Graduate School of the Environment
Centre for Alternative Technology
Machynlleth
Powys
SY20 9AZ
Tel: 01654 705981

School of Architecture Computing and Engineering
University of East London
Docklands Campus
4-6 University Way
London E16 2RD
Tel: 020 8223 3000

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Should we paint all classroom roofs white to improve learning in Tanzania?

Working Paper

MSc Sustainability and Adaptation in the Built Environment

Jamie Proctor

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Abstract

A growing literature base has developed from Global North contexts, showing a clear link between classroom temperature and student learning outcomes. However, there is very little evidence showing how this impact translates to Low and Middle Income Countries (LMICs), - where average classroom temperatures are often higher. The hypothesis for the research was that classroom temperatures in Tanzania are high, and that a white paint cool roof intervention would help mitigate these high temperatures.

Firstly a literature review was undertaken, to understand the classroom policy in Tanzania, the established links between temperature and learning, and to assess temperature retrofit options. An experiment was then undertaken to trial a white paint cool roof, against a blue paint roof and an unpainted control roof. Finally, analysis of the data was undertaken to predict the intervention effects over a full year and the subsequent impact on learning outcomes. The learning outcomes analysis included a cost effectiveness analysis, using the Learning Adjusted Years of Schooling (LAYS) metric.

Empirical evidence of temperatures inside classrooms in Dar Es Salaam were collected, which suggests that the temperature often exceeds 40℃. Literature searches suggest that this is the first time classroom air temperatures have been recorded and published for East Africa.

A low-cost retrofit intervention to reduce temperature - by painting the classroom roof blue or white - was then experimentally tested over eight days. Results showed that the White Paint Intervention (WPI) reduced the temperature by around 3.7℃ over the course of the school day and up to a maximum of 5℃. The White Paint Intervention was roughly twice as effective as the Blue Paint Intervention at reducing interior air temperatures. The White Paint Intervention results were then modelled to estimate the classroom temperature reduction over the course of a full year, based on the assumed 3.5℃ reduction. Finally, using estimates taken from the existing literature, the learning impact of the intervention was calculated. The results suggested that learning would be improved by 7.1%. This translates to an estimated 3.2 Learning Adjusted Years of Schooling (LAYS) per classroom per year, at a cost effectiveness of 5.3 LAYS per US$100.

The paper shows the impact of high temperatures in classrooms is likely undermining the funding being channelled to improve learning outcomes in the region. Further, a white paint cool roof retrofit intervention is effective at reducing classroom temperatures in Tanzania. Due to climate change induced temperature increases, the intervention effectiveness is likely to increase over the coming decades.

Acknowledgements

This research would not have been possible without the support and input from some brilliant people. Many thanks to Godfrey Mwangalimi for helping organise a team to paint the roof, without your guidance the research would not have happened. Thanks to the headteacher and School Management Committee (SMA) at St Peter's primary school for welcoming the intervention and being so helpful throughout. I hope that the cooler classrooms and the light blue colour are helpful for your students and teachers.

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Taking nearly five years to complete an MSc is a long time. Particular thanks to The Mlambe Project Team, especially Lucy, Saalim, Steven and Geoffrey, for having heard the most about ideas that have come out of the course. Thanks to Sophie for being always supportive. Thanks to Andy for proof reading everything. Thanks to Liz for your encouragement. Thanks to other friends and family who have put up with me talking about classroom design, heat flows or Life Cycle Analysis for such a long time. I don't think it will end now, so thanks for the patience in future.

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1. Introduction

The hotter a country is, the poorer it tends to be. It has been shown that on average a 1℃ increase in temperature correlates with an 8.1% reduction in Gross Domestic Product (GDP) per Capita (Dell, Jones and Olken, 2009; Park *et al.*, 2020)**.** A growing literature base has developed from Global North contexts, showing a clear link between classroom temperature and student learning outcomes (Wargocki, Porras-Salazar and Contreras-Espinoza, 2019; Park *et al.*, 2020). However, there is very little evidence showing how this impact translates to Low and Middle Income Countries (LMICs), where average temperatures are often higher (Hanna and Oliva, 2016; International Monetary Fund, 2020). This research will conduct an experiment to assess the efficacy of a low cost retrofit intervention to reduce classroom temperatures. It will then use data from this experiment to predict the intervention impact on learning outcomes.

