lies a central social gathering space, providing a multipurpose space where the school community and experience can flourish.

Ultimately, this thesis presents a holistic design, a school building that considers the climate, respects local material and aspires to provide a high-quality learning environment for its users. by a continuous overhang and raised floor deck, providing sheltered circulation while offering protection against flooding. At the heart of the campus lies a central social gathering space, providing a multipurpose space where the school community and experience can flourish.

Ultimately, this thesis delivers a holistic design : a climate-responsive school that honors local materials and traditions while striving to create a safe, comfortable, and high-quality learning environment for its users.

Reflection

Reflecting on the project brought the initial goal of creating a perfect indoor climate into perspective. Achieving optimal climate conditions while balancing all the preset design criteria proved more challenging than anticipated, leading to a simplification of the original ambitions. Designing for a climate with such varied extremes, ranging from cold periods to intense heat and humid periods to dry periods, alongside heavy rainfall added complexity to the process.

Additionally, conducting a thesis focused on a developing country in East Africa introduced unforeseen challenges. Due to time constraints, a site visit was not possible, requiring reliance on secondary data sources. This proved difficult, as detailed and accurate data for the region was often limited. Consequently, assumptions and data from nearby locations were used, which may affect the precision of some results.

Simulations

The LCA calculations and Climate Studio (CS) simulations were simplified to enhance clarity of the results. Both LCA and thermal simulations focused solely on what was assumed to be the most critical classroom in terms of overheating; however, this space may not represent the most critical conditions for daylight or ventilation.

Simplifications include the exclusion of the foundation in the thermal simulation, as the software does not account for it. Additionally, some materials used in the design were unavailable in CS, so substitutes with similar properties were used instead.

Similar limitations were experienced with LCAByg due to gaps in the material database. To compensate, external EPDs were manually imported, though these may lack full accuracy or miss certain life cycle stages. A list of these manually added EPDs is provided in appendix X. Another simplification is that all walls were treated as exterior walls in the LCA calculations, despite one being an adiabatic interior wall. Furthermore, the LCA assessment did not include the D stage (end-of-life and reuse), which could be significant given that some of the used materials are organic and potentially reusable beyond the building's lifespan.

Energy

The project is assuming that there is no mechanical heating or cooling system to rely on on the project site. This assumption is based on the lack of data regarding concrete numbers as well as for practical reasons. This means that the energy numbers are the same for all iterations, allowing to assess and compare the results without having additional factors influencing the outputs.

However, another strategy could have been to include these numbers in the total GWP assessment of the building, allowing for a total comparison of total energy needed including transportation costs heating/cooling energy and the GWP of the materials themselves. In this way, a decrease in energy need could be evaluated in relation to a higher total GWP of materials.

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List of figures

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Antje Heyselberghs		
Zin Sadik		
Title of the thesis: **From Earth to Education: A Sustainable Approach to Climate Resilient School Design in Rural Zambia**		
Supervisor´s name: **Christiane Berger, Endrit Hoxha**		
Submission date/year: **02/06/2025**		
Is the project confidential?	**Yes** ☐	**No** ☒
External collaboration*	**Yes** ☐	**No** ☒
External collaboration partner (name of company/organization): **-**		
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What is an external collaboration? Read more here.

Appendix

Appendix A

Thank you to the following for granting us permission to use their photos:

Pictures taken from the competition website are named the following (INSPIRELI Awards, 2024) and their access has been granted by Eva Machová.

Pictures taken from the website 'climate responsive design' are named the following (FoBE and Fielden Foundation (FCBStudios), 2015) and their access is granted by Randi Karangizi, who contacted the Fielden foundation for permission.

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People in the renders are taken from www.afrikut.com and greenpeace.org, and is listed in the bibliography.

Appendix B

LCA

Limitations:

> Since we are working with improved ICEB, cement as well as sand will be added to the mixture. Although cement is not a natural material, it has to be added to the earth mixture for the strength of the ICEB like mentioned previously. For the cement, a manufacture within a distance of 100km is found. Since there is no data about the amount of sand in the ICEB mixture, it will not be taken into account when calculating the U value or LCA. The five percent of cement added to ICEB will also not be taken into account in this study regarding U value, but will however be taken into account when calculating on the LCA.
>
> As established before, the site is situated within the Miombo woodland. However, when calculation on the properties in constructions, a more general wood type is assumed with similar properties. Pine, as well as oak are both very common in East Africa (Westerholm , 2023). Since oak is classified as a hardwood, as well as miombo wood, this material and its properties will be used when calculating.

