Thermal Analysis and Optimization Potential of Clamp Kilns for Fired Clay Brick Production

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Author(s):
Bossard, Anna

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Eidgenössische Technische Hochschule Zürich
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Prof. Elizabeth Tilley

Master Thesis

Thermal Analysis and Optimization Potential of Clamp Kilns for Fired Clay Brick Production

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Supervised by:
Prof. Dr. Elizabeth Tilley
Dr. Marc Kalina

Author:
Anna Bossard

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Author(s)

Anna Lea	Bossard

Supervising lecturer

Elizabeth	Tilley

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Contents

Preface

"Why don't they just..."
That was the beginning of many discussions I had when I told people about the topic I picked for my Master's Thesis. And to admit it, I did the same when Prof. Tilley asked me if I would like to explore the optimization potential of traditional brickmaking methods in Malawi.
The traditional production of fired clay bricks is a compellingly simple process: It only requires clay, water, moulds, and some firewood. The moulded, sun-dried bricks are stacked on a pile, a fire is lit, the bricks are baked, done. Sustainably sourced, this is a carbon-neutral way to produce relatively robust building materials. Yet, the ever-increasing demand puts a lot of pressure on the natural environment in Malawi. So the question is: How can Malawians produce clay bricks in a more environmentally compatible way?

"Why don't they just replace the trees they harvested? Or use them to build their homes, instead of using them as fuel? Do they not know that deforestation is bad?"
"Why don't they use concrete instead, or switch to more efficient technologies? There must be lots of examples of other countries that they can follow."
"Aren't there plenty of new, sustainable materials that can even incorporate waste? I think I once saw an article about this startup, I can send you the link if you'd like..."

It was a refreshing experience for me to for once be able to discuss my studies with the non-engineers in my life. Topics like Computer Vision and Thermodynamics usually do not spark such lively discussions. Yet, as you, valued reader of this Thesis, are about to see, things are not as simple as they appear at the first glance.
With these opening remarks, I hope you will enjoy exploring the intricacies of Malawi's brickmaking industry just as much as I did during the course of my research for this thesis.

Abstract

Fired clay bricks are the primary building material in Malawi, traditionally produced in small-scale clamp ovens. However, the country's construction sector faces significant challenges. Malawi experiences rapid growth and has one of the highest rates of urbanization globally, resulting in a high demand for building materials. Unfortunately, wood, the predominant fuel for clay brick production, is increasingly scarce due to the depletion of natural forests over the past decades.

Despite the existence of more efficient technologies, clamp kilns are likely to continue being used in rural areas of Malawi for years to come due to their advantageous properties, including ease of use and low investment costs. However, there is a lack of quantitative analysis on their efficiency in the available literature. Therefore, the goal of this Master's Thesis is to investigate the optimization potential of clamp kilns.

To achieve this, an experimental setup was designed to measure temperatures at 16 different points during a firing period in a small brick clamp located in Chembe, Malawi. These temperature measurements were used to assess the quality of bricks produced in various sections of the kiln. The results served as a basis for identifying areas within the clamp where the brick quality was insufficient.

In order to simulate the impact of different kiln layouts on brick quality and fuel consumption, a thermal simulation using the Finite Element Method was developed. A 3D model of the kiln was analyzed, and the temperature measurements were used as a reference to validate the accuracy of the model.

Based on the temperature measurements, it was observed that surface heat losses adversely affect brick quality. To address this issue, different layouts with increased width and length were simulated. The results showed that by increasing the width and length of the kiln, the proportion of insufficiently fired bricks could be reduced by 40.5%, while the fuelwood demand decreased by 20%. Thus, increasing the width and length of the kiln proved to be a simple way to save fuelwood and improve brick quality using clamp kiln technology. However, increasing the height of the oven did not yield beneficial results due to poor heat transfer to the top layers.

Even though the utilization of clamp kiln technologies can be improved, there are inherent flaws in their design that hinder the uniform firing of clay bricks and result in heat losses. These issues, such as the intermittent nature of the firing process and the fixed position of the fired bricks, are addressed in the design of more advanced kiln types. Therefore, efforts to industrialize Malawi's brick sector are important in order to reduce the environmental impact of the country's construction industry.

Chapter 1

Introduction

1.1 Clay Bricks: A Popular Building Material with Serious Environmental Consequences

1.1.1 A Success Story Throughout the Millenia

Brick production is one of the oldest industries in the world with the first bricks having been produced more than 8000 years B.C. in what is now modern-day Turkey [1]. Brickmaking technologies were invented independently by several civilisations all over the world and to date, the earth-based building material is still indispensable. This is no surprise, given the many favourable properties it possesses, such as high strength and durability, a resistance to both fire and rain, and low thermal conductivity, leading to an agreeable indoor climate [1][2][3]. Moreover, the most basic brick production methods require little more than clay soil, water, and fuelwood, which is probably the most important factor in making fired clay bricks a global success story.

While today, concrete has become the dominant building material, especially in industrialized countries, fired and unfired clay bricks remain central in many world regions. The majority of fired bricks are produced in Asia, specifically China and India [4].

1.1.2 Traditional Brickmaking Methods: The Enduring Appeal of Clamp Kilns

Over time, new brickmaking technologies have been developed, improving brick quality and enabling mass production. Machines were developed to extrude or press the clay into molds, leading to increased production rates and greater consistency in the size and shape of bricks. A variety of new kilns were developed in the 20th century and became widespread in industrialized countries, such as the Hoffmann Kiln or the Tunnel Kiln, but many countries continue to use the original brickmaking method: the Clamp Kiln [5].

In this oven type, unfired bricks are stacked in a pile with room for fuel (commonly either wood or coal), which is then burned to heat the bricks to a high temperature.

Even though this technology requires a lot of energy input per brick and the resulting brick quality is rather poor compared to more modern production methods, a lot of countries continue to use it for several reasons. Clamp kilns are a low-cost technology that requires minimal investment in infrastructure and machinery. The required materials can be sourced locally and the clamp can be constructed close to the building site, shortening transportation paths. This makes them accessible to small-scale brick producers who may not have access to more advanced technologies or resources.

Brick clamps are furthermore relatively easy to construct and operate, requiring only basic materials and knowledge of traditional firing techniques. This makes them a viable option for brick producers who may lack formal training or education in brick-making.

Additionally, this technology has been used for millenia in many parts of the world. This means that there is a cultural and social familiarity with brick clamps, and it may be difficult to shift to newer, unfamiliar technologies.

Finally, the disadvantages of this technology such as deforestation or air pollution may be seen as a necessary sacrifice in the pursuit of economic development. In fact, there is a clear link between the progression of deforestation and economic development, especially in Sub-Saharan Africa [6]. Therefore, many countries may prioritize economic gains over long-term environmental concerns. But as these once long-term environmental concerns are starting to manifest as serious, present-day issues that impact the livelihood of people, it is becoming clear that new approaches are needed, as the case of Malawi shows.

1.2 A Multitude of Challenges for Malawi's Building Sector

Malawi, a landlocked country in southeastern Africa, primarily relies on fired and unfired clay bricks in its building sector. The country borders Lake Malawi, which is one of the world's largest, and has a landscape dominated by the Savannah's dry grasslands and the Miombo woodlands [7]. But Malawi's scenery is changing rapidly: it is estimated that the country has lost more than half its forest cover over the past 50 years. Despite the reforestation efforts of the Malawian Government, no counter-trend can yet be perceived [7][8]. One key factor that contributes to the issue is the rising demand for land to feed and house the growing population of Malawi. The country has an urbanization rate of over 4%, one of the highest in the world [9].

This means that Malawi, a country that is consistently ranked among the world's poorest, must be able to provide affordable and environmentally sustainable housing in the face of declining forest cover and limited resources. It is a monumental task with many open questions, some of which we will try to answer in this Master Thesis.

The first question that needs to be asked is: Will the current approach to brickmaking and housing construction in Malawi be viable in the long run? In the following sections the current state of Malawi's building industry and the ways it is negatively impacting the country's environment and inhabitants will be analyzed.

Figure 1.1: A small-scale brickmaking site in Chembe, Malawi.

1.2.1 Malawi's brickmaking industry and its negative influence on the natural environment

A survey by the South African Development Cooperation from the year 2017 estimates that industrial brick production constitutes about 50% of total clay brick production in Malawi, while the informal sector is responsible for the remaining half [10].

Although more than one technology is used, the vast majority of clay bricks are produced in small- to medium-sized brick clamps (Figure 1.1 and Figure 1.2). These non-permanent structures are built by layering dried, unburnt bricks, and leaving gaps for fuelwood. Then, these chambers are filled with stacks of wood and the brick burning begins. Once the kiln is fired, there is little control over the process, which takes about three to four days, depending on the kiln size.

Research has shown that in brick clamp kilns, up to 45% of the bricks are of low quality because they are not optimally fired [11]. Due to the high demand, these second-grade bricks are still sold and used to make floors or build barns.


Figure 1.2: The brick clamp: A popular, but wasteful technology.

Figure 1.3: Deforested area in front of Lake Malawi National Park in Chembe.

Deforestation

Like much of subsaharan Africa, Malawi relies primarily on biomass to cover its energy needs, with only 10% of the population having access to electricity. While the electricity production is primarily based on hydropower, is estimated that about 98% of the remaining energy demand is covered by biomass[12]. Households are the largest consumers, using wood or charcoal to prepare food. It is commonly predicted that with increased incomes, the country will transition to other energy forms and sources of primary energy such as electricity or LPG. But recent findings suggest that factors such as convenience, energy preferences and insurance against irregular supply leads to the reliance on energy mixes rather than a complete transition. Apart from the use of biomass as an energy source, agricultural expansion is another major driver for the receding forest cover [7].

While deforestation has been halted in protected areas in Malawi, the logging continues almost everywhere else (Figure 1.3) [8]. As a consequence, brickmakers have to transport fuelwood over increasingly longer distances, which impacts the price of bricks as well.

Apart from impacting the livelihood of brickmakers, the rampant deforestation has a wide range of negative consequences, both for the environment and for Malawian society. Some of the most significant consequences

of deforestation include soil erosion and degradation, which reduces agricultural productivity [13], as well as the loss of biodiversity with resulting ripple effects throughout ecosystems[14]. Also, a receding forest cover can impact the ability of the soil to store water and reduce the availability of water in communities [15]. Moreover, a loss of vegetation can heighten the severity of flood damages [16]. Last but not least, deforestation can have economic impacts, particularly for those who rely on forests for their livelihoods.
All of these factors can severely impact Malawi's economy, ecosystem, and consequentially, its inhabitants.

Land Degradation

As established in the previous section, deforestation can lead to soil erosion and reduced soil quality, negatively impacting agricultural yield [13]. But the production of fired clay bricks can contribute to land degradation in other ways as well.
Clay mining is often done on agricultural land, where the fertile topsoil is scraped off to access the underlying clay resources. This removal of fertile topsoil can lead to soil erosion, reduced soil quality, and decreased agricultural productivity. There is no research on the impact of the use of clay mining on agricultural productivity in Malawi, but research from other countries suggests that the impact on the yield can be very significant [17].
Asfaw *et al.* (2020) estimate that continued soil erosion in Malawi can reduce the agricultural yield by up to 20%, with the consequental welfare loss affecting primarily least-productive households [18].

Air Pollution

As Malawi relies primarily on biomass for its energy demand, the levels of air pollution in settlements can be dangerous for human health [19]. The traditional brick-making process involves burning wood and other biomass fuels in kilns to fire the bricks, which produces significant amounts of smoke and particulate matter, as well as other pollutants such as sulfur dioxide, nitrogen oxides, and carbon monoxide. There are no available numbers on the emissions caused by the Malawian brick sector, but research from India points to a clear link between brick production and local air pollution, especially in urban areas where the demand for bricks for construction is high [20].
The dangers related to air pollution from brick production are significant. Exposure to air pollution can have adverse effects on human health, particularly for vulnerable populations such as children, pregnant women, and the elderly. In Malawi, where access to healthcare is limited, the impacts of air pollution on health can be particularly severe. Exposure to air pollution can cause or aggravate respiratory problems such as asthma, chronic obstructive pulmonary disease (COPD), and bronchitis, as well as cardiovascular disease, cancer, and reproductive problems. It can also contribute to premature mortality [20]. Brickmakers are especially at risk, as they can be exposed to polluted air in their work [21]. This highlights the importance of introducing cleaner alternatives for brick production in Malawi.

1.3 The Struggle of Moving Towards More Sustainable Building Materials

As analyzed in the previous sections, Malawi's brickmaking sector is responsible for numerous environmental challenges. To address these challenges, it is important for Malawi to improve the sustainability of its building materials.
In the following sections, an overview of potentially more sustainable alternatives for both brick production and other building materials will be given as well as remaining challenges that may currently prevent them from replacing traditional building materials in Malawi.

1.3.1 Improved Materials

Brick Additives

In recent years, there has been a growing interest in the use of additives that can enhance the environmental performance of bricks. Bories *et al.* (2018) evaluated literature on different brick additives and conclude that many of them can improve the durability, thermal properties, and mechanical strength of bricks [22]. However, it is important to consider the local context and resources when selecting pore-forming agents for use in brick production. These additives can be derived from a variety of waste materials, such as fly ash,

glass, or even discarded plastic. In this way, brick additives have the potential to make the production of bricks more sustainable and contribute to waste management efforts [22].
Mahdjoub *et al.* (2021) tested the mechanical strength of fired clay bricks with incorporated crushed post-consumer waste glass. The authors suggest that the use of post-consumer waste glass and burnt clay bricks has the potential to provide a sustainable and cost-effective solution for construction in Malawi and other regions where waste materials and traditional building techniques are abundant. However, further research is needed to optimize the mix design and production process, as well as to evaluate the long-term performance and durability of these materials in construction. [23]
Another potentially interesting brick additive for Malawi could be tobacco husks, as the export of tobacco is one of the economic staples of the country [24]. A study conducted by Demir (2008) compared the influence of varying contents of sawdust, tobacco residues, and grass in brick-clay on the mechanical and thermal properties of fired clay bricks. The author concludes that the addition of organic residue as pore-forming agents is an environmentally save way to improve brick quality and help save fuel. Pore-forming agents can improve the insulation properties of bricks [25]. But whether the tobacco industry itself can help reduce deforestation is questionable, as 31 kg of firewood is needed to cure 1 kg of tobacco. Due to that, the tobacco industry itself accounts for around 26% of deforestation in Malawi [26]. This leads to the conclusion that while such an approach may help to save some fuel and improve brick quality, it does not solve the underlying issue: Fuelwood is usually not sustainably sourced in Malawi.

Cement Stabilized Earth Blocks (CSEBs)

CSEBs are made from a mixture of soil, stabilizers (such as cement), and water. They are compressed in a machine and cured for several days before use. CSEBs are more environmentally friendly than burned clay bricks as they require less energy to produce and do not contribute to deforestation. Furthermore, they have better thermal insulation properties [27][28]. Potentially, they could even be used for passive solar heat storage [29].
Bredenoord and Kulshreshtha (2023) suggest that CSEBs can be a promising material for low-cost social housing [30]. Cement Stabilized Earth Blocks can be made from locally available soil, which reduces transportation costs and makes them more affordable than materials that need to be transported from distant locations. The blocks can be produced using simple machines that are relatively inexpensive and easy to maintain, which reduces capital costs compared to more complex manufacturing equipment [30].
Despite these favourable properties, further research may be needed to promote wider adoption of CSEBs as a sustainable building material. For one, there is still a lack of standardization in CSEB production, which can affect the quality and durability of the blocks. Another weakness is the potential for water damage to the blocks if they are not properly protected from moisture. Furthermore, more work needs to be done to investigate the long-term durability and strength of CSEBs [27].
Another barrier for the mass implementation of CSEBs in Malawi is the volatile cement price. Rising fuel prices and high inflation have led to massive price hikes in the southern African country [31].
Moreover, cement production is very energy intensive one of the main contributors to anthropogenic climate change: Currently, it accounts for 8% of anthropogenic CO_2-emissions [32]. As the African continent is most affected by climate change, the question needs to be asked whether this is not yet another building material that will harm Malawi in the long run [33]. At least, as long as cement is imported, some of the direct environmental impacts of fired brick production could be alleviated.
Still, as fuelwood becomes more and more scarce in Malawi, and it is expected to become more expensive, Cement Stabilized Earth Blocks may be an interesting alternative.