This section will:

- Explain the subject of the paper: the impact of temperature inside classrooms on learning outcomes in Tanzania.
- Show why the research question is important in relation to the significant funding and interest focused on learning outcomes in Tanzania and LMICs.
- Explain how the research will address these questions in three stages: pilot, experiment and modelling.
- Define the scope of the study, using the conceptual model in Fig. 1.
- Outline the research questions for each stage of the paper.

In LMICs, including Tanzania, major education donors tend to focus their funding on improving learning outcomes (Global Education Evidence Advisory Panel, 2020; Hamadeh, Von Rompaey and Metreau, 2021). For example, in 2019 the UK devoted US$1.3 billion of Overseas Development Assistance (ODA) funding on education, aligned to a policy aimed at trying to "Get Children Learning" (DFID, 2018; Donor Tracker, 2020). Despite this focus on improved learning, there is currently very limited research investigating the effect of high temperatures on learning outcomes in LMICs. Indeed, the role of education infrastructure has received little research or policy attention in recent times (Bangay, Forthcoming). In the UK, the National Education Union regards a classroom temperature above 26℃ as unacceptable, whilst in South Africa a study recorded a classroom temperature at 53.8℃ (Bidassey-Manilal *et al.*, 2016; National Education Union, 2019). There is therefore the real possibility that the physical school environment is undermining the high level of funding being channelled to improve learning outcomes, without donors or governments being aware of the level of the challenge. Furthermore, with climate change induced temperature increases, any effect is likely to be significantly exacerbated over the coming decades (IPCC, 2018, 2021; Pohl *et al.*, 2021).

The aim of this paper is to build understanding of temperatures in classrooms in East Africa, in order to stimulate further research and provide a basis for policy recommendations regarding the low-cost retrofit intervention being assessed. This paper will provide empirical evidence of the temperature inside a classroom in Tanzania. It appears, from the literature searches, that this is the first time classroom temperatures have been recorded and published for East Africa. The research will then experimentally measure the effect of a low-cost retrofit intervention to reduce temperature, by painting a classroom roof blue and then white. These two interventions are referred to as the White Paint Intervention (WPI) and the Blue Paint Intervention (BPI). This type of ‘cool roof’ intervention has been shown to reduce temperatures and has been tested extensively in other contexts (Haberl and Cho, 2004; Akbari, Levinson and Rainer, 2005; Synnefa, Saliari and Santamouris, 2012; Gao *et al.*, 2014). Finally, a prediction of the learning impact of the intervention will be modelled and calculated. This will use the new Learning Adjusted Years of Schooling (LAYS) measure, and the derivative cost efficiency metric LAYS per USUS$100 spent (Filmer *et al.*, 2018). This will then allow the intervention to be compared with other education sector interventions, both in terms of learning and cost effectiveness.

The experimental scope of the paper is to measure classroom temperatures at a Government school in Dar Es Salaam, and test the effectiveness of the retrofit intervention. The paper will go on to predict the intervention impact on student learning outcomes, using data inferred from the literature as outlined in Fig. 1.