Distances:

> Base materials
>
> Bamboo plantation: 200km
>
> Timber factory (assuming oak): 90 km
>
> Straw from grain farming: 120 km
>
> Stone (common = granite): 250 km
>
> Earth: assume in surroundings: 10 km

Additional materials

> Cement: 100 km
>
> Plywood: 228 km
>
> Kenaf fibre: 1752 km
>
> Cedar wood: 1859 km
>
> Mineral wool: 233km
>
> Aluminium: 235 km

Calculations

Final LCA calculation

Final proposal

Product	Wall earth	Wall straw	Wall cement	Roof kenaf	Roof wood	Roof Plywood	Roof aluminium	Roof bamboo	Floor wood	Floor earth tiles	Floor straw	Found. Stone	Found. Cement
Area in m²	199.5	199.5	9.975	111	111	111	111	111	110	110	110	21	1.05
Depth in m	0.28	0.12	0.28	0.28	0.078	0.02	0.02	0.1	0.072	0.02	0.13	0.5	0.5
total in m³	55.86	23.94	2.793	31.08	8.658	2.22	2.22	11.1	7.92	2.2	14.3	21.5	1.55
GWP in kg CO2e	869.05	354.00	853.65	213.00	382.00	611.00	46.03	41.18	293.8	35	96	1086.67	393.13
GWP total in kg CO2e			**2077**					**1293**			**425**		**1480**
GWP per m²/year	0.16	0.06	0.16	0.04	0.07	0.11	0.01	0.01	0.05		0.02	0.20	0.07
GWP total per m²/year			**0.38**					**0.24**			**0.07**		**0.27**

Component	Wood	Straw	Kenaf fibre	Earth	Stone	Bamboo	Plywood	Aluminium	Cement
Density in kg/m³	750	140	100	1.500	2700	600	680	2700	1500
Quantity in kg	12434	5354	3.108	87090	58050	6660	1510	5994	6515
Quantity in t	12.43	5.35	3.11	87.09	58.05	6.66	1.51	5.99	6.51
Distance in km	90	120	233	10	250	200	228	235	100
Truck in kgCO2e/tkm	0.090	0.090	0.090	0.064	0.064	0.090	0.090	0.090	0.090
Total in kgCO2e/tkm	0.18	0.18	0.18	0.13	0.13	0.18	0.18	0.18	0.18
GWP in kg CO2e	**200.75**	**115.64**	**130.35**	**112.17**	**1857.60**	**239.76**	**61.95**	**253.55**	**116.87**
GWP per m²/year	**0.04**	**0.02**	**0.02**	**0.02**	**0.34**	**0.04**	**0.01**	**0.05**	**0.02**

Note: Simplification regarding the final proposal have been made in LCAByg where additions like insulations and vapour barriers are not included in the calculations, in order to be able to compare them to the prior iterations.

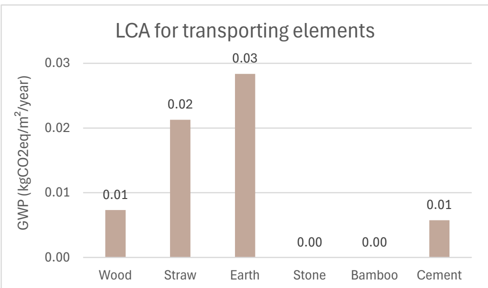
Note: the truck transportation values are taken from the carbon calculator spreadsheet (Kanafani K. 2024)

LCA process calculation

Base model

Product	*Wall earth*	*Wall cement*	*Roof straw*	*Roof wood*	*Floor earth*	*Found. earth*
Area in m²	*168*	*8.4*	*111*	*111*	*110*	*21*
Depth in m	*0.14*	*0.14*	*0.35*	*0.03*	*0.425*	*0.5*
total in m³	*23.52*	*1.176*	*38.85*	*3.33*	*46.75*	*10.5*
GWP in kg CO2e	*370.43*	*430.57*	*1077.00*	*105.60*	*752.93*	*169.11*
GWP total in kg CO2e		***801***		***1183***	***753***	***169***
GWP per m²/year	*0.07*	*0.08*	*0.20*	*0.02*	*0.14*	*0.03*
GWP total per m²/year		***0.15***		***0.22***	***0.14***	***0.03***