1.3.2 Alternative Fuels

Sustainable Wood Sourcing

As we have seen, the use of brick clamp technology is very well suited to the local context in Malawi, with many of the negative aspects mostly being connected to the use of unsustainably sourced fuelwood. While the effectiveness and pitfalls of reforestation or sustainable wood sourcing programs would warrant another separate Thesis, it is worth taking a brief look at what makes them so difficult to establish.
In 1986, *World Development* called deforestation in Malawi an unsolvable problem, arguing that the low price of fuelwood from community grounds, compared to other cash crops, makes even subsidized governmental interventions ineffective. The author concluded that it may be more helpful to focus on combating the

adverse effects of deforestation, such as damage to agricultural lands, instead of deforestation itself [34]. So far, these predictions seem to have been correct: Although exact numbers are difficult to obtain, it is estimated that the forest cover in Malawi has more than halved in the past 50 years and policy interventions such as a ban on selling charcoal have failed [7].
Facing the reality that poor households especially will continue to rely on the use of woodfuel for their energy needs in the coming decades, viable alternatives to illegal logging are required. Practices such as agroforestry as a way to both reduce soil erosion, improve soil health and produce woodfuel as a byproduct have (re-)gained a lot of attention [35].
As we have seen, deforestation is not simply an environmental concern, but affects agricultural productivity and livelihoods of people as well.

Other Biomass Fuels Where available, alternative biomass fuels or agricultural waste materials like sawdust, crop residues, or animal dung could be utilized for the manufacturing of fired clay bricks. This would constitute an environmentally friendly alternative to unsustainably sourced woodfuel. However, there is a lack of statistical data regarding the availability of these alternative fuels and their current utilization within Malawi's brickmaking industry.

Coal

Coal is a frequently used fuel in the production of fired clay bricks. In the context of environmentally friendly fuels, coal is certainly not the first one that comes to mind, and it seems counter-intuitive to even consider it as a potential replacement for woodfuel. And for good reason: Evidence from India, where a majority of kilns are coal-fired, suggests that brick kilns are a major drivers of air pollution and greenhouse gas emissions. Therefore, they can have adverse effects on the local environment [20].
Despite its environmental drawbacks, coal has become one of the most widely used fuels worldwide due to its more advantageous properties. It has a high energy density, is easy to store, and relatively cheap. Moreover, employing coal instead of unsustainably sourced woodfuel for brick firing could alleviate pressure on Malawi's forest reserves.
Considering that Malawi possesses coal reserves that could be further exploited, there is a possibility of coal partially replacing woodfuel in the future. However, this prospect depends on factors such as availability and price [12]. Whether this is truly a desirable scenario is debatable for the reasons mentioned above. However, as opposed to unchecked deforestation, one could argue that it might be the lesser of two evils.

1.3.3 Types of Brick Kilns

Another, and perhaps obvious, approach is to switch to more efficient, and thus, more environmentally friendly kiln types to produce fired clay bricks.
Modern types of kilns such as the tunnel kiln or the Vertical Shaft Brick Kiln (VSBK) only need a fraction of the energy to produce bricks compared to clamp kilns. Economic analysis shows that there are also more efficient technologies that have a higher return on investment [3][36]. Many countries that originally formerly relied on artisanal brickmaking practices are in the process of adopting more efficient technologies. China and India especially invest a lot of resources to lower the air pollution caused by brick production [37].
To understand what advances have been made with regards to improving brick ovens, here is a brief overview on different kiln types and their working principle. Some of the most widely employed kiln types are visualized in Figure 1.4.

Intermittent and Continuous Kilns

Common fuels for brick firing include wood, coal, and natural gas. The kilns are often classified as one of two main types: intermittent or continuous kilns. In intermittent kilns, bricks are fired and cooled in batches. The process of drying, firing and cooling is restarted for each fresh batch of bricks and the escaping heat from the process is lost. Intermittent kilns are widespread in much of the Majority World, where a lot of the small- to medium-scale production makes use of the technology. Examples of intermittent kilns are clamp kilns
In a continuous kiln, the burning process is ongoing. There is less heat loss because the drying, heating and cooling processes can be combined for different batches. Flue gases from the firing process are used to preheat

or dry green bricks. Fresh bricks are added and the fired bricks are removed continuously. Large-scale brick production is usually done in continuous kilns[3].

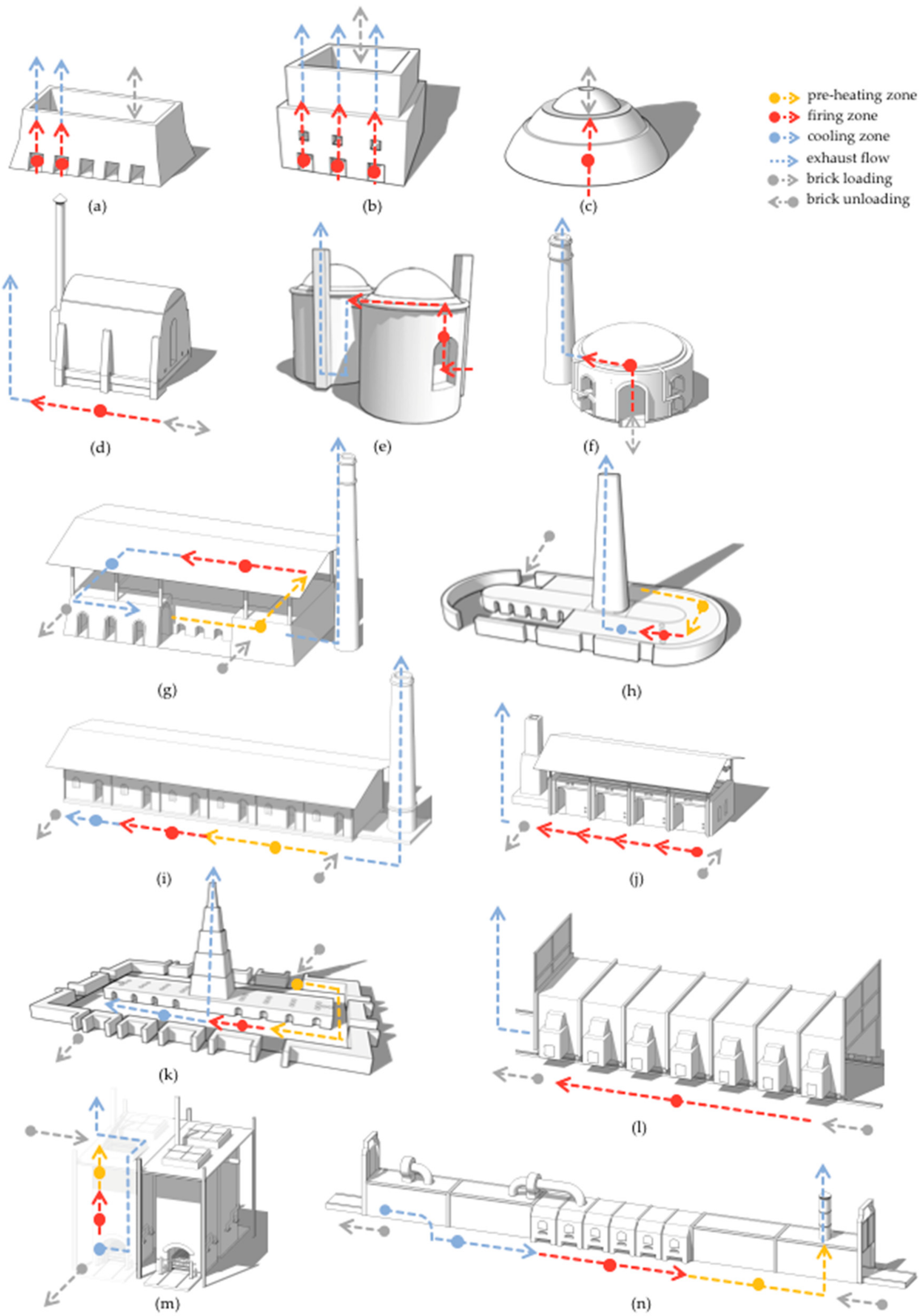

Figure 1.4: Schematics of different intermittent [i] and continuous [c] kilns: The arrows indicate the air flow direction. (a) Clamp [i], (b) Scotch [i], (c) open kiln without fixed walls [i], (d) down-draught [i], (e) Marquez Kiln, (f) dome [i], (g) Hoffman [c], (h) Bull's Trench [c], (i) Cedan[c], (j) multi-chambers [c], (k) Zig-Zag [c], (l) mobile-modular [c], (m) VSBK [c] and (n) tunnel [c]. [3]

Furthermore, the oven types can be distinguished by the way the air flow is directed. In some construction types, chimneys are used create a draught through the structure (e.g. Bull's Trench or Down-Draught Kiln), which improves combustion and creates a more even heat flow. Better control of the combustion process reduces the fuel demand and leads to less pollution [3].
Summing up, the main levers to reduce fuel demand in improved brick kilns are the prevention of heat losses through surfaces, waste heat recovery, and improved control of the combustion process.
With the application of these principles, the most efficient kiln types (e.g. the Vertical Shaft Brick Kiln (VSBK), the Tunnel Kiln, and the Zig-Zag Kiln), only require an energy input of 0.8-1.2 MJ to produce one kilogram of bricks. For comparison: Clamp kilns are estimated to consume 3.5-5 MJ/kg [38][11].
The main technologies that are used in Malawi are the Clamp, Vertical Shaft Brick Kiln (VSBK), Tunnel, and Bull Trench Kiln (BTK), with the Clamp constituting the largest share of production, especially in the informal sector [10].

Clamp Kilns

A brick clamp is an intermittent kiln, where a batch of dry green (unfired) bricks is stacked in multiple layers, with trenches at the bottom where the fuelwood is placed (Figure 1.2). The amount of trenches varies depending on the desired amount of bricks to be produced in the batch.
In clamps that are fired with coal, the layout can be different. Typically, there are coal layers at the bottom of the kiln, similar to the wood-fired clamp. Additionally, there can be fuel layers higher up in the structure, or the fuel is added in firing holes from the top of the oven. Coaldust is sometimes incorporated in the clay as well, where it works as an internal fuel.
The bricks are fired over a period of several days. Clamp kilns rely on natural air circulation and the stack's insulation properties for firing. The firing process is uncontrolled, and temperature variations can occur throughout the kiln. It is the most widely used kiln type in much of the Global South [39].
If the sides of the clamp are sealed with clay, this variation is referred to as a scove type clamp. A clamp with permanent walls for isolation is called a scotch oven. The brick production process in a scove oven in Chembe, Malawi, is documented in Figure 1.5 and Figure 1.6.

Figure 1.5: Construction of a Scove Clamp out of hand-moulded, dried bricks.

Figure 1.6: Burning of the stacked bricks using fuelwood.

1.4 Firing Clay Bricks

As shown in the previous section, there are many ways to produce fired clay bricks. Since the aim of this Thesis is to determine if there are ways to improve the brick quality and lower the fuel input of clamp ovens, it is important to define how the quality of a fired brick can be judged. For this, the different chemical processes that take place during the firing of clay bricks and their influence on the properties of the final product will be reviewed.

1.4.1 How Firing Temperatures Influence Brick Quality

Desirable properties that define a high quality brick are high mechanical strength, low thermal conductivity, and low water absorbtivity. How are these properties achieved?

Processes During the Firing of Clay Bricks

The exact composition of fired bricks made from clay soil can vary from site to site. But traditionally, ceramics are made from clay-based materials, with the initial components usually being a clay mineral (e.g. kaolinite, montmorillonite, or illite), fluxing agents such as feldspars, and filler materials (e.g. silicia, alumina, magnesia) [2].
When heating a clay substance, the following processes take place [2]:

- $100 - 200°C$: Loss of absorbed water
- $500 - 600°C$: Dehydroxylation of kaolinite and subsequent formation of metakaolin. Carbonaceous matter burns off.
- $573°C$: Quartz inversion temperature
- $300 - 900°C$: Oxidation processes
- $900 - 1200°C$: Sintering of clay particles, leading to a sharp increase in mechanical strength.
- Above $1200°C$: Risk of deformation

Optimal Firing Temperatures

The optimal firing temperature for clay bricks depends on the raw brick composition. Values found in literature range from $950 - 1050°C$ [2] or even higher at $1050 - 1200°C$ [40][41] with the minimum firing temperature usually placed at around $900°C$. This is when glassy phases start to occur and the sintering process that significantly increases the mechanical strength of clay bricks, starts [40][42]. There is a lot of research on the optimal firing temperatures for different clay compositions, which is important to know for industrial production using modern kiln types. In an industrialized context, the optimal firing temperature is the temperature at which the quality of the bricks produced meet the regulatory requirements. This type of research helps producers to use the least amount of fuel necessary (for both economic and environmental reasons) to produce bricks that fulfill the building requirements in their (industrialized) customer countries. In traditional oven types, such temperatures are often not achieved. What does that imply about the quality of bricks that are produced in in these ovens? And how might the requirements for brick quality in non-industrialized countries be different?

Low-Temperature Sintering of Clay Bricks: Sub-Optimal but Sufficient for some Applications

Monteiro *et al.* (2004) show that even at $600°C$ solid state diffusion mechanisms can occur and be sufficient to achieve the consolidation of unbonded clay particles into a more dense body. The authors were able to show that sintering mechanisms could theoretically take place at lower temperatures than what is usually accepted as the minimum. This is mainly due to the dehydroxylation of clay particles that turns the clay crystals into active sites for bonding consolidation [42]. A study conducted by Prasertsan and Theppaya (1995) shows that the mechanical strength of clay bricks that are fired between 600 and $900°C$ increases significantly with the increase of the firing temperatures. On the other hand, the authors state that $600°C$ were found to be sufficient to produce bricks that do not dissolve in water [43].
Arguably, the mechanical strength of bricks that are used for low-rise buildings in rural areas of non-industrialized countries such as Malawi does not need to reach the same level as bricks that will be used to build multi-story houses. On the other hand, properly fired bricks being weather-proof is one of the main advantages they hold over sun-dried, unfired clay bricks which are also often used as a building material in Malawi. If they are not weatherproof, they are not durable and thus not worth the investment.
Therefore, bricks that have been fired at $600°C$ will be classified as sufficiently fired (Grade 2) in the analyses made in this Thesis. Bricks that reach temperatures between $900 - 1200°C$ will be labelled as good quality (Grade 1). The minimum soaking temperature will be set as two hours, based on work by García Ten (2010) that demonstrated that longer soaking durations do not necessarily contribute to better mechanical properties [44]. "Soaking temperature" refers to the highest temperature reached during brick firing, while "soaking duration" refers to the period of time for which these temperatures are maintained. Bricks that do not fulfill these requirements are classified as insufficiently fired (Grade 3). The quality labels are summarized in Table 1.1.

Soaking Temperature	Quality Label
$900 - 1200°C$	Grade 1
$600 - 900°C$	Grade 2
$< 600°C$ and $> 1200°C$	Grade 3

Table 1.1: Brick quality labels depending on firing temperature.

1.5 Aims of this Thesis

Acknowledging that there are many potential ways for Malawi to improve the sustainability of its building sector, it is also evident that there is no obvious solution to the many challenges the country faces in that regard. Therefore, this Thesis will focus on the optimization potential of traditional brickmaking methods.