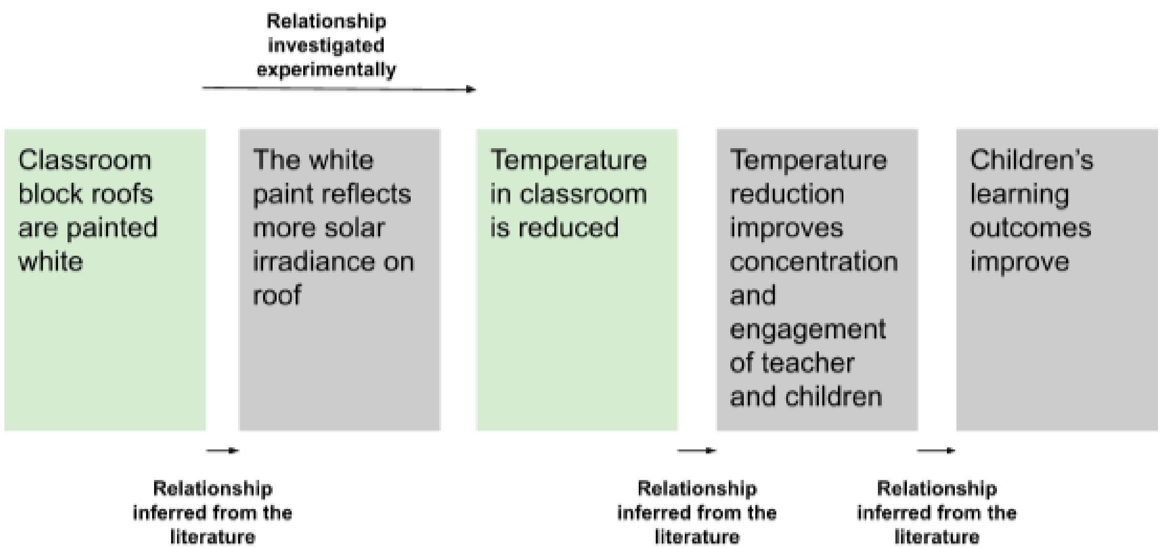


Figure 1: The theoretical model for the relationship between painting classrooms and learning outcomes.

The paper does not make any recommendations for policy change, given the identified limitations of the research. Most notably, the experiment only assessed the intervention in one school, with measurements recorded over a relatively short eight-day period. However, the data does show the strong potential impact of the intervention in Dar Es Salaam and the wider region. Therefore, the paper makes a strong case for further research, to record temperature and assess the intervention over the course of a year. Further, it recommends a design for a future nimble Randomised Control Trial (RCT) measuring learning outcomes as well as temperatures, with the aim of demonstrating a direct causal impact between the intervention and learning outcomes.

1.1. Research Questions

The overarching Research Question (RQ) is detailed below. There are also a number of sub-Research Questions (sub-RQs), which break down the main question and provide an added level of detailed insight.

The overarching question the paper seeks to answer is:

- *Does painting classroom roofs in Tanzania have the potential to be a cost-effective intervention for reducing classroom temperatures and improving learning outcomes?*

The research sub-questions, which are pertinent to different phases of the research, are as follows:

- Literature Review:
    - *How and why are learning interventions funded in Tanzania?*
    - *What is the evidence that links temperature and learning?*
    - *What classroom designs and classroom policy currently exists in Tanzania?*
    - *What are the key factors that influence classroom temperatures?*
    - *What are the options for retrofit interventions to reduce temperatures?*
- Experiment:
    - Pilot:
        - *What paints are available locally in Dar Es Salaam?*
        - *Which paint would be most appropriate for the intervention?*
    - Experiment:
        - *What are the daily temperatures in classrooms in Tanzania?*
        - *What effect does painting a classroom roof have on temperatures recorded?*
    - Learning Outcomes Analysis:
        - *Using data and insight from the existing literature, what is the predicted subsequent effect on learning from the temperature reduction identified?*
        - *What is the subsequent predicted cost effectiveness of the intervention in Learning Adjusted Years of Schooling per US$100 spent?*
        - *How does the intervention compare to other interventions available?*

2. Literature Review

2.1. Education

2.1.1. The Global Learning Crisis and Education Interventions in Tanzania

Question addressed:

- *How and why are learning interventions funded in Tanzania?*

From 1998 to 2008, the net[1] enrollment in primary education in Tanzania increased from 49.4% to 98.9% (The World Bank, 2020). Increasing school access was a key focus of the Millenium Development Goals and this rapid increase in enrollment is attributed largely to the introduction of fee-free education in 2001 (Valente, 2015; Lyanga and Chen, 2020; United Nations, no date). However whilst enrollment rapidly increased, the quality of education in Tanzania has either remained stagnant or fallen (Valente, 2015). This is a trend that has been observed globally in LMICs, with the sustained lack of learning improvement referred to as the ‘Global Learning Crisis’ by the World Bank (Al-Samarrai and Zaman, 2007; Imchen and Ndem, 2020).