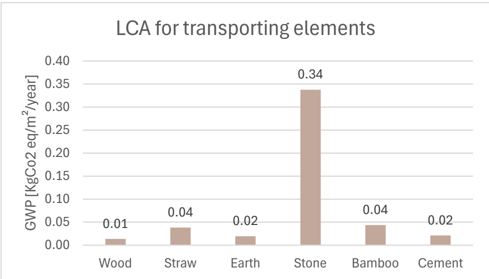
Component	*Wood*	*Straw*	*Earth*	*Stone*	*Bamboo*	*Cement*
Density in kg/m³	*750*	*140*	*1.500.00*	*2700*	*600*	*1500*
Quantity in kg	*2498*	*5439*	*121.155.00*	*0*	*0*	*1764*
Quantity in t	*2.50*	*5.44*	*121.16*	*0.00*	*0.00*	*1.76*
Distance in km	*90*	*120*	*10*	*250*	*200*	*100*
Truck in kgCO2e/tkm	*0.090*	*0.090*	*0.064*	*0.000*	*0.000*	*0.090*
Total in kgCO2e/tkm	*0.18*	*0.18*	*0.13*	*0.00*	*0.00*	*0.18*
GWP in kg CO2e	***40***	***117***	***156***	***0***	***0***	***32***
GWP per m²/year	***0.01***	***0.02***	***0.03***	***0.00***	***0.00***	***0.01***



Iteration 1

Product	Wall earth	Wall Straw	Wall cement	Roof straw	Roof wood	Roof bamboo	Floor wood	Floor straw	Found. Ston	Found. Cement
Area in m²	199.5	199.5	9.975	111	111	111	110	110	21	1.05
Depth in m	0.28	0.1	0.28	0.35	0.03	0.1	0.056	0.1	0.5	0.5
total in m³	55.86	19.95	2.793	38.85	3.33	11.1	6.16	11	21.5	1.55
GWP in kg CO2e	869.05	202.16	853.65	1083.00	152.64	41.18	285.6	154.7	1086.67	393.13
GWP total in kg CO2e			**1925**			**1277**		**440**		**1480**
GWP per m²/year	0.16	0.04	0.16	0.20	0.03	0.01	0.052	0.028	0.20	0.07
GWP total per m²/year			**0.35**			**0.23**		**0.08**		**0.27**

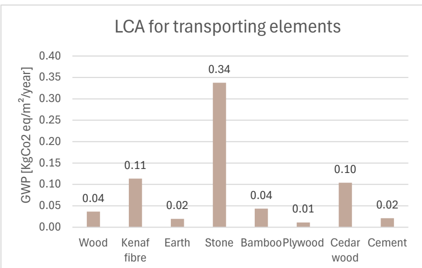
Component	Wood	Straw	Earth	Stone	Bamboo	Cement
Density in kg/m³	750	140	1.500.00	2700	600	1500
Quantity in kg	4623	9772	83.790.00	58050	6660	6515
Quantity in t	4.62	9.77	83.79	58.05	6.66	6.51
Distance in km	90	120	10	250	200	100
Truck in kgCO2e/tkm	0.090	0.090	0.064	0.064	0.090	0.090
Total in kgCO2e/tkm	0.18	0.18	0.13	0.13	0.18	0.18
GWP in kg CO2e	**75**	**210**	**108**	**1858**	**240**	**117**
GWP per m²/year	**0.01**	**0.04**	**0.02**	**0.34**	**0.04**	**0.02**



Iteration 2

Product	*Wall earth*	*Wall cement*	*Roof straw*	*Roof wood*	*Floor earth*	*Found. earth*						
Area in m131	*168*	*8.4*	*-110.3*	*111*	*110*	*21*					Found. Stone	Found. Cement
Depth in m	*0.14*	*0.14*	*-220.95*	*0.03*	*0.425*	*0.5*					21	1.05
Depth in m	0.28	0.14	0.28	0.28	0.078	0.02	0.04	0.1	0.072	0.13	0.5	0.5
total in m³	0.0392	0.0196	-61.866	0.0084	0.03315	0.01	0	0	0	0	21.5	1.55
GWP in kg CO2e	869.05	206.00	853.65	213.00	382.00	611.00	2510.00	41.18	293.8	105	1086.67	393.13
GWP total in kg CO2e			**1929**					**3757**		**399**		**1480**
GWP per m²/year	0.16	0.04	0.16	0.04	0.07	0.11	0.46	0.01	0.05	0.02	0.20	0.07
GWP total per m²/year			**0.35**					**0.68**		**0.07**		**0.27**

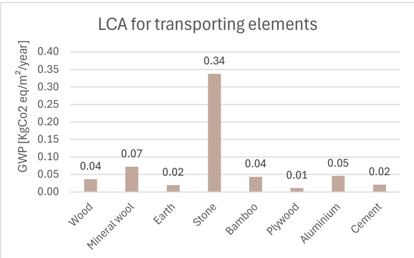
Component	Wood	Kenaf fibre	Earth	Stone	Bamboo	Plywood	Cedar wood	Cement
Density in kg/m³	750	27	1.500	2700	600	680	385	1500
Quantity in kg	12434	1.979	83.790.00	58050	6660	1510	1709	6515
Quantity in t	12.43	1.98	83.79	58.05	6.66	1.51	1.71	6.51
Distance in km	90	1752	10	250	200	228	1859	100
Truck in kgCO2e/tkm	0.090	0.090	0.064	0.064	0.090	0.090	0.090	0.090
Total in kgCO2e/tkm	0.18	0.18	0.13	0.13	0.18	0.18	0.18	0.18
GWP in kg CO2e	**201**	**624**	**108**	**1858**	**240**	**62**	**572**	**117**
GWP per m²/year	**0.04**	**0.11**	**0.02**	**0.34**	**0.04**	**0.01**	**0.10**	**0.02**