1.5.1 Efficiency of Clamp Kilns: A Literature Review

There is little quantitative research on improving the energetic efficiency of traditional brick production methods such as the clamp or scove kiln. There are only a few works where clamp kiln technology is the main focus. Research involving traditional brickmaking methods often focuses on the environmental impacts connected to their use [20][3][37][45][17][46], or on ways to replace them (see e.g. [1][5][43][47][48]).
Rodriguez-Emmenegger *et al.* (2007) evaluated the quality of bricks fired in a clamp (batch size: 30'000 bricks) in Uruguay based on temperature measurements and a derived heat model. The raw bricks contained sawdust, which served as the main fuel in the firing process. To start the ignition of the sawdust, a woodfire was lit under the lowest brick layer, similar to the process described in Section 1.3.3. The authors conclude

that this method is able to produce high-quality bricks with temperatures around $1000°C$ achieved in most layers. The energy efficiency of the process is not discussed [49].
Akinshipe and Kornelius (2018) constructed a test clamp to be able to measure the atmospheric emissions of coal fired clamp kilns under different kiln combustion conditions in South Africa [38]. They found that within the 13 analyzed firing cycles the energy required in the most efficient batch was 36% lower than in the most energy-intense batch. Energy intensity was not the focus of their research, and the only suggestion they make is to ensure that the bricks are properly dried before firing to reduce the required energy.
Research on the embodied energy of fired clay bricks in Tanzania and Uganda states that due to the high heat loss through the cooling surface, small brick clamps are 60% more energy intensive than larger kilns [11], although the authors base that estimation solely on the surface to volume ratios of different kiln geometries, a World Bank report from 1989 [50], and an estimation for the embodied energy of "Simple Clay Products" from The Inventory of Carbon and Energy by the University of Bath.
The World Bank estimates that for one tonne of bricks, $0.5\,m^3$ of woodfuel is needed. To improve the energy efficiency of artisan brick production, they propose a number of measures: Reducing energy losses through waste gases by better controlling the air inflow, constructing square clamp bases, splitting firewood to better control the amount supplied, and incorporate inspection holes in the clamp structure to monitor the firing progress. The authors estimate that with a combination of these measures, energy savings of up to 35% are possible. The same report states that in small-scale artisan kilns, up to 45% of the bricks are of subpar quality. The quality is judged by the brick color and whether or not the bricks crack during the firing process or transport [50]. No follow-up reports on testing the suggested measures on real kilns could be found.

1.5.2 Scope and Methods

Concluding, there is a distinct lack of tangible data and numbers when it comes to traditional brickmaking technologies. This is an all-too-common occurrence when it comes to research on technologies that concern financially weak world regions. Yet, despite being an uninteresting technology from a financial perspective, clamp kilns are still widely used, and can be expected to stay around for years to come for reasons that were discussed in the previous sections. Therefore, we aim to contribute towards filling some of these gaps in this Master Thesis. In the end, we hope to answer the question: Can the use of brick clamps be energetically optimized, and what could be ways to achieve that?
In the hopes of contributing to a better understanding of the firing process and the quality achieved in brick clamps, an experimental setup was designed to measure the temperature distribution over one firing period at different points of a small-scale clamp with a batch size of 5000 bricks. The experiment was carried out at a brickmaking site in Chembe, Malawi, and the data from 15 measuring points were successfully collected.
Based on a literature research, three labels for brick quality depending on firing temperature and duration were defined. The temperature measurements were used to draw conclusions on the efficiency of the firing process and resulting suggestions for design changes.
Consecutively, these insights were used to test the effect of these design changes in a heat flow simulation. The temperature measurements were used as a baseline to test the accuracy of the heat model.

1.5.3 Limitations

The brick manufacturing process using clamp technology can vary greatly depending on the country, the number of bricks produced, fuel involved, or even between firing cycles. Therefore, it is important to keep in mind that the results of the experiment that was carried out in the scope of this Thesis are only valid for this specific type and size of oven and described methods. Nonetheless, a similar setup could be used to repeat the described experiment on other kilns.

Chapter 2

Methodology

2.1 Data Collecion

The data collection took place in Chembe, Malawi. Chembe is a village located in the vicinity of Lake Malawi National Park, known for its picturesque location between mountains, which makes it a popular tourist spot. Owing to its economic prosperity, the village has experienced a surge in population in recent decades. The expanding population requires more housing, and as in other parts of the country, many houses in Chembe are made with wood-fired bricks.

However, the village's growth and prosperity have had some negative impacts, as evidenced by the increasingly barren hills around it. Deforestation has reached an extent where it is perceived as an issue by the local population. They have to cover increasingly long distances to collect woodfuel and they notice increased temperatures in the village for a lack of shade.

2.1.1 Description and Aims of the Planned Experiment

An experimental setup was designed to collect data on the temperature distribution over time of the bricks within a clamp kiln in Chembe. The goal was to be able to use this data to gain insights towards the optimization potential of brick clamps. Based on research on the required temperatures to fire clay bricks as a basis (see Chapter 1), the measurements allow one to quantify the brick quality in different locations within the clamp.

Furthermore, the data will serve as a baseline to create a model that captures the relevant dynamics of a brick clamp and can be used to test alternative clamp layouts. Eventually, the aim is to be able to evaluate whether there is room for improvement in the layout of traditional brick clamps that would reduce the amount of fuelwood used.

2.1.2 Sensor Choice

Requirements

In order to choose the necessary equipment to measure the temperature distribution in a clamp kiln, the requirements for the setup were defined. The requirements were based on a literature research on the firing process in clamps and a preliminary visit to the brickmaking site in Chembe.

During the preliminary visit, local guide Harry Dickson and brickmaking company owner Goodwin Chasimpha shared their knowledge of the brickmaking process in clamps and enabled us to observe the various steps involved at different sites. It became evident that data collection would be challenging due to the site's location. Typically, brickmaking sites are located at a distance from settlements, making it impossible to protect equipment from dust and rain, or secure it overnight. Additionally, there is no access to electricity.

Furthermore, it was noted that the measuring system should not obstruct the brickmakers' access to the firing chambers when adding wood, as this could affect the firing process and create a risk of damaging the equipment.

Moreover, the tightly-stacked bricks for structural stability mean that any equipment placed inside the clamp may be subjected to mechanical stress and should therefore be robust.

All kiln surfaces are very hot during the firing process and cannot be touched to remove or adjust sensors in that time.
Based these learnings, the following requirements for the choice of equipment were defined:

- Temperature range: The sensor should be able to detect the expected minimum and maximum temperatures of 0 - 1100°C.
- Measuring period and frequency: Multiple measurements should be taken over the full firing process, which lasts up to 4 days. A frequency of 1 measurement per hour was defined as the minimum because of the long firing duration and slow dynamics of the heat transfer within the oven.
- Sensor placement: The sensors have to detect temperatures within the clamp, between bricks, as well as outside. Eight interesting measuring points near the burning chambers, in the center, and towards the outside of the clamp have been identified for one cross section (see picture). We wanted to measure two such cross sections to be able to compare them. The maximum distance of a measuring point to the kiln surface was estimated at 1.5 m.
- Robustness: The sensors have to be able to withstand difficult environments with exposure to dust, hot gas, potentially even open flames and rain. A minimum protection standard of IP65 is thus required.
- Failure risk: Halting the process for troubleshooting would not be possible, since once the firing has started, there is no way to intervene without altering the outcome. Therefore, risk of sensor failure should be minimized.
- Cost: The total cost for the measuring concept should not exceed CHF 20'000.

Considered types of thermal sensors

Thermocouples Thermocouples are temperature measuring devices which are based on thermoelectrical effects in metals. They usually consist of a measurement probe containing two different metals which are connected in the front, but disconnected in the back. The different electrical conductivity of the metals, when exposed to heat, generates a voltage at the back end of the probe. This voltage allows to reconstruct the temperature at the front end [51].
While there are thermocouples that are suitable for the specified temperature range, other requirements are harder to fulfill with such sensors. A major concern is measuring at the maximum depth of 1.5 m: Even high heat cables only tolerate temperatures of up to 400°C, which means that a long measuring probe is required. The probe would then be lodged between bricks, which poses a risk of stress-induced damage. Standard thermocouples have a probe length of 100-150 mm, but a few producers could be found that offer thermocouples with probes of length 1.5 m and more: Endress+Hauser with their TAF-Series and RS Pro with their flexible steel probe thermocouples.

Figure 2.1: RS Pro Thermocouple Type K [52]

Figure 2.2: Process Temperature Control Rings (PCTR)

Thermal Cameras Thermal cameras are able to measure the surface temperature of objects using the infrared light spectrum [53]. Therefore, they could be used to measure the temperatures inside the trenches of the clamp as well as on the outer surface. While we are primarily interested in the temperature distribution within the kiln, this could be an interesting addition, since even a low-resolution thermal camera produces many times more measuring points than would be possible with other sensors. This could give a more detailed view on the evenness of temperature distribution.
Thermal cameras for high heat processes and difficult environments are expensive: The considered models FOTRIC 346A, FLIR E86-42 and Fluke RSE 300 cost between CHF 5'500 and CHF 17'660.
A visit to a brickmaking site in Chembe, Malawi further revealed that many surfaces of interest are not visible during the firing process. The sides of the clamp are coated with mud during the firing to retain heat, leaving little indication for the brick temperature underneath. The fireholes are closed with fired bricks for hours at a time to minimize heat losses, control the burning rate and induce upwards draft of hot gases through the clamp. This means that during that time, the trenches are not visible to the thermal camera.
For this reason it was concluded that the benefits of having a thermal camera on site do not justify the high acquisition cost.

Process Temperature Control Rings (PTCR) Another approach to measure temperature is based on the deformation of a material when exposed to heat. A cheap and easy way to determine whether a certain process temperature has been reached in ceramic ovens is the use of pyrometric cones. They start to tilt when their deformation temperature is reached [54]. But a more precise tool to control the evenness of the temperature distribution within an appliance are Process Temperature Control Rings (PTCR) (see Figure 2.2). These ceramic rings shrink when exposed to heat, which allows to reconstruct a so-called "ring-temperature" when measuring the rings afterwards [55].
The main advantage of PCTR is the robustness and low risk of failure that comes from their simple design. The cost is low as well, with rings available for CHF 1-2. One ring gives one point measurement for the time that the ring was placed inside the clamp, therefore, they would need to be replaced regularly over the course of the firing process. This could be achieved by connecting multiple rings to a wire, which is then pulled through the clamp in intervals at the designated measurement points over the required duration.
One major downside of PCTR is that the ring temperature does not directly equal the process temperature, but is rather a measure of the absorbed heat, with the primary use of PTCR being process control and not temperature measurement. The ring temperatures allow one to compare different positions within one oven and over multiple heating processes. Therefore, using the measurements to construct a heat profile would give us valuable information about the temperature distribution over time in the clamp, but it would be difficult to use the measurements as inputs to our heat model.

Comparison and final sensor choice

After investigating and comparing different sensor types and models, it became clear that in terms of useful data, thermocouples are the best choice. The RS Pro thermocouples (Figure 2.1) with the flexible measurement probes, continuous measurements and low price were identified as the most suitable option. The three options are compared in Table 2.1. The price was calculated for the complete setup. For thermocouples, this includes cables and data loggers, while for the PCTR it is based on the amount of rings needed for the required resolution.

Table 2.1: Strengths and weaknesses of three different sensor types

Criterium	Thermocouple	Thermal Camera	PCTR
T_{max}	✓	✓	✓
Robustness	medium	medium	high
Placement	✓	no full coverage	✓
Failure risk	medium	low	low
Resolution	high	high	low
Price (setup)	from CHF 4860	from CHF 5500	from CHF 2400

If the risk of sensor failure is to be minimized, PCTR might be an option. Through their simple design, they are robust towards external disturbances such as rain, dust, or hot gases. They also do not require additional components that add complexity, for example by needing electricity. If the relative temperatures of different points within the kiln are sufficient, and no exact temperature measurement is required, PCTR are a suitable alternative to thermocouples.

2.1.3 Measuring Concept

The selected measuring concept consists of the following components:

- 16 RS Pro thermocouples Type K with the following lengths: 2 m (6x), 1 m (4x), and 0.5 m (6x).
- 4 RS PRO 1384, 1361C 4-Channel data loggers to store temperature measurements [56].
- 16 K-type plugs and cables with a length of 5 m to connect the sensors to the data loggers at the side of the clamp [57].

The sensors should mainly be installed pointing vertically downwards so that the sensor heads and cables do not interfere with the refueling of the clamp. With cables of suitable length, the data loggers can be placed next to the structure. A visualization can be seen in Figure 2.3, where one of the three cross-sections to be measured is shown. One cross-section should be close to the front of the kiln, and one in the kiln center.

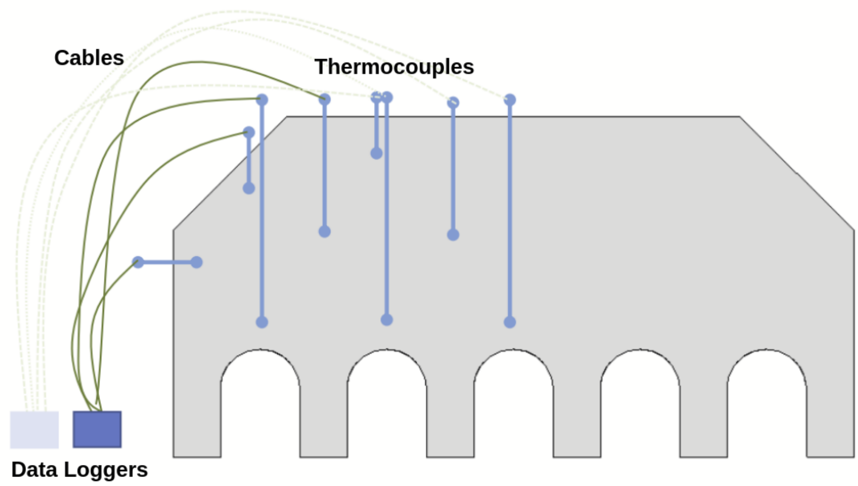

Figure 2.3: Planned placement of sensors, cables and data loggers for one measured cross-section.

2.2 Data Collection in Chembe, Malawi

2.2.1 Preparation

After designing the experimental setup and ordering the components, the data collection was planned. Malawian research associate Jonathan Kwangulero, who would accompany and support me for the duration of the experiment, facilitated the planning of the experiment by contacting Mr. Dickson and Mr. Chasimpha in Chembe. Arrangements had to be made in advance to plan the production of unfired bricks and firewood collection prior to our arrival. It was agreed with Mr. Dickson, who had planned to buy clay bricks for the construction of a water tower on his farm, to use his batch of bricks to build our experimental oven.
Mr. Dickson was hired as a local coordinator. He hired three experienced local brickmakers who started with the production of sun-dried bricks a few days before the arrival of Mr. Kwangulero and me to ensure that the experiment could be conducted in a timely manner. Furthermore, he had the firewood delivered on-site and assisted in the supervision of the brickmaking, clamp construction, and firing.

2.2.2 Conducting the Experiment

Kiln Construction

A kiln was built out of 5000 sun-dried bricks, which is a fairly standard size according to the brickmakers. A clamp for this amount of bricks typically has five burning chambers. Three brickmakers were hired to produce the bricks and construct the clamp over a period of seven days. The brickmaking site was situated 30 minutes outside the village, on a field owned by Mr. Dickson.
The experiment was conducted at the beginning of November, which is towards the end of the Malawian hot season. The daily temperatures reach over 35 degrees, and the site had very little protection from the sun, except for a large bush in the proximity. As the brick production and kiln construction require intense physical labor, we were usually on site from 5am to make use of the cool morning air.
To produce the raw clay bricks, the clay is mixed with water and is then hand-applied into a mould (Figure 2.4). The raw bricks are then left to dry in the sun for several days. Straw may be used as a cover to prevent the bricks from cracking.

Figure 2.4: Moulding and drying of raw bricks.

Sensor Placement and Installation

Sensors After the bricks were sufficiently dried, the clamp could be constructed. One half of the kiln was equipped with thermal sensors to track the temperature development over one firing cycle. The sensors had to be built in during the construction of the clamp as the bricks are stacked very tightly, leaving no room to insert the sensors at a later stage (Figure 2.5). Mr Kwangulero, who translated my instructions to the brickmakers, and I were on site to install the sensors and help build the oven. The exit point of the sensor probes were marked with tape to document the exact insertion depth.

Figure 2.5: Building the oven and installing the temperature sensors.

Cabling Next, the cabling was installed, with each cable being labelled with a number. The thermocouple probes were long enough to protrude at least 30 cm from the top of the clamp. Due to that, the sensor heads could be used to lead the cables over the top of the oven without contacting it directly. The cables were not allowed to touch the clamp surface during the firing process because of the high temperatures. To ensure there was no contact to the sides of the clamp, the cables were guided down to the ground with an improvised structure made from branches.