In practice, the Global Learning Crisis means 75% children are unable to read a simple sentence after two-three years of study, as shown in a report focused on the experiences of Tanzania, Kenya and Uganda (Uwezo, 2013; World Bank, 2018). More recently, in Tanzania, a national study in 2017 showed only 45% of children in Standard 3 were able to complete basic tasks that were set at the Standard 2 level (Uwezo, 2019). Furthermore, 14% of children leave school after seven years of study, unable to read a basic Standard 2 level story (Uwezo, 2019).

In order to quantify the difference in learning levels across countries, Filmer *et al.* (2018) devised a measure for Learning Adjusted Year of Schooling (LAYS). The metric is calculated by comparing a year of schooling in a particular country, to the top performing country in the world, as shown in Equation 1. The learning data is normally collected through assessment data collection and using globally benchmarked assessments, such as the Programme for International Student Assessment (PISA) or Trends in International Mathematics and Science Study (TIMSS) (Filmer *et al.*, 2018). This provides a measure to compare education quality across countries, beyond the previously used metric ‘years of schooling’ which only gives a view on access to education not attainment.

$$LAYS_C = S_C \cdot \frac{L_C}{L_N}$$

(Equation 1)

Where:

$LAYS_C$ = Learning Adjusted Years of Schooling (LAYS) for country C

S_C = Years of Schooling for country C

L_C = Average learning-per-year in country C

L_N = Average learning-per-year in country N (often where where country N is the globalloy top performing country)

(Filmer *et al.*, 2018)

According to the latest World Bank (2020) Human Capital Index data, the expected LAYS for a child entering the education system in Tanzania is 4.48 years, despite an expected 7.22 years of schooling (shown in Fig. 2). This compares unfavourably with the global median

[1] Net Primary Enrollment ratio is the total number of primary school age children divided by the total number of children of primary school age in the country. The Gross Primary Enrollment ratio is the total number of children enrolled in primary school divided by the total number of children of primary school age in the country. Given that there are often children repeating years or enrol early, the gross enrollment ratio can be over 100% (as there are more children in school than of primary school age). (United Nations, 2013)

average at approximately 8 LAYS or with regional neighbour Kenya that scores 8.47 LAYS. Tanzania can therefore be regarded as being at the forefront of the 'Global Learning Crisis', and it is unsurprising that so many global actors are focused on addressing it.