Iteration 3

Product	Wall earth	Wall mw.	Wall cement	Roof mw.	Roof wood	Roof Plywood	Roof aluminium	Roof bamboo	Floor wood	Floor mw.	Found. Stone	Found. Cement	Test concret
Area in m²	199.5	199.5	9.975	111	111	111	111	111	110	110	21	1.05	21
Depth in m	0.28	0.19	0.28	0.28	0.078	0.02	0.02	0.1	0.072	0.23	0.5	0.5	0.5
total in m³	55.86	37.905	2.793	31.08	8.658	2.22	2.22	11.1	7.92	25.3	21.5	1.55	21.5
GWP in kg CO2e	869.05	1599.00	853.65	6643.00	382.00	611.00	46.03	41.18	293.8	3449	1086.67	393.13	6167.00
GWP total in kg CO2e			**3322**					**7723**		**3743**		**1480**	
GWP per m²/year	0.16	0.29	0.16	1.21	0.07	0.11	0.01	0.01	0.05	0.63	0.20	0.07	1.12
GWP total per m²/year			**0.60**					**1.40**		**0.68**		**0.27**	**1.12**

Component	Wood	Mineral wool	Earth	Stone	Bamboo	Plywood	Aluminium	Cement	Test concrete
Density in kg/m³	750	100	1.500	2700	600	680	2700	1500	2400
Quantity in kg	12434	9.429	83.790.00	58050	6660	1510	5994	6515	51600
Quantity in t	12.43	9.43	83.79	58.05	6.66	1.51	5.99	6.51	51.60
Distance in km	90	233	10	250	200	228	235	100	235
Truck in kgCO2e/tkm	0.090	0.090	0.064	0.064	0.090	0.090	0.090	0.090	0.064
Total in kgCO2e/tkm	0.18	0.18	0.13	0.13	0.18	0.18	0.18	0.18	0.13
GWP in kg CO2e	**201**	**395**	**108**	**1858**	**240**	**62**	**254**	**117**	**1552**
GWP per m²/year	**0.04**	**0.07**	**0.02**	**0.34**	**0.04**	**0.01**	**0.05**	**0.02**	**0.28**



EPD’s taken in all iterations

The following EPD’s have been used from ‘Oekobaudat’ because of the absence of it in the database of LCAbyg or because a more simple version of the material was wanted.

Cement: data from ‘Zementmörtel’

Straw: data from ‘FASBA e.V. Baustroh; 100 kg/m³‘

The following EPD’s have been used from ‘data.environdec.com’ because of the absence of it in the database of LCAbyg or because a more simple version of the material was wanted.

Granite: data from ‘Natural Granite Products’

Bamboo: data from ’dasso Traditional Bamboo’

Hemp fibre: data from ‘S-P-10546 EKOLUTION® Hemp Fibre Insulation’

The following EPD’s have been used from ‘ecosmdp.eco-platform.org’ because of the absence of it in the database of LCAbyg or because a more simple version of the material was wanted.

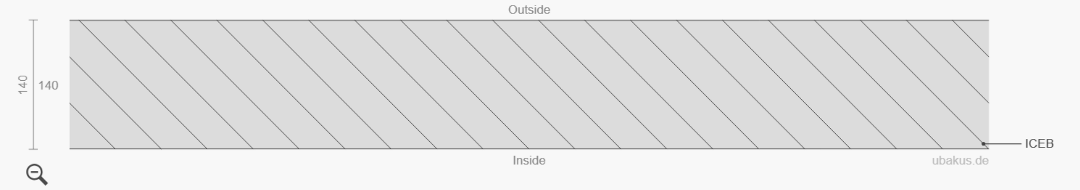
Ceder shingles: data from ‘Profiled TermoAsh and Ceder, untreated and painted - Cedar (Untreated)