Data Loggers The data loggers were placed in a safe distance from the oven and protected against dust and rain using plastic bags. During the day, they were covered with a bucket to protect them from the sun. These steps are shown in Figure 2.6.

Data Collection and Monitoring

Finally, the firing process began and data was collected continuously over a period of 72 hours. The equipment was monitored and the data was saved periodically during that time in case that issues should arrive.
The brickmakers agreed to stay on site and guard the equipment at night. After successful completion of the experiment, the clamp had to be disassembled to remove the sensors (Figure 2.7).

Expenses

Table 2.2 gives an overview of the different expenses that were made in the successful conduction of the experiment. The transport of fuelwood was the largest single expense. One big reason for this is that the seven tonnes of wood we bought had to be transported in from outside of the village using a truck. Due to a drastic fuel shortage, the fuel for the truck cost around 3500 MKW/liter. For comparison: 1000 MKW (Malawi Kwacha), corresponded to approximately 1 CHF.

Table 2.2: Expenses for the brickmaking experiment

Description	Cost [MKW]
Manufacturing of 5000 sundried bricks	50'000
Clamp construction	25'000
Wood	65'000
Wood transport	100'000
Sale of leftover wood	-30'000
Food for brickmakers	80'000
Nightguards	40'000
Local coordinator	40'000
Total	370'000

Figure 2.6: Cabling and data loggers during the firing process.

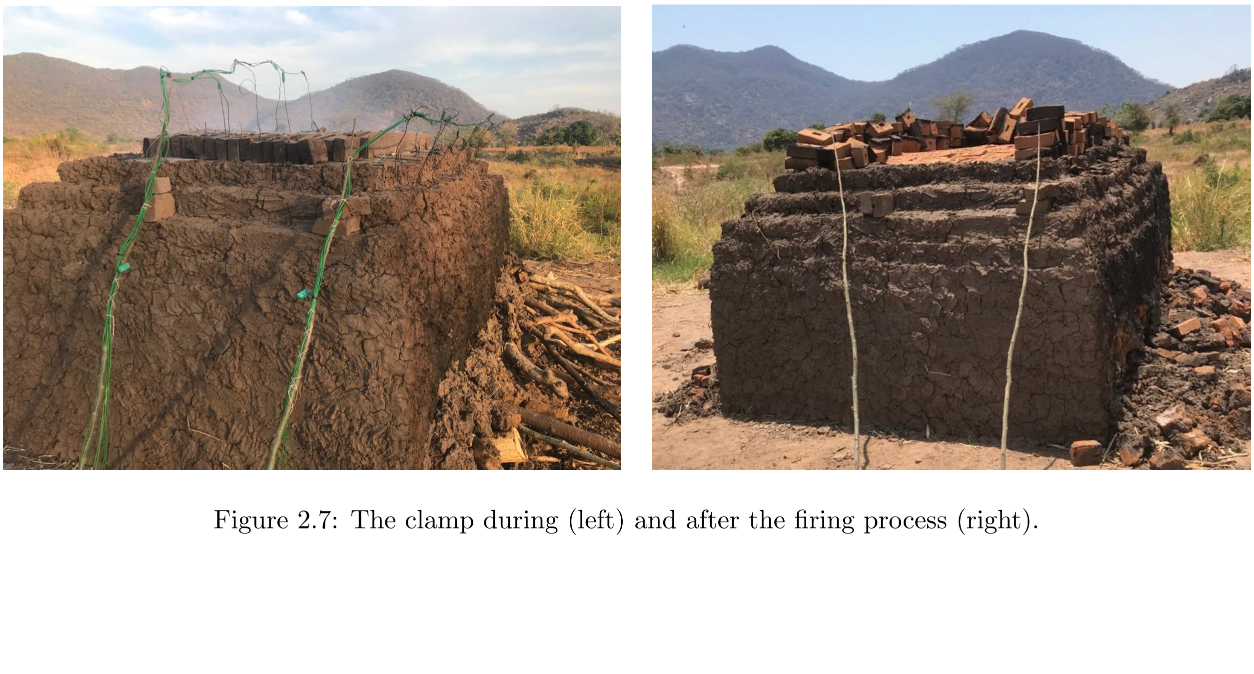

Figure 2.7: The clamp during (left) and after the firing process (right).

2.3 Heat Flow Simulation in a Brick Clamp

Most research on modelling heat flows in brick kilns is focused on optimizing modern oven types such as tunnel kilns. The only example of an approach on modelling the thermal behaviour of clamp kilns that was found in literature is a study conducted by Rodriguez-Emmenegger *et al.* in 2007 [49]. The authors took temperature measurements at two layers in a clamp kiln consisting of 30'000 bricks in Uruguay. The bricks contained sawdust as internal fuel, with the woodfire only serving to start the ignition of the sawdust. After the lowest layers ignite, the firing process proceeds on its own: A "heat front" travels upwards, and the hot bricks ignite the sawdust in the layers above. No further addition of fuelwood is necessary [49].
For the development of their thermal model, the researchers assume that the thermal behaviour is dominated by conduction and the combustion of the internal fuel. Temperature measurements that were taken on the surface and in the center of single bricks in an electric furnace were used to determine the thermal diffusivity of the bricks. The resulting heat model was found to replicate the temperature measurements that were taken within the clamp very well [49].
Because of the differences in the firing method and clamp size, as well as due to the presence of internal fuel, this approach cannot be applied directly to model the oven we measured in Chembe.
Therefore, a model was developed based on basic thermodynamic considerations, which will be detailed in the following sections.
The developed simulation will then be used to test the influence of different kiln geometries on the quality of bricks produced and the required fuel input.

2.3.1 CAD-Reconstruction

A CAD-Model of the brick clamp was created using Siemens NX. It is based on the dimensions of the test clamp where the temperature measurements were taken (Figure 2.8)
A single brick has the dimensions 17.5 cm x 10 cm x 6 cm. The bricks are tightly stacked in a total of 9 layers above the clamp base. The slight air gaps between the bricks were neglected in the CAD model, because it would add a lot of complexity in the heat flow calculations.
The model of the clamp has a maximum width, length, and height of 4 m x 2.5 m x 1.8 m. The layouts of the upper four layers of bricks decrease in size.

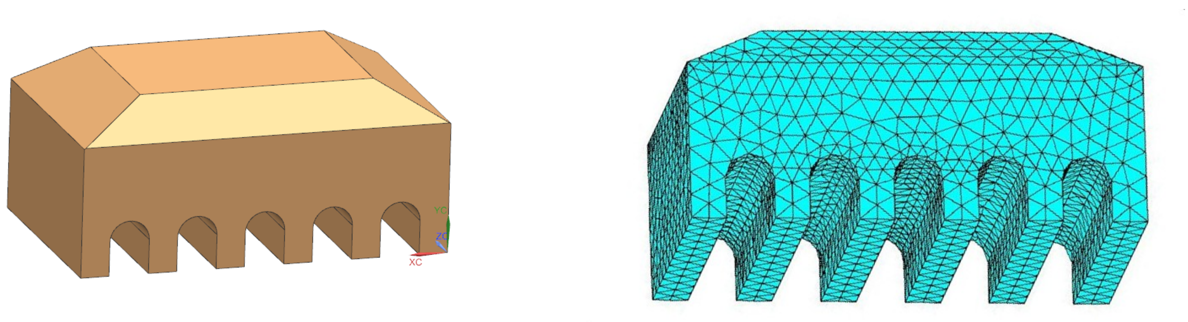

Figure 2.8: CAD-Model and mesh of the oven.

2.3.2 Heat Model and Boundary Conditions

A heat model was developed using the MATLAB Partial Differential Equation Toolbox. This toolbox allows the user to import geometries, apply boundary conditions and solve the heat transfer equations.
The kiln geometry was taken from the CAD model and could be input into the program in STL format. A mesh was created from the geometry (Figure 2.8) and the heat flows were calculated using the Final Element Method (FEM).
The thermal boundary conditions that were applied to the oven are detailed in the following sections. An overview is shown in Figure 2.9.

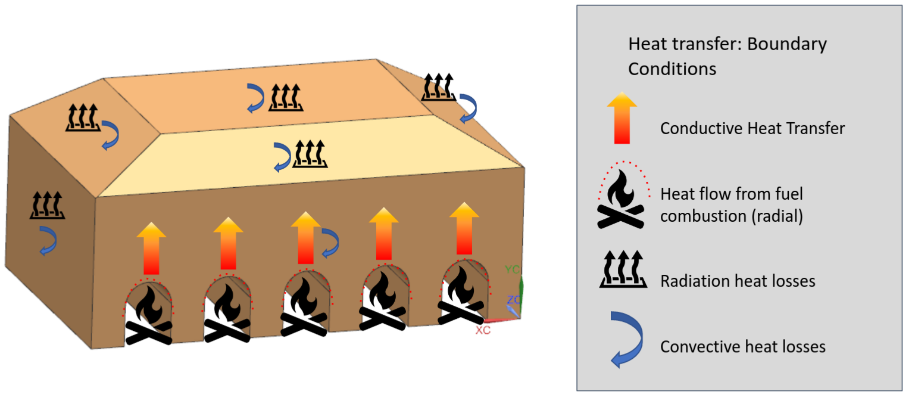

Figure 2.9: The CAD-Model with the applied boundary conditions.

Heat Flux from Fuel Combustion

During the combustion of wood, heat is released due to the changes in chemical composition. Furthermore, a mass flow of hot combustion gases enters the stack of brick from the burning chambers and transfers heat. The assumptions that were made to approximate these processes are detailed in the following sections.

Fuel demand and energy content The specific energy demand for wood-fired clamps can be estimated using the weight and energy content of the fuelwood. The wood that was used for our test clamp stemmed from Eucalyptus tree which has a lower heating value (LHV) of $19.2\frac{MJ}{kg}$ [58].
Different sources estimate the energy demand of clamp kilns between 3.5-5 MJ per kg of bricks produced [3][47][59], corresponding to between 175 g and 250 g of fuelwood per kg of brick.
In our test kiln, we produced approximately 17.5 tonnes of brick using 4 tonnes of fuelwood. This results in 229 g of wood with an energy content of 4.4 MJ for 1 kg of brick, which is in line with the values found in literature.
Not all of the released heat will be used to burn the bricks, as there will be energy lost through escaping flue gases as well as radiation. Furthermore, the combustion may be incomplete.

Wood combustion dynamics The main reactions that take place during wood combustion are drying, pyrolysis, char gasification, and combustion of volatile gases, tar and gasified char.
Wood combustion modeling is very complex, as there are hundreds of reactions that take place in the process of burning wood, the most important of which are shown in Figure 2.10.
According to Nussbaumer (2003), the combustion of biomass can be simplified to:

$$CH_{1.44}O_{0.66} + \lambda \cdot 1.03\mathrm{O_2} + 3.76\,\mathrm{N_2} \longrightarrow \mathrm{CO_2} + 0.72\,\mathrm{H_2O} + (\lambda - 1)\,\mathrm{O_2} + \lambda \cdot 3.87\,\mathrm{N_2} - 439kJ/kmol$$

with simultaneous creation of intermediates $(\mathrm{C}, \mathrm{CO}, \mathrm{H_2}, \mathrm{CO_2}$, etc.) [61].
However, modeling these parameters is extremely challenging, since there can be a lot of variation in the firing conditions for each batch of bricks. To be able to model the heat release rate, the adiabatic flame temperature, and the creation of combustion products during the combustion of wood, it is key to know the excess air ratio λ [61].
However, the air flow into the firing chambers is uncontrolled: At times, the chambers are open to allow for an inflow of fresh air, and then they may be closed using old, broken bricks. If the wind is too strong, only one side might be open. At times, the openings are open, but obstructed by fuelwood.
What about the mass flow of the fuel? At the beginning of the firing process, the brickmakers completely fill the fueling chambers with wood and start the fire. When the firing progresses, more wood is added. The

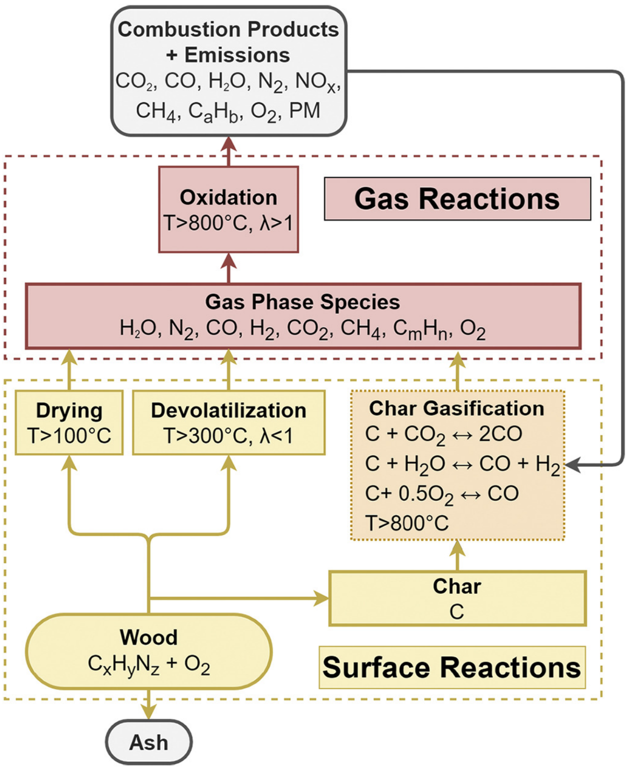

Figure 2.10: Wood combustion: an overview [60].

fuel is not weighed, and the brickmakers do not have access to scales. The mass of fuelwood that is burning at a given time is therefore difficult to predict.
With the amount of uncertainty for both air flow and fuel input over time, and due to the complexity of the wood combustion process, some simplifications had to be made in order to obtain meaningful results in the scope of this Thesis. For this, we will make use of the temperature measurements that were collected in the experiment described in Section 2.1.
As a simplification, we are going to relate the heat release rate to the temperature measurements of the sensors that were placed closest to the burning chambers in the center of the oven.

Heat release rate model Assuming that the heat release rate is proportional to the temperatures in the burning chambers:

$$\dot{Q} \sim T_{fire} \tag{2.1}$$

and that the temperatures in the burning chamber are similar to the measured temperatures one brick layer above:

$$T_{fire} \approx T_{brick,lowlayer} \tag{2.2}$$

We arrive at the following approximation for the heat flow into the walls of the burning chambers:

$$\frac{\dot{Q}(t)}{\cdot A} = \frac{1}{c} \cdot T(t)_{fire} \tag{2.3}$$

With c being a scaling factor that is to be determined using the energy content of the fuel Q_{tot} and the temperature measurements as a basis.
For a discrete-time simulation with 100 time steps, we derive the following relation for the heat flux into the burning chamber walls with area A_{wall}:

$$\frac{\Delta Q_i}{\Delta t \cdot A_{wall}} = \frac{c \cdot Q_{tot} \cdot \Delta T_i}{\Delta t \cdot A_{wall} \cdot \sum_{i=0}^{100} \Delta T_i} \tag{2.4}$$

In our model, the heat flow that enters the kiln from the burning chambers is proportional to the heat release rate. In reality, a part of the heat flow that enters the structure stems from convective heat transfer from combustion gases in the burning chambers, while a part is radiated heat from the fire.

Conductive heat transfer through the kiln structure

The heat flow that enters the walls of the burning chambers heats up the bricks above and is passed on to higher brick layers via conductive heat transfer.
Conductive, transient heat transfer takes place within a material based on molecular interaction according to the following law [62]:

$$\frac{\partial T}{\partial t} = \frac{k}{\rho \cdot c_p} \cdot \nabla^2 T + \frac{\dot{q}_0}{\rho \cdot c_p} \tag{2.5}$$

The time shift between the peak temperatures in the lower layer and the upper layer gives us an indication on the value of k, the heat transfer coefficient. The higher the value of k, the faster the heat flow spreads to the upper layers of the clamp, and thus the smaller the temporal spacing between peak temperatures.

Convective Heat Transfer

In the modelled brick clamp, convective heat transfer takes place between the outside air and the outer surfaces of the clamp. Heat exchange between a fluid and the surface of a solid body can be expressed as follows [63]:

$$\frac{\dot{Q}}{A} = \alpha_k \cdot (T_B - T_\infty) \tag{2.6}$$

with α_k being the convective heat transfer coefficient, and $T_B - T_\infty$ being the temperature difference between body and fluid.
For the heat transfer on the outer surfaces of the clamp, a constant heat transfer coefficient $\alpha_{k,air}$ of 15 $\frac{W}{m^2 \cdot K}$ was assumed [64].
In reality, convective heat transfer also takes place between hot combustion gases gases and inner brick surfaces (Figure 2.11. Modelling the heat transfer from passing hot combustion gases to the bricks, however, is more challenging than modelling the surface heat losses: the above relation is not valid because the fluid temperature is not constant. Nonetheless, the resulting dynamics can be included based on qualitative considerations.
The flow of passing combustion gases transports heat from the burning chambers towards the upper surface of the kiln. The larger the temperature difference between gas and bricks, the more energy is transferred (Equation (2.6)). As the mass of bricks within the clamp is much larger than the mass of combustion gases generated, this means that the combustion gases gradually cool down while streaming past bricks.
At the beginning of the combustion process, the most energy will be passed to the yet-cool bricks in the lower layers with bricks higher up not taking up much heat. When the heat spreads upwards, the passing gases are able to transfer more heat to higher layers.
This effectively means that the streaming gases accelerate the upwards heat flow as opposed to a pure conductive heat transfer. In the developed heat model, this will be approximated as an increased heat conduction rate k.

Radiation Heat Losses

Bodies radiate heat over their surfaces, depending on their temperature and material properties. The corresponding heat flow can be calculated as follows [65]:

$$\frac{\dot{Q}_\epsilon}{A} = -\epsilon\,(T) \cdot \sigma_S \cdot T^4 \tag{2.7}$$

with ϵ being the material-dependent emissivity and $sigma_S \cdot$ the Stefan-Boltzmann constant. For this analysis with red clay brick, the emissivity is set to $0.902 \frac{W}{m^2 \cdot K}$ [66]. With the high temperatures that are reached in a brick oven, radiation heat transfer may be a significant cause of heat losses to the environment. For that reason, it was included as a boundary condition on the outer surfaces of the kiln (Figure 2.9).
Furthermore, as the tightly packed kiln could be viewed as a porous body, radiation heat transfer between brick surfaces may influence the thermal conductivity. At high temperatures, radiation heat transfer could thus increase the heat transfer coefficient in the oven [67]. This was neglected for the scope of this Thesis, but could be investigated in future work.

Figure 2.11: Hot flue gases accelerate the transport of heat from the burning chambers to the top surface.

Heat loss at trench openings

The heat loss through the clamp openings was approximated by linearly decreasing the heat flow into the clamp towards the openings, starting from a distance of 50 cm from the trench openings. The length of our test oven was 2.5 m.

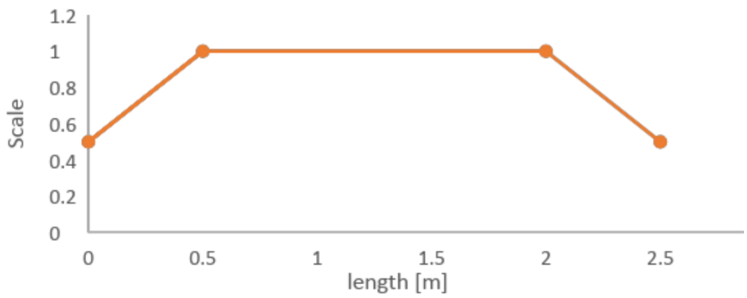

Figure 2.12: Heat flow scaling depending on location within the burning chamber.

Model Parameters

Parameter tuning Due to the uncertainties that were described and the approximations that were made for the model, some of the parameters of this model will be tuned using the measured temperature values as a baseline. Table 2.3 shows the parameters that can be adapted to better replicate the measured values.

Table 2.3: Parameters to be optimized in the model

Symbol	unit	Property	Influence
k	$\frac{W}{mK}$	Conductivity	Amplitude and temporal spacing of peak temperatures
α	$\frac{W}{m^2K}$	Heat transfer coefficient	Heat loss over clamp surface
c	-	Scaling factor	Scales heat flow, peak temperatures, efficiency

Thermal properties The thermal conductivity and heat capacity of the green bricks were taken from literature on thermal properties of dried clay bricks [64][48][68][69]. The consulted sources gave a range

of values for both properties, depending on the respective clay samples. Furthermore, Kočí *et al.* (2020) state that the specific heat of clay can strongly depend on the chemical composition and the temperature-dependent chemical processes that take place during the firing of brick [69].
Therefore, without testing a clay sample from one specific location, the values can only be approximated. The thermal conductivity k of brick is assumed to be $0.8\frac{W}{m \cdot K}$ and the heat capacity c_p simplified as a constant $900\frac{J}{Kg \cdot K}$, both in the range of values obtained from literature. These values will be used as a starting point for the parameter tuning.

2.3.3 Limitations of the Model

The developed model was based on an energy balance of the oven and the three basic modes of heat transfer. Some approximations were made that impact its accuracy.

Constant properties Over the course of the firing process, the temperature, water content and chemical properties change. This influences the properties of the clay, which are assumed to be constant in this model. Furthermore, endo- and exothermic processes due to the temperature-dependent chemical reactions in the clay and the influence on the heat transfer were excluded in the scope of this Thesis.

Lack of standardization There is no standardized way to produce clay bricks in clamps. Clamps vary highly in size, the brick composition is different from site to site, and even within the same clamp, it can happen that the trenches are not equally fired, leading to quality differences. Also, different brickmakers may make alternations to the process. The described simulation is therefore only an approximation of one specific case. Still, we expect that the basic process is the same for most cases and that we can still draw meaningful conclusions from our work.

Fluid dynamics and heat transfer To better capture the effect of hot flue gases on heat transfer, the model could be refined using Computational Fluid Dynamics. Our approximation that the flue gases accelerate the heat transfer upwards is reasonable when the kiln is heating up. When the fire has burned down, however, this is no longer the case and the model will likely underestimate the time it takes for the oven to cool down.
To examine the quality of the bricks produced, accurate modeling of the peak temperatures depending on the location in the clamp is key, which we hope to achieve with this approximation.

Chapter 3

Results and Discussion

3.1 Temperature measurements

The results of the 15 successful temperature measurements are displayed in Figure 3.2, while Figure 3.1 shows the location of the sensors within the structure. In the following sections, we will analyze the different measuring points and discuss what can be learned from the data.

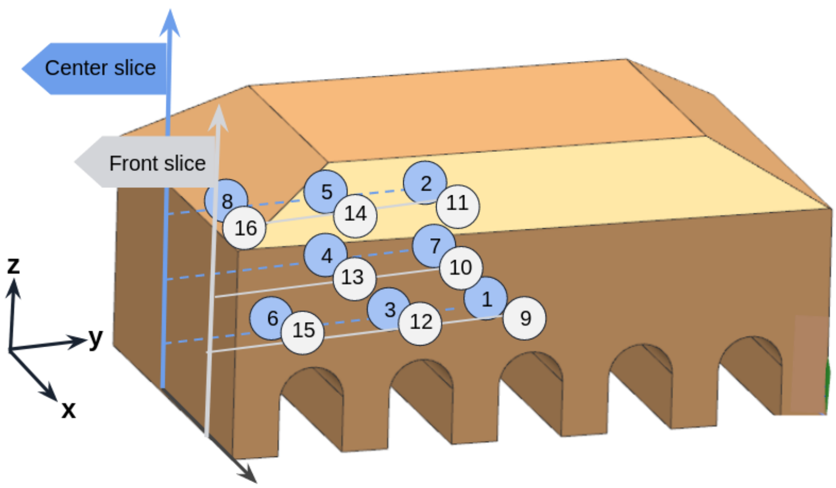

Figure 3.1: The location of the 16 temperature sensors within the clamp.

Sensors (center)	(x, y, z) [cm]	Sensors (front)	(x, y, z) [cm]
1	(125, 200, 70)	9	(238, 200, 70)
2	(125, 163, 164)	10	(238, 163, 112)
3	(125, 126, 70)	11	(238, 163, 135)
4	(125, 90, 112)	12	(238, 126, 70)
5	(125, 90, 159)	13	(238, 85, 112)
6	(125, 53, 60)	14	(238, 85, 140)
7	(125, 163, 112)	15	(238, 53, 70)
8	(125, 35, 126)	16	(238, 40, 126)

Table 3.1: The coordinates of the sensors within the clamp.

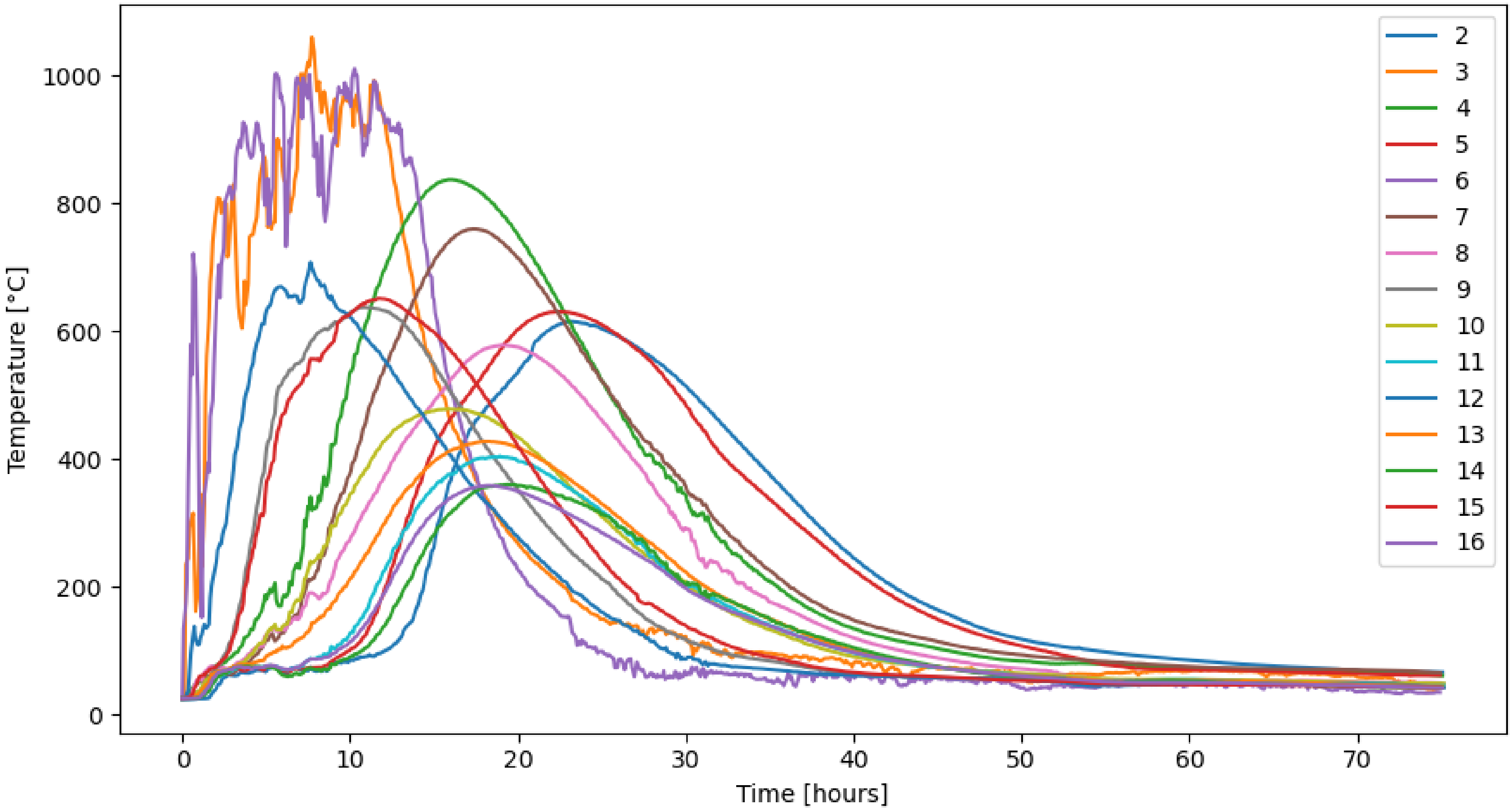

Figure 3.2: Temperature measurements from 15 different points over one firing cycle in a clamp kiln.

3.1.1 Overview

Let us put the measurements in relation to what was happening at the site. The brick firing takes place in three stages:

1. Starting fire and continuous addition of fuelwood (5h). In the measurements we see that the temperature rises rapidly in the low layer during that time, faster in the center slice (sensors 3 and 6) than in the front slice (sensors 9, 12 and 15).

2. Closing of burning chambers and subsequent soaking (24-30h). More fuel is added periodically in the first four hours, then the burning chambers stay closed. Over time, the temperatures reach their peak in all layers.

3. Opening of burning chambers, combustion of remaining embers, cooling down (36-48h).

As is evident from the data, while the overall shape of the temperature curves is similar over all measurements, there is quite a difference in the amplitude as well as a time shift depending on the location of the sensors. Sensor number 1 was wired incorrectly and did not produce correct measurements.
Figure 3.3 and Figure 3.4 visualize how the maximum temperatures at the different measuring points change depending on the minimum distance to the kiln surface. For the minimum distance we only considered the directions along the x and z axis to be able to compare the differences between the two measured kiln slices.

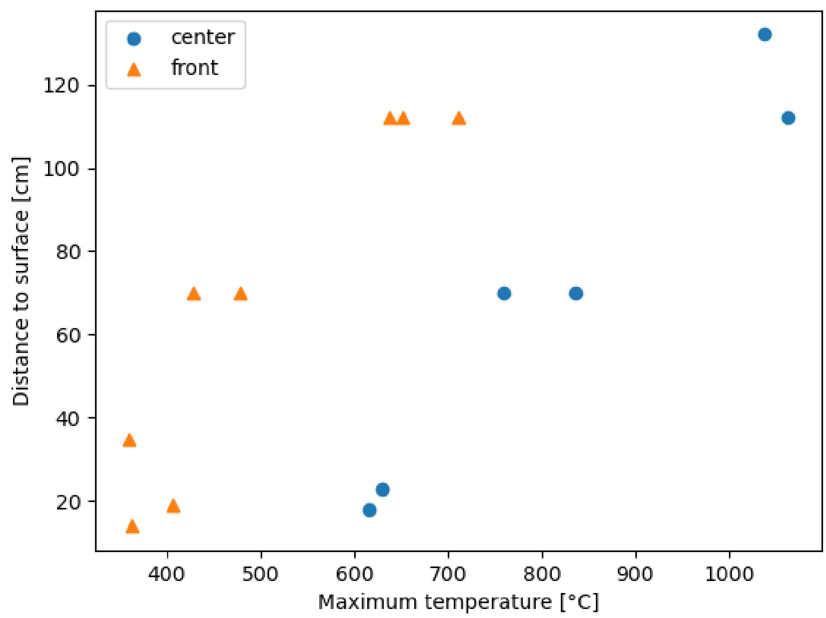

Figure 3.3: Relation of peak temperatures to sensor depth (front slice and center slice).

When comparing sensors at similar insertion depths in the center of the kiln to those close to the front surface, one can see that the peak temperatures are significantly lower for the latter (Figure 3.3). The further from the surface, the larger the difference becomes, which makes sense since convective heat losses increase with the temperature difference, in this case between oven and outside temperature. This temperature difference depending on the distance to the surface shows how influential heat losses over the clamp surface are for the heat distribution and brick quality.
The time shift between the peak temperatures near the kiln surface and the sensors one brick layer above the burning chambers is more than 17 hours (Figure 3.4). This time shift can be attributed to the slow conductive heat transfer.