Appendix C

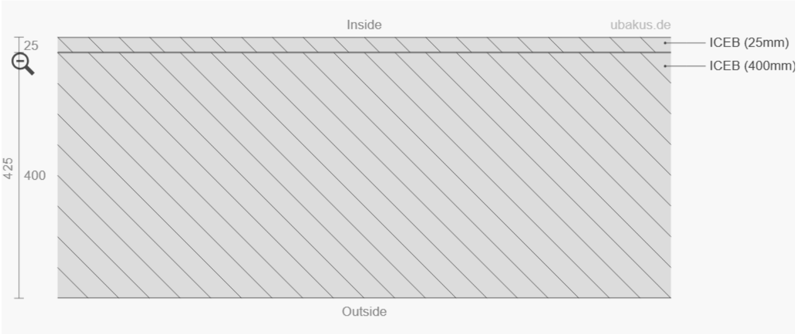
Construction, U values taken from Ubakus

Base model

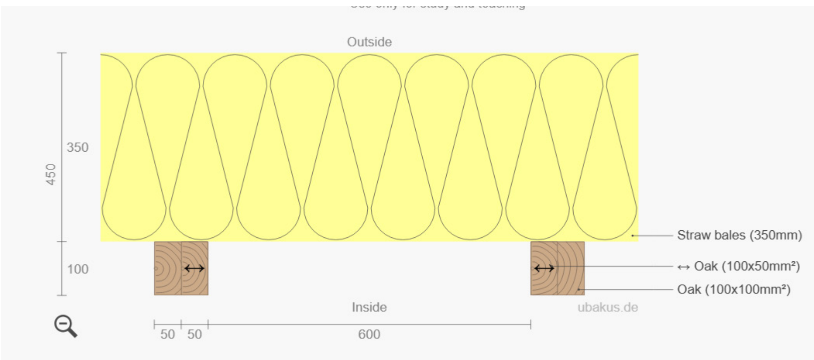
Wall: 2.70 W/m²K



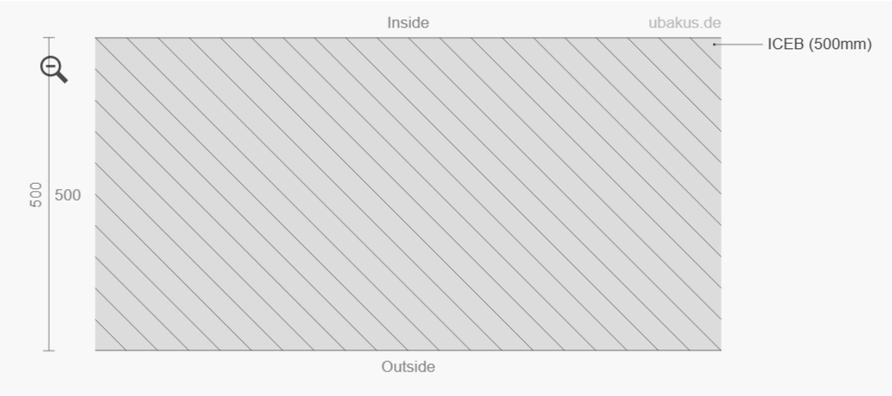
Floor: 1.20 W/m²K



Roof: 0.14 W/m²K

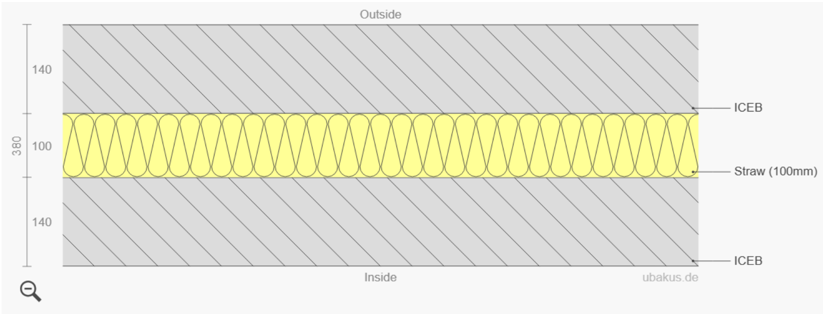


Foundation: 1.08 W/m²K

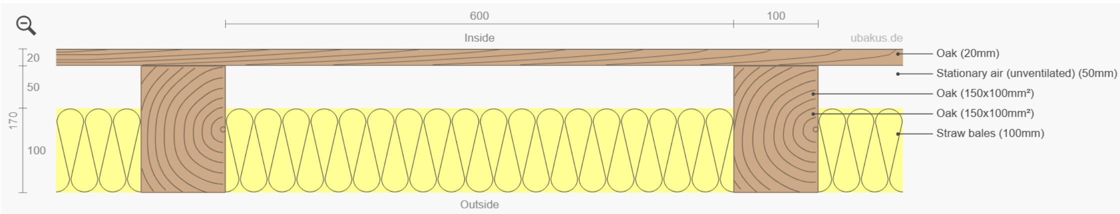


Iteration 1

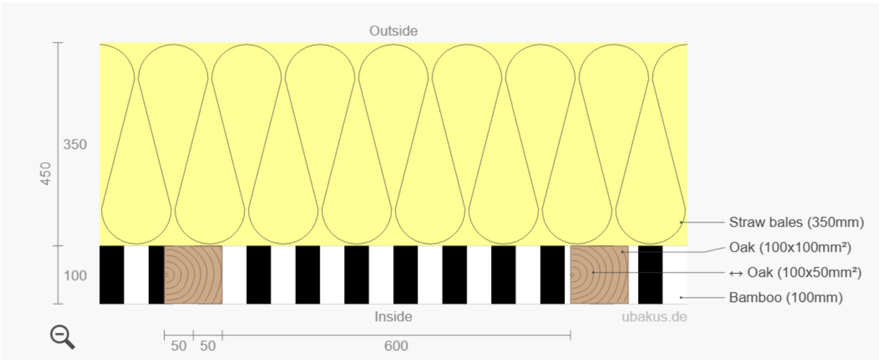
Wall: 0.39 W/m²K



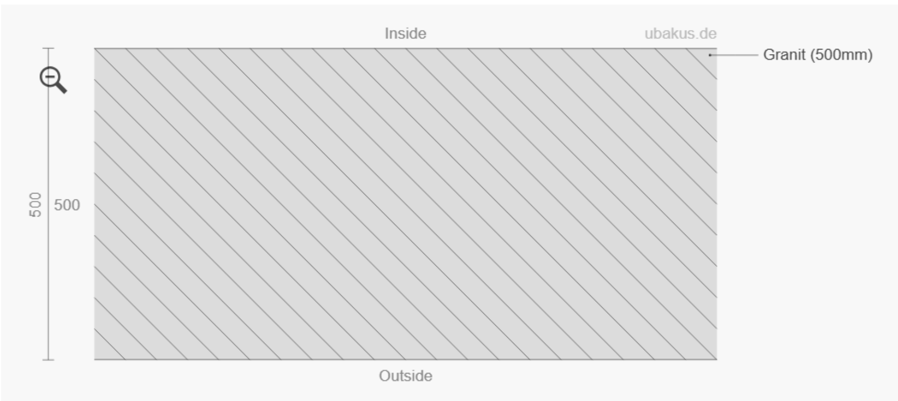
Roof: 0.48 W/m²K



Roof: 0.13 W/m²K

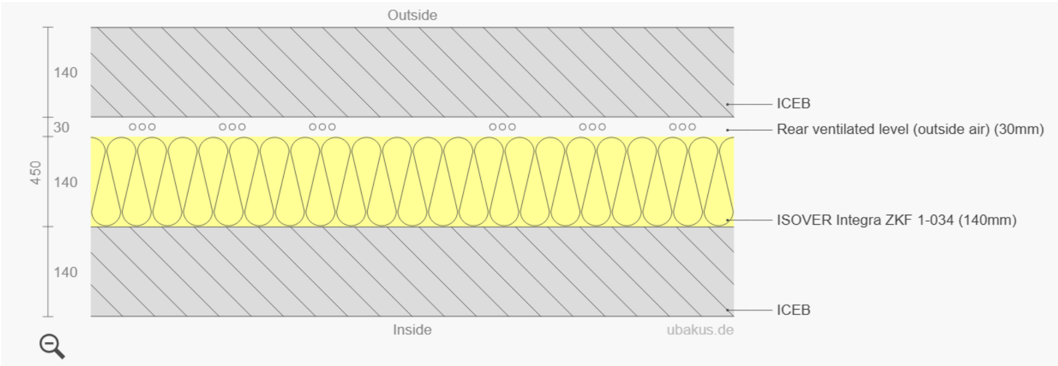


Foundation: 2.60 W/m²K

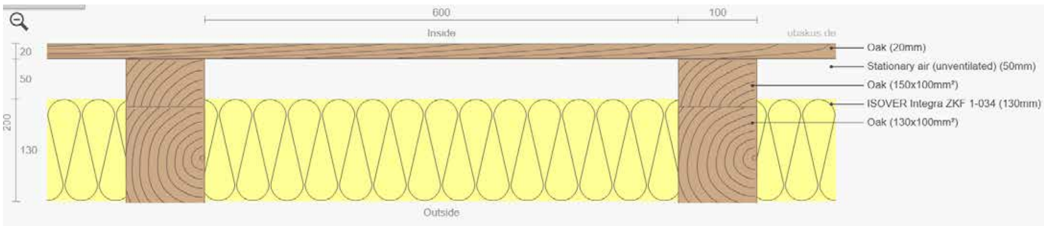