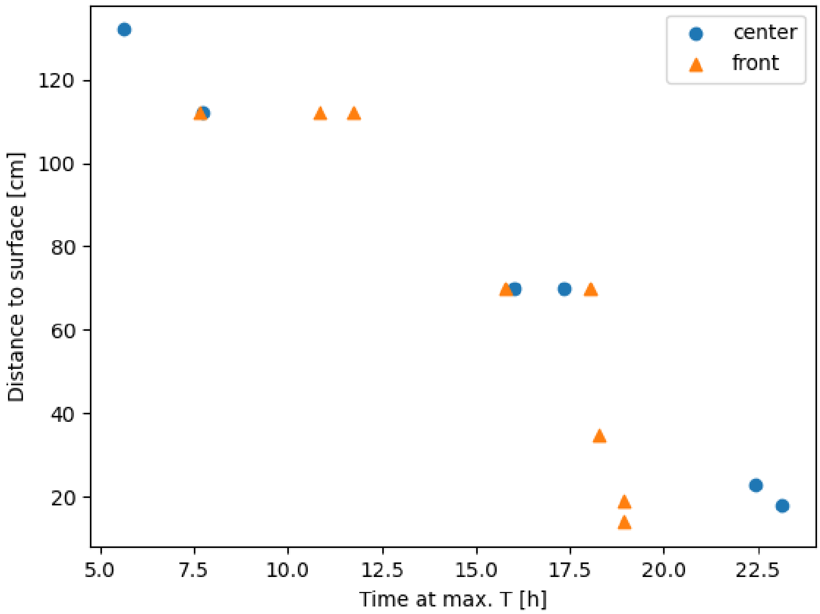

Figure 3.4: Time until peak temperatures are reached, depending on sensor insertion depth.

Conclusions regarding heat transfer

Based on the similarly shaped temperature curves and their temporal spacing, it can be concluded that conductive heat transfer is the dominant method mechanism that shapes the temperature distribution. The conductivity must be low, as evidenced by the rather large time shift. Given that both brick and air, which make up the interior of the clamp, are bad heat conductors, that is to be expected. Convective and radiation heat losses gain significance with proximity to the kiln surface.
The fluctuating temperature curves that are observed for sensors 3 and 6 (located in center of the clamp, above the burning chambers) could be caused by uneven combustion dynamics. As we described in Section 2.3, the heat release rate depends on the air flow into the buring chambers, which is uncontrolled in clamp kilns. These temperature fluctuations are less accentuated for sensors 9, 12, and 15 (front layer, above burning chambers). Possible explanations could be the better ventilation at the front of the burning chambers, which leads to more even firing conditions, combined with the loss of heat through the trench openings (leading to lower peak temperatures).

3.1.2 Brick quality by layer

As explained in Section 1.4.1, bricks that reached temperatures of at least $600°C$ for a minimum of two hours can be considered adequately fired (Grade 2), while a minimum soaking temperature of $900°C$ is desired for high quality bricks (Grade 1). Firing temperatures under $600°C$ and over $1200°C$ mean the brick is under- or overfired and therefore Grade 3 quality.
In the next sections, the brick quality in different parts of the oven will be discussed.

Lowest layer

The lowest sensors (3, 6, 9, 12, and 15) were each placed one brick layer above a firing chamber. Sensor 6 slid down and partly protruded into the chamber, which likely happened during the installation. This movement was not detected until the setup was disassembled after the experiment. The temperature curve looks similar to the measurement of the neighbouring sensor 3 and exhibits a lot of fluctuation. Therefore, it can be assumed that the temperatures in brick layers close to the firing chamber are still strongly influenced by the wood combustion dynamics.

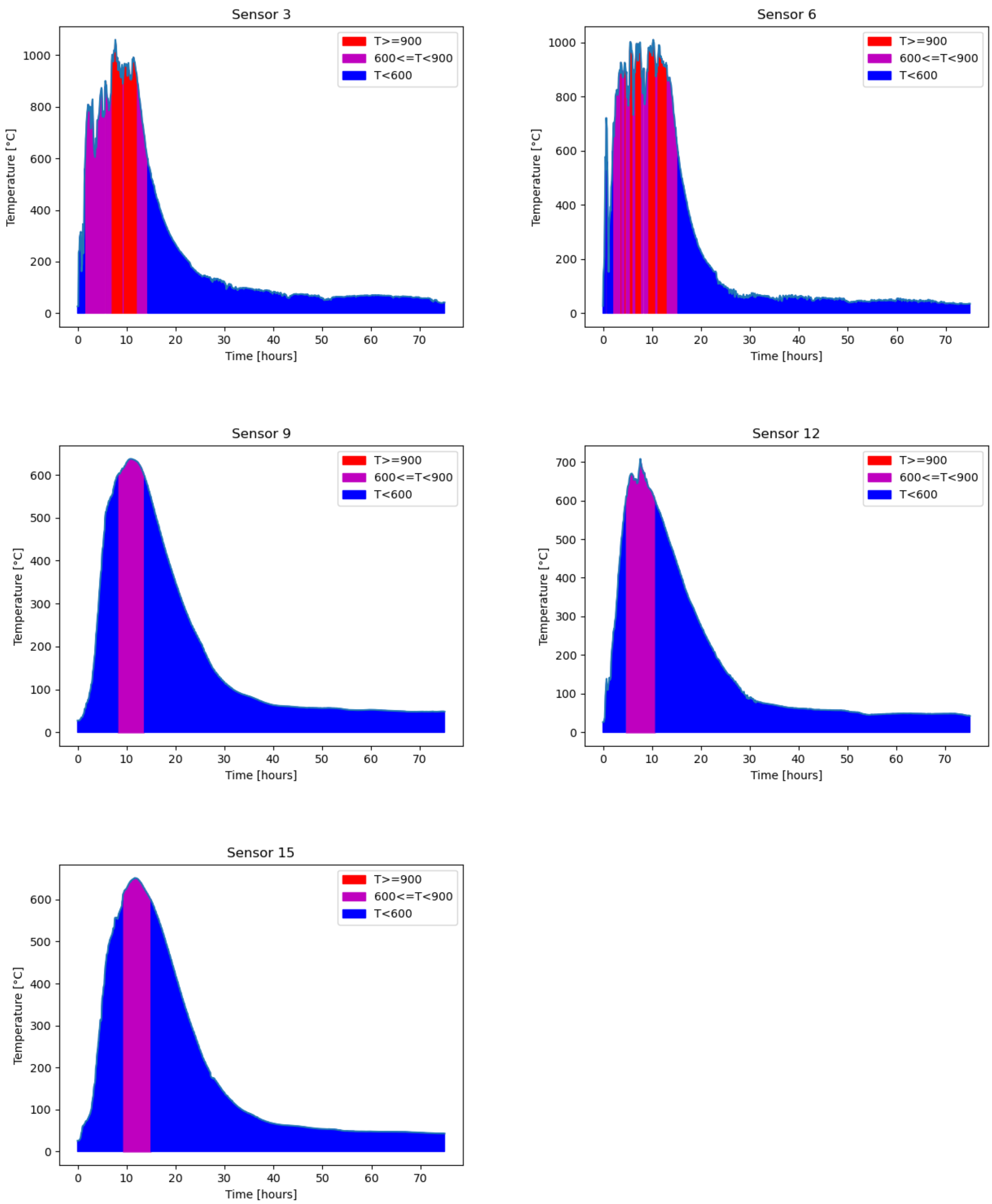

Figure 3.5: The temperatures one brick layer above the firing chambers.

Sensors 6 and 3 were placed in the center slice of the clamp. At their respective positions, temperatures over $900°C$ were achieved and the produced bricks can be assumed to be of high quality.
The measurements from sensors 9, 12, and 15, however, show that for the same depth in closer proximity to the trench openings, the achieved peak temperatures are much lower. The fired bricks in that area only reach Grade 2 quality, likely due to the heat losses through the trench openings and front surface area.

Middle layer

Similar temperature differences between the front and center slice can be observed for the sensors that were placed in the middle layer of the clamp, approximately 112 cm from the upper surface. While sensors 4 and 7 indicate adequate brick quality at this depth ($> 600C°$) in the center slice of the oven, in the front area (sensors 10 and 13) the quality is already insufficient, with the maximum temperatures between 300 and $400°C$. The temperature difference is in the magnitude of several hundred degrees (as is shown in Figure 3.3), which again demonstrates how influential heat losses are for the achieved brick quality.
It should be noted that sensors 10 and 13 were placed only 12 cm from the outer surface, which means that both the convective heat losses as well as the heat losses through the firing chamber openings may impact the measured temperatures.

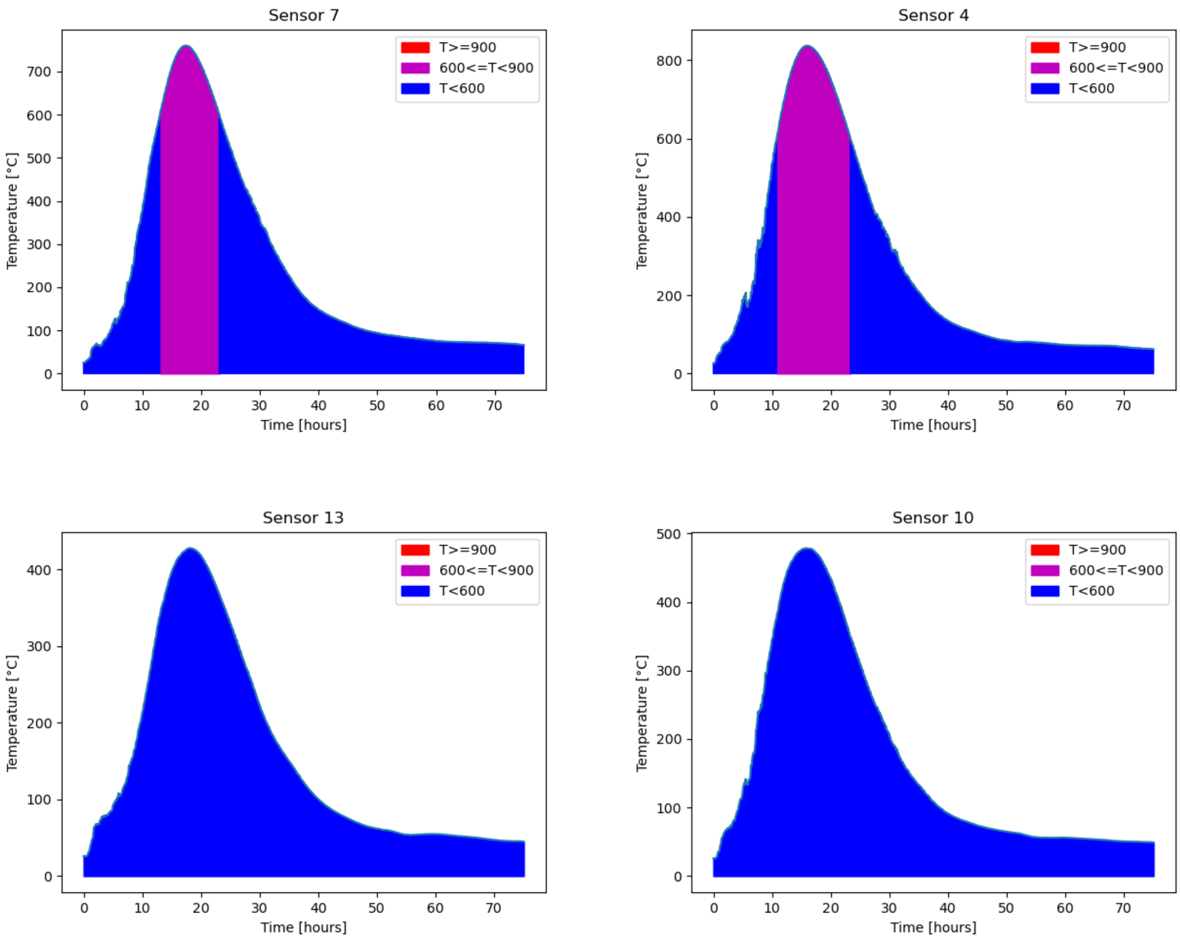

Figure 3.6: The temperatures four brick layers above the firing chambers.

Surface layer

The measurements of the six sensors that were placed in proximity to the surface at various locations in the oven are displayed in Section 3.1.2.
As one can see, the temperatures climb to their maximum around 20 hours after the firing begins. There is a first small "bump" in the temperature curves for most sensors, which is likely caused by the passing hot flue gases.
At the top of the center slice, adequate firing conditions were achieved (sensors 2 and 5). The temperatures at the clamp corners (measurements 8 and 16) were found to be insufficient in both measured slices. The bricks close to the front slice, again, were inadequately fired (sensors 11 and 14).
The bricks near the surface in the center region of the clamp still achieved sufficient temperatures, which demonstrates that the brickmakers stopped firing at the right time. Notably, the active firing (addition of wood) stopped hours before the temperatures peak in the upper layers. This leads to the conclusion that the firing duration can not be shortened in order to save fuel and the kiln was appropriately fired.

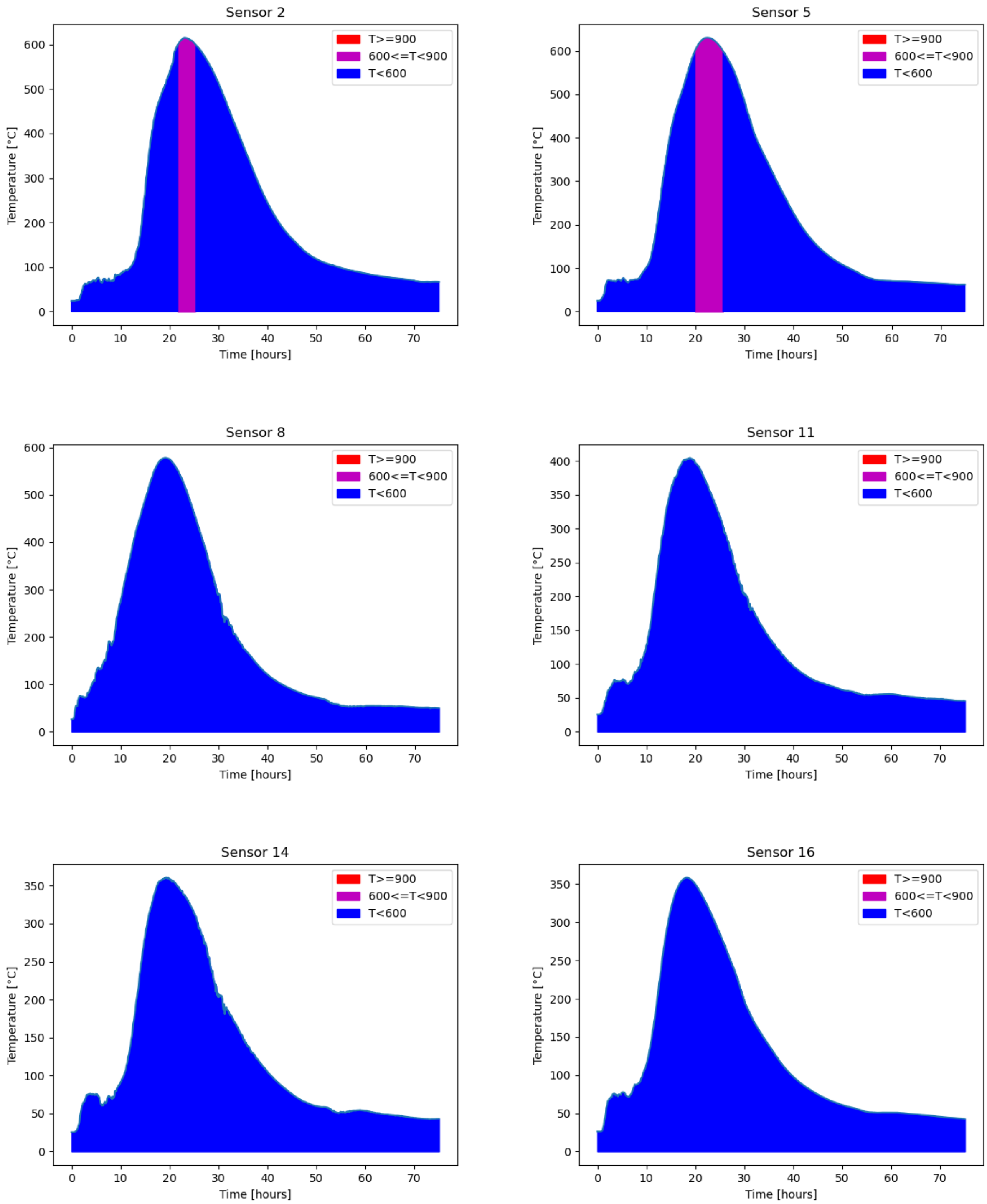

Figure 3.7: Measurements two layers from the clamp surface

3.2 Simulation Results

Using the thermal model that was described in Section 2.3, the temperatures at the same measuring points were simulated for the same kiln geometry.
The heat flow was based on the following approximation of the temperature in the firing chambers (Figure 3.8): Because the firing chambers are opened 30 hours after the firing begins, the heat flow into the

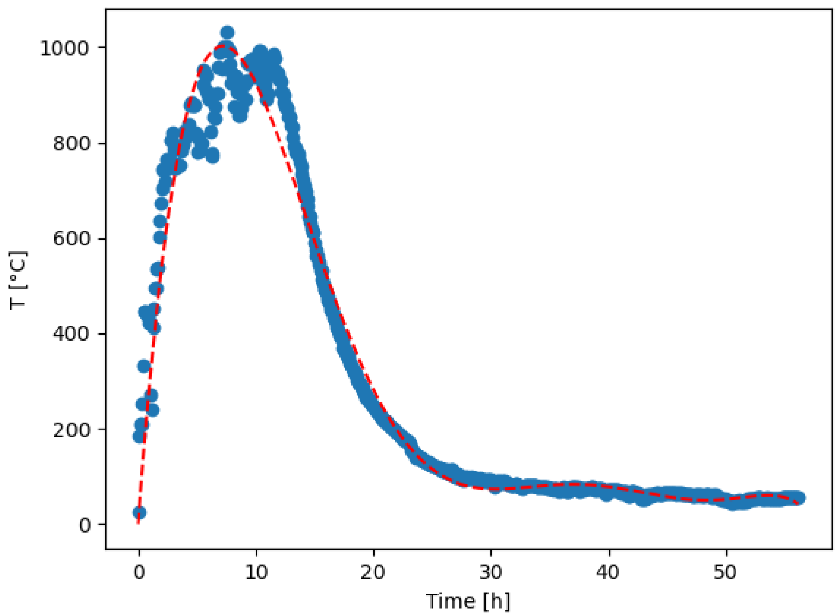

Figure 3.8: Quintic approximation of the temperature development in the burning chambers.

chamber is set to zero from that time onwards.
The resulting temperature curves at the location of the temperature sensors are displayed in Figure 3.9.
To relate this to the measured values, the measured and simulated temperature curves in the front slice and the center slice are displayed next to each other in Figure 3.10 and Figure 3.11.

3.2.1 Accuracy

Dynamics

As the comparison shows, the model captures the magnitude and temporal spacing of the peak temperatures fairly well, although the peak temperatures at the front slice are overestimated by approximately $100°C$ (Figure 3.11). A possible reason for this deviation could be an underestimation of the heat losses through the firing chamber openings.
Some of the variation can further be explained by varying firing conditions in the firing chambers of the real clamp. For example, the wood might start burning faster in one trench than the next, or there could be differences in the total amount of wood added per chamber. These differences can influence the peak time and magnitude. In the model, the same heat input dynamics were assumed for all burning chambers.
According to the developed model, there is a tendency for heat to accumulate towards the clamp center, with slightly higher temperatures being reached than for the same measuring depths than towards the clamp sides.
This effect was not observed in the real data, but due to the small sample size and the variation in firing conditions, this does not necessarily mean that this effect does not exist. It is also possible that the effect cannot be observed because the brickmakers know that less fuel is required in the clamp center and adapted the fuel addition accordingly.

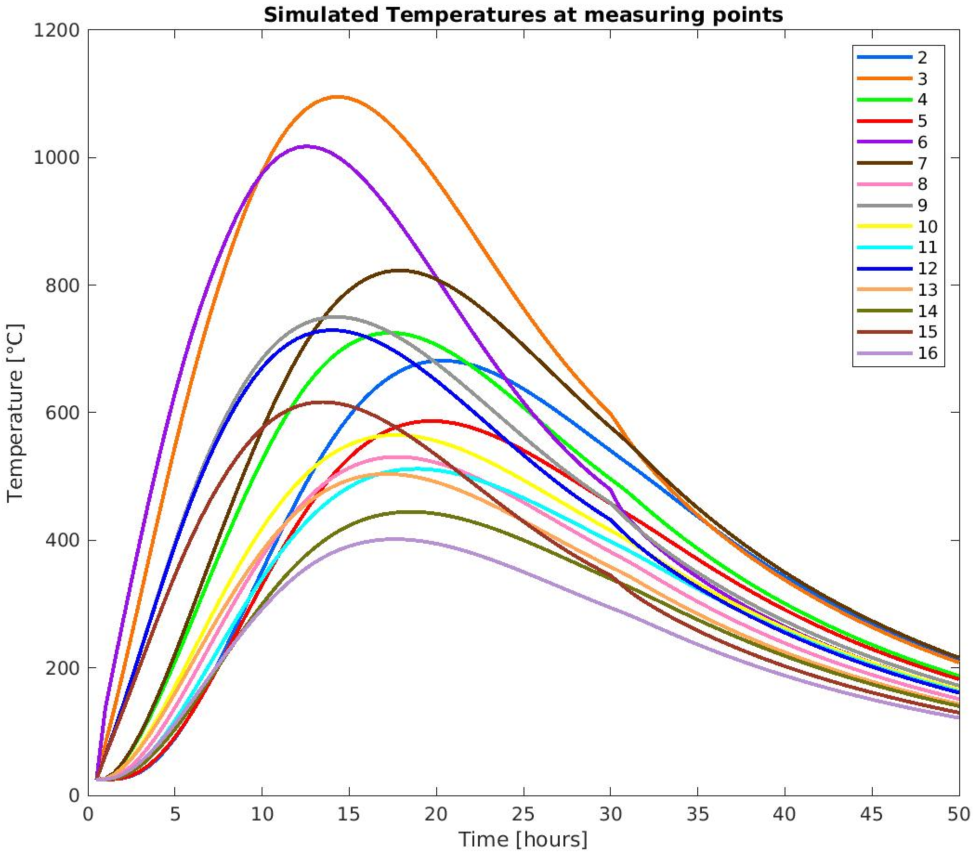

Figure 3.9: The simulated temperature curves at the 15 measured points.

Differences

A key difference in the dynamics of the measurements and the simulation is that the measuring points in the middle and top layer continue to heat up even after the temperatures in the lower layers begin to drop. Furthermore, the detected lower layer temperatures fall more rapidly than in the simulation model.
These differences are likely related to one of the simplified assumptions that were made in the model: The influence of the flow of gases from the combustion chamber upwards was included as a higher conductivity within the oven. Conductive heat transfer depends on the temperature difference between two points. In reality, the heat transfer also depends on the direction in which the gases move, which is upwards. Thus, it is accelerated in that direction. Furthermore, the temperature dependence of the thermal conductivity was neglected.

Implications

Since the magnitude and temporal spacing of the temperatures measurements are fairly well replicated by the model, this allows us to draw conclusions on the quality of bricks fired in this oven. Figure 3.12 displays the share of the bricks that reached a two-hour soaking duration of the respective temperatures.
According to the model, only 57.3% of the bricks reached at least adequate firing temperatures, with 19.7% being labelled as Grade 1 quality.
These results are very poor, but to be expected based on qualitative considerations. The basic design does not allow for exposure of all bricks to even and equal heat flows. The bricks in closer proximity to the firing chambers will reach higher temperatures, and the bricks in the outer layers experience heat losses to the environment. One or two brick layers from the surface, the brick quality can be assumed to be insufficient.
These results imply that to increase the share of adequately fired bricks, the surface-to-volume ratio should

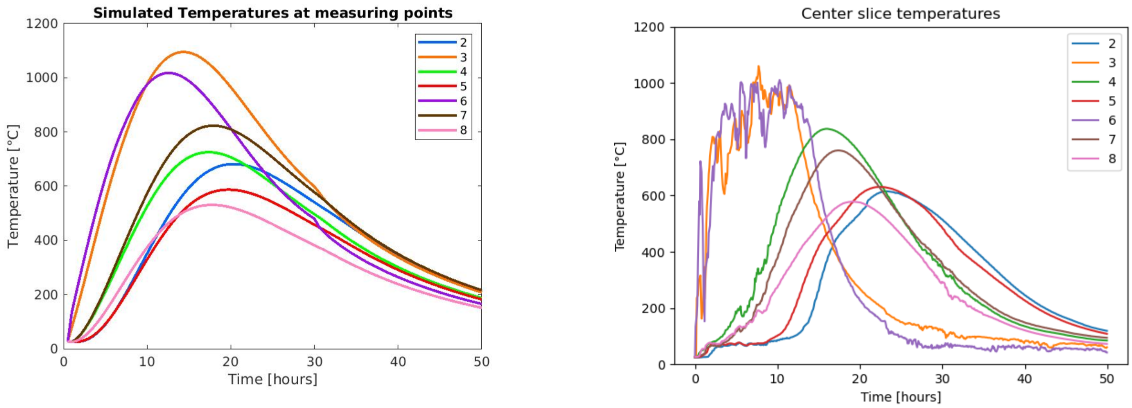

Figure 3.10: The measured temperature values in the clamp center.

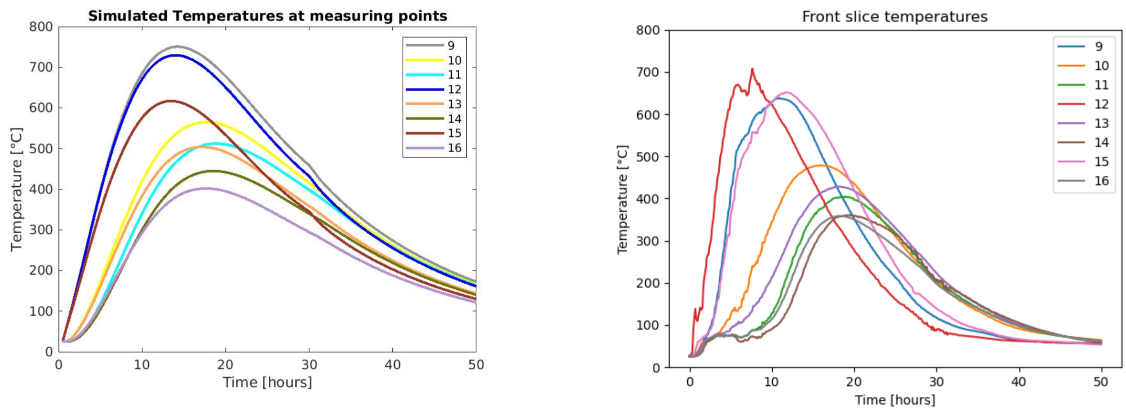

Figure 3.11: The measured temperature values in the clamp front.

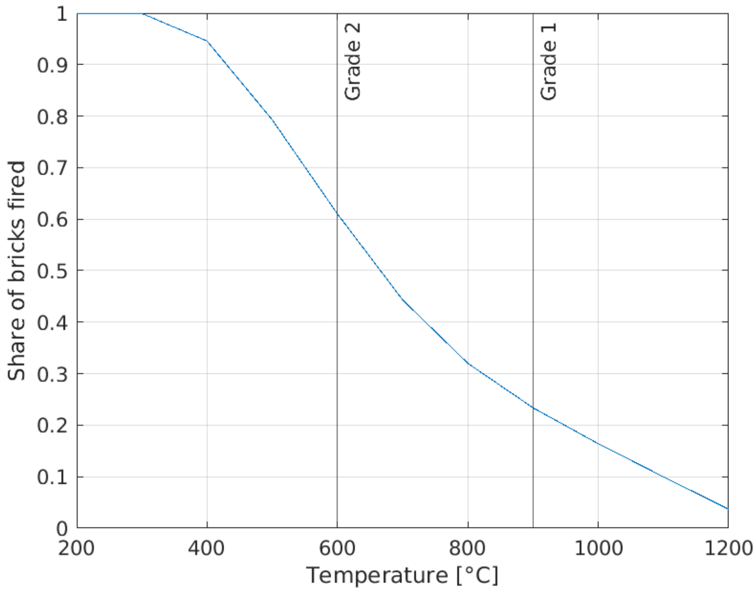

Figure 3.12: Reached soaking temperatures in the simulated clamp kiln with five burning chambers.

be decreased. Therefore, the effect of different kiln layouts on the achieved quality of the fired bricks will be simulated.

3.2.2 Adapted Kiln Layouts

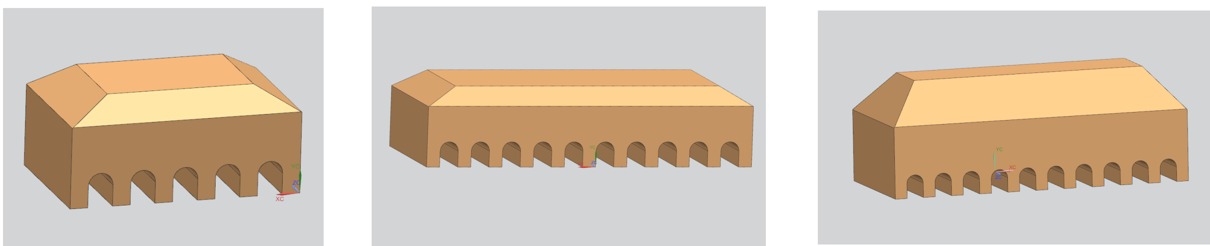

Figure 3.13: Modelled layouts with increased trench length, number of burning chambers, and height.

The easiest way to adapt the kiln layout is to add more firing chambers. By building a wider kiln, the influence of the emissive and convective heat losses over the side surfaces on the brick quality decreases.
Ideally, the firing chambers would be longer, too. As we learned from the comparison of the temperature measurements from the front and center slice, the heat losses through the openings of the burning chambers have a very significant impact on the achieved temperatures. However, their length can not be increased indefinitely without more changes to the structure. For one, the brickmakers need to be able to place woodfuel everywhere in the chambers, and this becomes more difficult with increased lengths. Arguably, by cutting the wood in smaller pieces and with the help of utensils to push it towards the center, this could be possible. However, it is possible that with the increased trench length, oxygen flow to the trench center is decreased. Consequently, the combustion could be negatively impacted and measures need to be taken to improve ventilation, be it structurally or with the use of tools.
Furthermore, the effect on fuel efficiency of adding more brick layers on top of the oven will be evaluated.

Increased Number of Burning Chambers

An adapted clamp layout with 10 burning chambers instead of five was modelled using the same boundary conditions that were applied to the smaller model in Section 2.3.2. Fuel input was the same for all burning chambers.

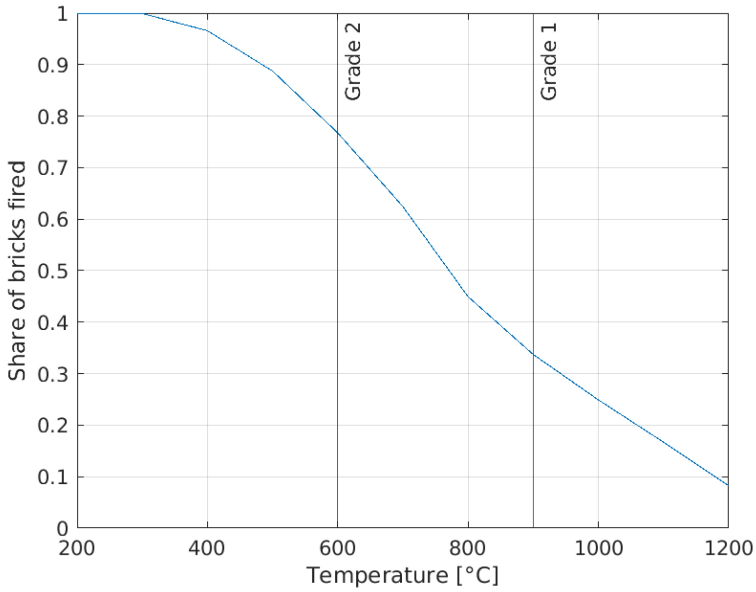

Figure 3.14: Reached soaking temperatures in the simulated clamp kiln with 10 burning chambers.