Iteration 2

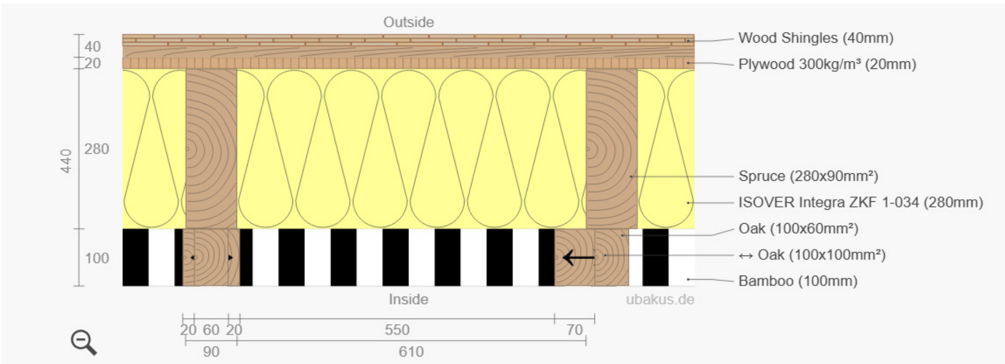
Wall: 0.22 W/m²K



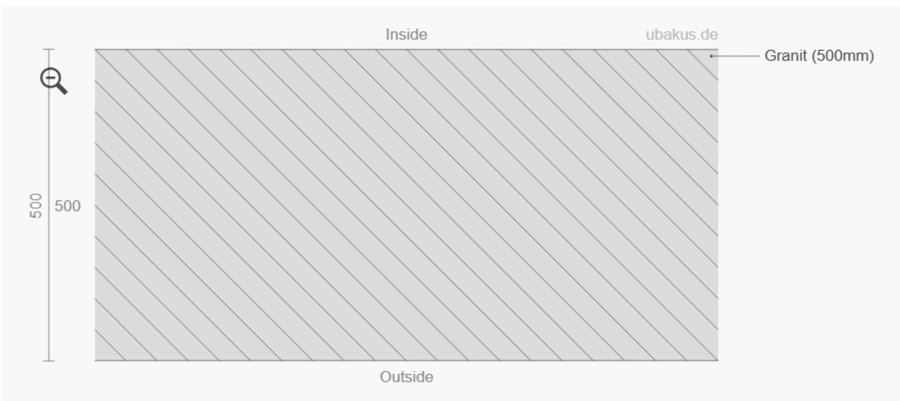
Floor: 0.33 W/m²K



Roof: 0.13 W/m²K

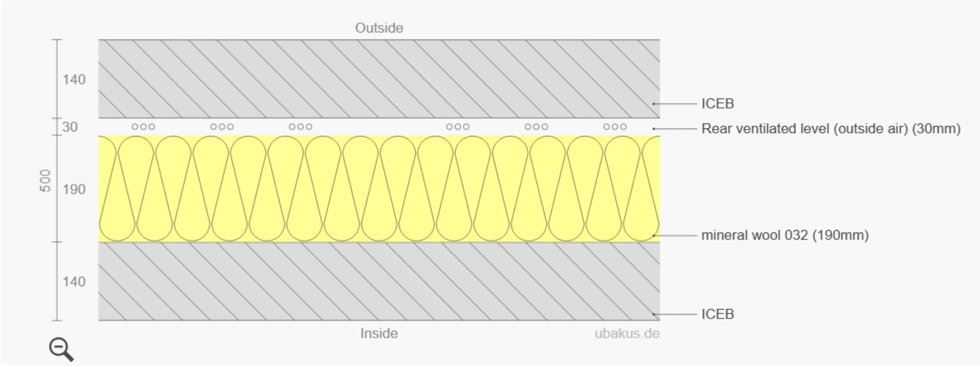


Foundation: 2.60 W/m²K

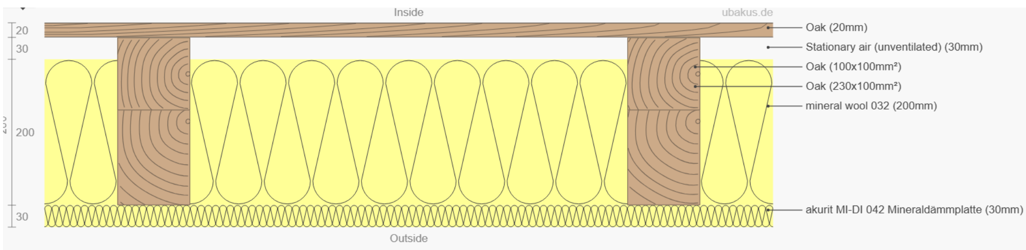


Iteration 3

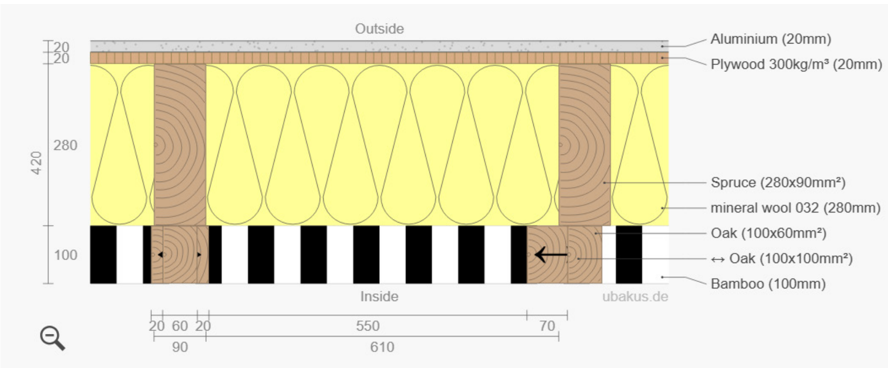
Wall: 0.16 W/m²K



Floor: 0.19 W/m²K



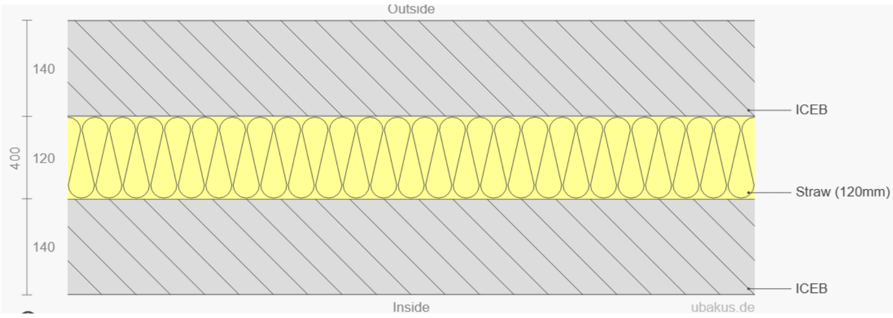
Roof: 0.13 W/m²K



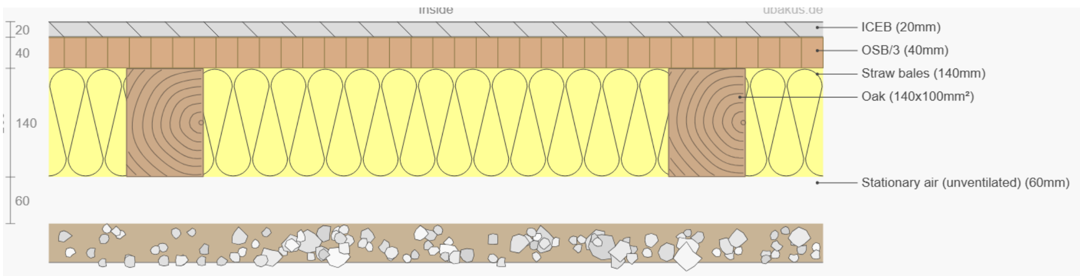
Foundation: 2.60 W/m²K

Final proposal

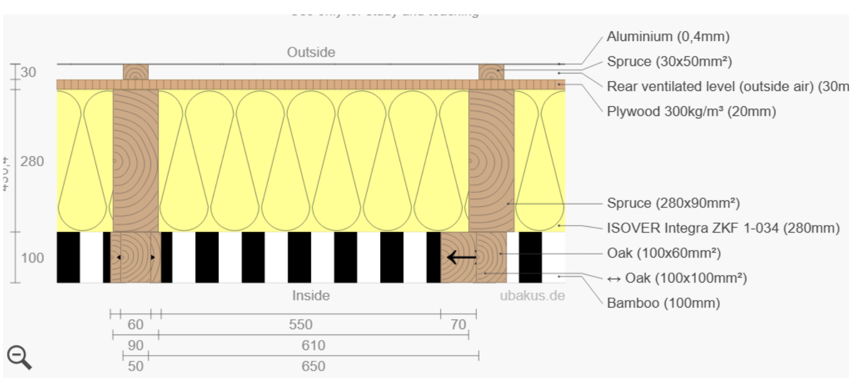
Wall: 0.34 W/m²K



Floor: 0.38 W/m²K



Roof: 0.14 W/m²K



Foundation: 2.60 W/m²K