The results show that with the same fuel input, the share of adequately or well fired bricks rises to 68.5%, with 25.5% being Grade 1 quality (Figure 3.14). The share of inadequately fired bricks decreases to 31.5%. As we have seen, the heat accumulates in the clamp center. Figure 3.15 shows a heat map of the clamp after 14 hours, and it is evident that there are even bricks in the clamp center that are overfired (up to 1400°C). This accumulation of heat is also evidenced by the higher share of bricks that reached soaking temperatures of 1200°C and more (Figure 3.14). Therefore, the fuel input can and should be lowered in the center of the oven.

Summing up, the addition of five burning chambers decreases the share of inadequately fired bricks with less fuel required than in the original design. Therefore, this is a measure that is both effective and easy to implement from a technical point of view, as no fundamental changes are necessary.

Increased Length of Burning Chambers

The second identified measure to improve the clamp efficiency was to increase the length. Since this is more challenging to implement due to possible issues with refueling and ventilation, the length increase was limited to 1 m. The effect of the length increase was tested using a model with five burning chambers as well as a version with 10 burning chambers.

If only the length in direction of the burning chambers is increased by 1 m, the share of bricks with sufficient quality is 60.5%, with 21.0% high quality bricks.

A clamp with both increased width and length produces 64.6% bricks of sufficient quality with the same fuel input per brick according to our model.

These results demonstrate that increasing the length of the burning chambers can be impactful with regards to brick quality per fuelwood input. However, due to the decreased heat losses, the fuel input needs to be lowered to prevent overfiring of the bricks in low layers.

Effect on Required Fuel Input

Due to the observed reduction in heat losses and accumulation of heat, the fuel input can and should be reduced towards the center of the kiln.

For the kiln models with ten firing chambers, the fuel input per chamber was lowered to 75-85% of its original value for the inner eight chambers. It was not reduced for the two firing chambers that are closest to the outer surface of the kiln because the bricks in their vicinity are affected by heat losses through the clamp surface.

The results (also summarized in Table 3.2) confirm that it is possible to produce more adequately fired bricks with less fuel by increasing the layout of the clamp.

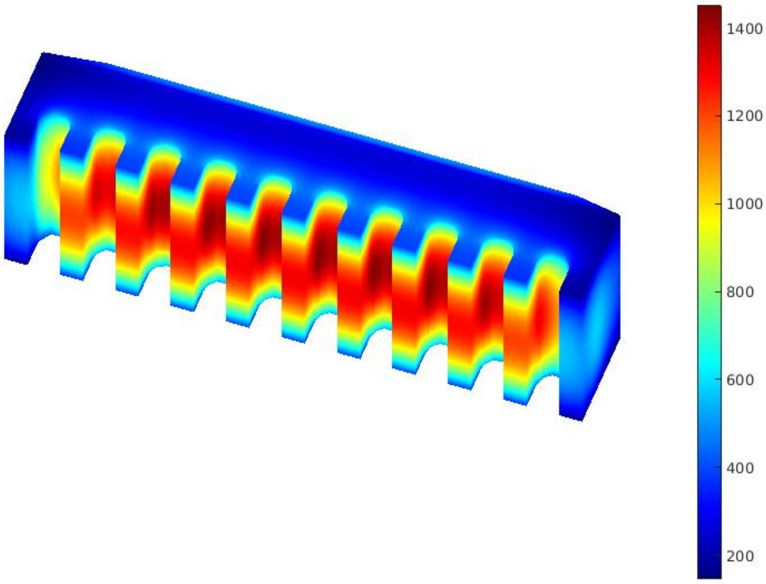

Figure 3.15: Heat map of the simulated clamp with ten firing chambers after 14 hours.

The best results were achieved for the layout with both increased width and height. With 20% less fuel, it was possible to decrease the amount of Grade 3 bricks by 40.5%. Furthermore, this tested measure prevented the overfiring of bricks in the simulation (Figure 3.18 (Overfired bricks reach temperatures of more than $1200°C$).

Kiln Dimensions	Fuel input $[\frac{MJ}{kg}]$	Grade 1	Grade 2	Grade 3 (overfired)
4.0x2.5x1.8 m	4.4	19.7%	37.6%	42.7% (3.7%)
7.8x2.5x1.8 m	4.4	25.5%	43.0%	31.5% (8.3%)
4.0x3.5x1.8 m	4.4	21.0%	39.1%	39.9% (13.4%)
7.8x3.5x1.8 m	4.4	33.6%	28.0%	35.4% (19.5%)
7.8x2.5x1.8 m	3.8	22.6%	46.4%	31.0% (0%)
7.8x3.5x1.8 m	3.5	26.1%	48.5%	25.4% (0%)
7.8x3.5x2.8 m	3.0	18.5%	24.7%	56.5% (12.9%)

Table 3.2: Quality of bricks fired with different kiln dimensions and fuel input

Increased Height

Lastly, the influence of increased kiln heights on the efficiency of the brick burning process will be discussed. For this, the height of the model with increased width and height was raised by 1 m.
As described in Section 3.1.2, the amount of fuelwood added in the investigated firing process was sufficient to heat the bricks in upper layers of the clamp center to adequate temperatures during the experiment. The firing duration was thus well-chosen under the given conditions.
For the model with the increased height, it was found that even with an increase in the firing duration, the temperatures at higher layers did not reach satisfactory levels when increasing the height of the kiln. This is due to the poor heat conduction to upper layers. Instead, increasingly more of the bricks close to the burning chambers were overfired.
Possibly, the height of the oven could be increased with the addition of internal fuel such as sawdust or tobacco husks to the raw bricks or between brick layers, which was not done in the measured furnace. In the kiln investigated by [49], however, temperatures of around $1000°C$ were still achieved in the 10th layer

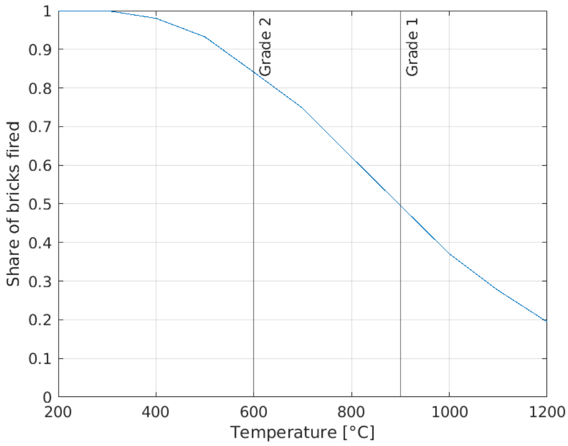

Figure 3.16: Brick quality with 4.4 MJ/kg fuel input.

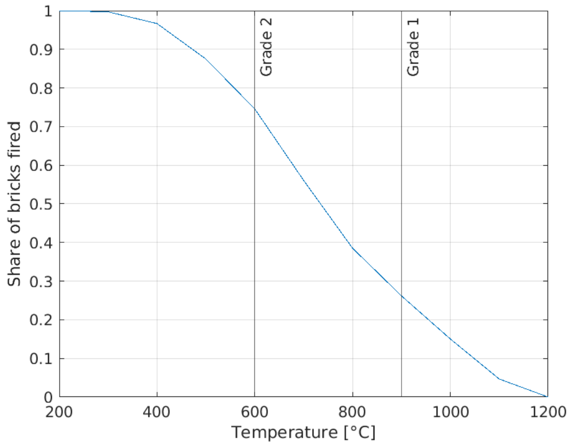

Figure 3.17: Brick quality with 3.5 MJ/kg fuel input.

Figure 3.18: Effect of fuel input reduction with increased width and length of clamp.

thanks to the sawdust that had been incorporated in the raw bricks. For comparison: The kiln that was measured in this Thesis only achieved such temperatures in the first three brick layers.

Chapter 4

Conclusions and Outlook

4.1 Improving Brick Clamps: Possible, but...

In this Master Thesis, an experiment was conducted to determine the temperature development over one firing cycle in a typical wood-fired brick clamp in Chembe, Malawi. Based on these measurements, a thermal simulation was developed to determine the influence of changing kiln geometries on fuelwood demand per bricks produced.

4.1.1 Adapted Layouts to Prevent Heat Losses

It was found that heat losses through the openings of the firing chambers and over the clamp surface are quite significant with regards to the brick quality. Consequently, a lower surface to volume ratio is desirable to lower the fuel input. Most impactful are the losses through the openings of the burning chambers, followed by the side walls of the clamp.
For the clamp geometry this implies that the clamp should be wider, as well as longer. More burning chambers can easily be added, increasing their length, however, is more challenging.
With longer burning chambers, it might be necessary for the brickmakers to cut the wood into smaller pieces and use utensils to shove the fuel towards the center.
However, as the clamp relies on natural circulation for combustion, it is possible that ventilation needs to be improved to ensure that there is enough oxygen available for the fire in the trench center. This could be achieved with the addition of air ducts in the construction, or by using bellows at the kiln entrances.
Adding more layers on top was found to be ineffective because the high thermal resistance of the oven prevents sufficient heat transfer to upper layers. If the height of the clamp is to be significantly increased, fuel needs to be added between layers.
Raising the number of firing chambers from five to ten while increasing the length of the burning chambers by 1 m led to a rise of the share of adequately fired bricks from 57.3% to 74.6%, while decreasing the fuel input by 20%. The share of high quality bricks rose from 19.7% to 26.1%. Therefore, building larger ovens is a simple and very effective way to improve the efficiency of clamp kilns.
Furthermore, the addition of organic waste material to the raw bricks can serve as internal fuel, lower the fuel demand, and improve the isolation properties of the final product. This could be another measure brickmakers can take to decrease the amount of wood required. However, it is possible that this is done in some regions where lots of organic waste materials are available, for example from tobacco production. At our test plant in Chembe, we learned that there are multiple measures that artisans take to improve the efficiency of the process. Local variations to the brick production methods within Malawi have never been systematically explored and documented.

4.1.2 Intrinsic Flaws That Remain

Still, even with these proposed measures, the clamp remains a rather inefficient technology, with a large share of the bricks not meeting adequate firing conditions.
This finding is due to the fundamental design of the oven, which does not create equal firing conditions for all bricks. Physically, it is not possible to achieve even firing conditions throughout the clamp, as opposed

to more modern kiln types where all bricks move through a firing zone and are more or less exposed to the same conditions.

While some of the effects of heat losses on the brick quality and fuel input can be alleviated by improved design, other flaws remain. The combustion process is difficult to control, heat is lost due to the intermittency of the process, and waste heat is not recovered.

More modern oven types that were also presented in this thesis are able to address these issues more effectively and should therefore gradually replace clamp kilns in the locations where transport and the cost of fuel warrant it.

4.1.3 Aspects Beyond Technology

The proposed measures to improve the efficiency of clamp kilns require an increase in the number of bricks fired at once. Since bricks are often produced on demand of one single customer, this would require multiple customers to coordinate their orders. What factors might play a role when trying to achieve that could be explored in future research.

A possible approach could be to support the creation of small businesses, who can coordinate the production of multiple orders at once. Goodwin Chasimpha, who owns the brickmaking company that helped us conduct our experiment, explained that building larger ovens is how he is able to make a profit and why his business flourishes in comparison to independently operating brickmakers. He is able to charge the same price as them while having lower fuel costs per brick produced.

However, one should keep in mind that with the high demand of building materials, the related issues such as deforestation and soil degradation will not be solved with improved brick clamps. Independent strategies need to be developed to find out how to effectively address these environmental concerns.

4.2 A Challenging Road Ahead

As we have seen in the previous chapters, the question of how Malawi can improve the sustainability of its building sector does not have one obvious answer. There are many possible levers that could be used in this transformation: From improved brick compositions, alternative fuels, or improved kiln types to different materials altogether. While these changes can influence the environmental impact of the building sector in Malawi to different extents, success or failure of the respective technologies does not depend on their sustainability alone. Neither is it guaranteed that the "best" technology, meaning the cleanest or most efficient, will prevail. Promising theoretical concepts often come to a hard clash with the complex realities of life in the Global South.

Volatile prices, rampant inflation, fuel crises, a lack of capital and skilled workforce, social norms, and last but not least, a lack of reliable data on these factors and their interconnections makes it difficult to predict how Malawi's building sector will develop.

4.2.1 Expected Developments in Urban Centers

There is one clear trend that shapes the country's development and impacts the way building materials will be produced in the future: Urbanization.

The expected growth of urban centers offers different opportunities from a technological point of view than are possible to establish in rural areas. Larger, continuously fired kilns could be a viable and more efficient alternative to small-scale, on demand brick production which is the dominant method today. Shorter ways of transportation, a more steady demand of bricks, and less logistical and supply issues than are present in rural areas might facilitate the transition to sustainable building materials. In light of the expected population growth and rise in demand of building materials in Malawi (and the rest of the African continent), it is extremely important to try to establish better technologies and materials already today.

The way forward might be facilitated by taking a look back: Other countries used to rely on the same brickmaking technologies, and struggled with similar environmental concerns. Although caution is warranted when comparing different countries due to the different climates, economies, and cultures, there might be some valuable insights to be gained from the history of brickmaking in

4.2.2 Perspectives for Rural Areas

Nonetheless, Malawi still has a large share of the population that lives in rural areas. These communities are likely to stick to intermittent, small-scale brick production for years or even decades to come because overall, these technologies are very well suited to the local requirements.

Malawi, as a landlocked country with bad roads and a weak economy, is highly vulnerable to global developments such as rising fuel or cement prices. Also, it faces devastating fuel shortages regularly. Therefore, building materials that can be produced locally with local resources have a huge advantage over alternatives that are imported, transported over long distances, and thus more likely to be subjected to price fluctuations.

As far as wood-fired kiln technologies are concerned, it is clear that improved technologies can slow the progress of deforestation at best. As long as the price of woodfuel is lower than the price of alternative fuels, or the price of wood-fired bricks is lower than the price of alternative materials, trees will continue to be cut down. And reforestation will remain challenging for the same reasons: As long as other cash crops have a higher and/or faster return on investment, tree plantations are at a disadvantage. What implications does this have for the construction sector in rural areas?

One possibility is that continued deforestation will drive the price of wood to levels where alternative fuels or building materials will become more attractive. This could lead to woodfuel for brick production being replaced by coal, or pave the way for the success of Cement Stabilized Earth Blocks or other alternative building materials.

From an environmental point of view, both of these are not highly desirable: Coal is even more polluting than wood, with connected adverse effects on human health and agricultural yields. CSEBs on the other hand require cement, the production of which is energy-intense and emits large amounts of CO_2. At least in this case one could argue that as long as the cement is imported, some of the environmental impact affects only the country of production.

Interesting for both urban and rural areas are technologies that incorporate post-consumer waste materials such as glass or plastic in construction materials. These technologies offer new approaches to waste management while simultaneously preserving clay soil resources.

Adding biomass to the clay mixture can improve the thermal and mechanical properties of bricks and reduce the energy demand for firing. There is a lot of potential for future research on the application of such technologies in the Malawian context.

4.2.3 Concluding Remarks

One of the key learnings when writing this thesis was to see how the clamp, while a poor technology with regards to energy efficiency and brick quality, is used very efficiently by the locals. For one, the brickmakers know how to apply various techniques to optimise the kiln firing. Furthermore, Malawians have found ways to use even cracked and low quality bricks, for example to make floors or build animal houses. It is primarily the high demand that creates the environmental issues we try to address in this thesis, and difficult economic circumstances that prevent them from being solved.

The transition to sustainable building materials is a challenge that is difficult to manage, even for countries with more resources than Malawi. In fact, there is not a single country in the world in which the built sector is not negatively impacting the environment. Industrialized countries may have managed to decrease the local environmental impacts, but by relying primarily on concrete, they are shifting the environmental burden to a global level by accelerating climate change. The adverse effects of climate change, however, disproportionately affect African countries.

Nonetheless, as we have seen in this thesis, there are multiple pathways that can and should be explored that have the potential to help Malawi to alleviate at least some of the environmental impact of its construction industry.

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