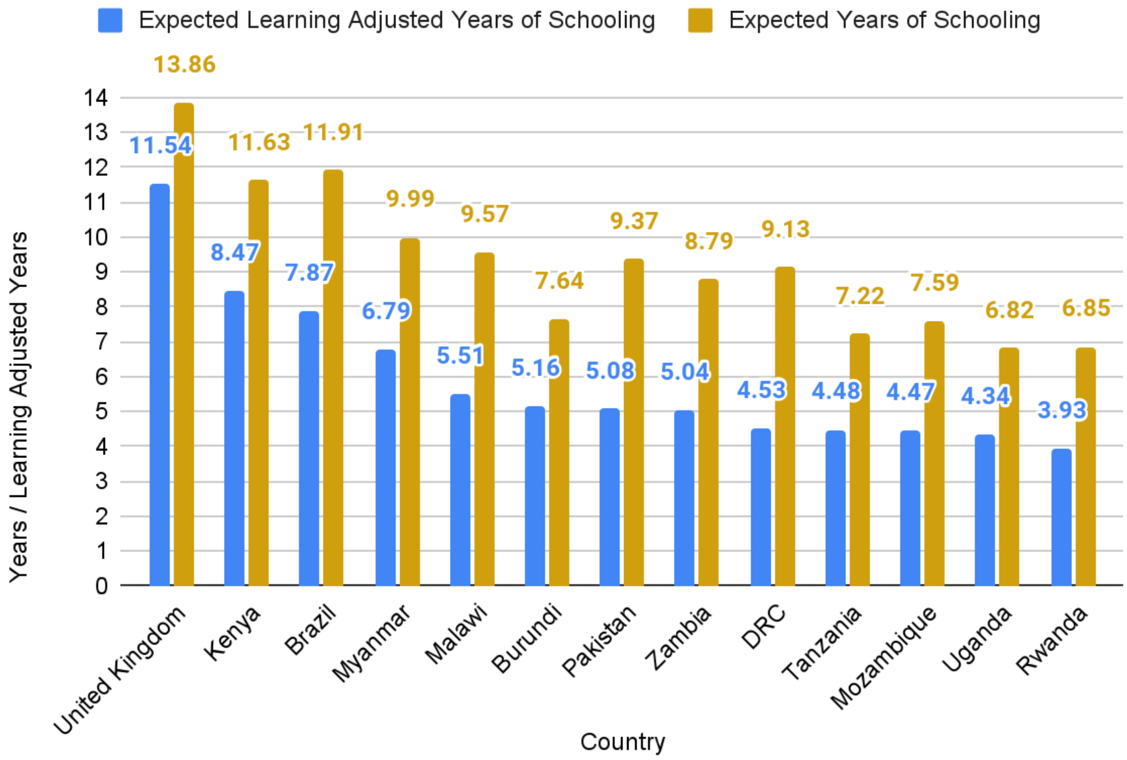


Figure 2: A graph showing the expected LAYS and the expected Years of Schooling for Tanzania, countries bordering Tanzania and a selection of global comparison countries (United Kingdom, Brazil, Pakistan, Myanmar).

Data source: (World Bank, 2020)

The risks attached to the learning crisis in Tanzania are exacerbated due to the predicted demographic transition (Lincoln, Ngasa and Luvanda, 2014; African Institute for Development Policy, 2018). As a country develops economically, it can experience a sharp decline in fertility and population growth. This has previously led to increases in the ratio of working age people to dependents, providing a temporary and powerful economic boost. This concept was first coined by Bloom, Canning and Sevilla (2003) as the 'demographic dividend'. In Tanzania, many organisations are working to support the Government in leveraging this demographic dividend, including the African Institute for Development Policy, the Gates Foundation and the UK Government (Lincoln, Ngasa and Luvanda, 2014; African Institute for Development Policy, 2018). In order to take full advantage of the demographic dividend, it is necessary to improve learning, so the growing workforce has the potential to engage in decent and productive work (African Institute for Development Policy, 2018). The need to improve learning is often described as increasing human capital, the combination of education and health capital of a population, and a population's subsequent productivity (Kraay, 2019). On the flip side, there are concerns about potential instability and conflict which could result from millions of unemployed youth, without the education to engage productively in the labour market (Reid and Smith, 1981; Lee and Reher, 2011; Azeng and Yogo, 2015; Canning, Raja and Yazbeck, no date). Hence the implications of the learning crisis are wider than simply ensuring children can read and write. Education is the very foundation for Tanzania as it moves through economic development and demographic shift.

Given the education quality constraints outlined, and the broad economic and social implications, education financing by multilateral and bilateral donors is largely focused on initiatives to improve learning outcomes (DFID, 2018; USAID, 2018; SIDA, 2020; Ahlgren *et al.*, 2022). In Tanzania, the majority of the finance for education system development is provided by these organisations. This is because the bulk of the domestic funding for education is used for non-development recurrent costs (such as salaries) with additional financing mostly used for school construction (UNICEF Tanzania, 2018; UNICEF, 2020). Therefore, in order to make an effective case for an education intervention (which donors will consider funding), it likely needs a demonstrable causal link to learning outcomes backed by independent research. Furthermore, it needs to show that the money would be spent in a cost-effective way compared to other potential interventions (such as those in Fig. 3). This approach has been underlined in the global Smart Buys Paper (Global Education Evidence Advisory Panel, 2020).

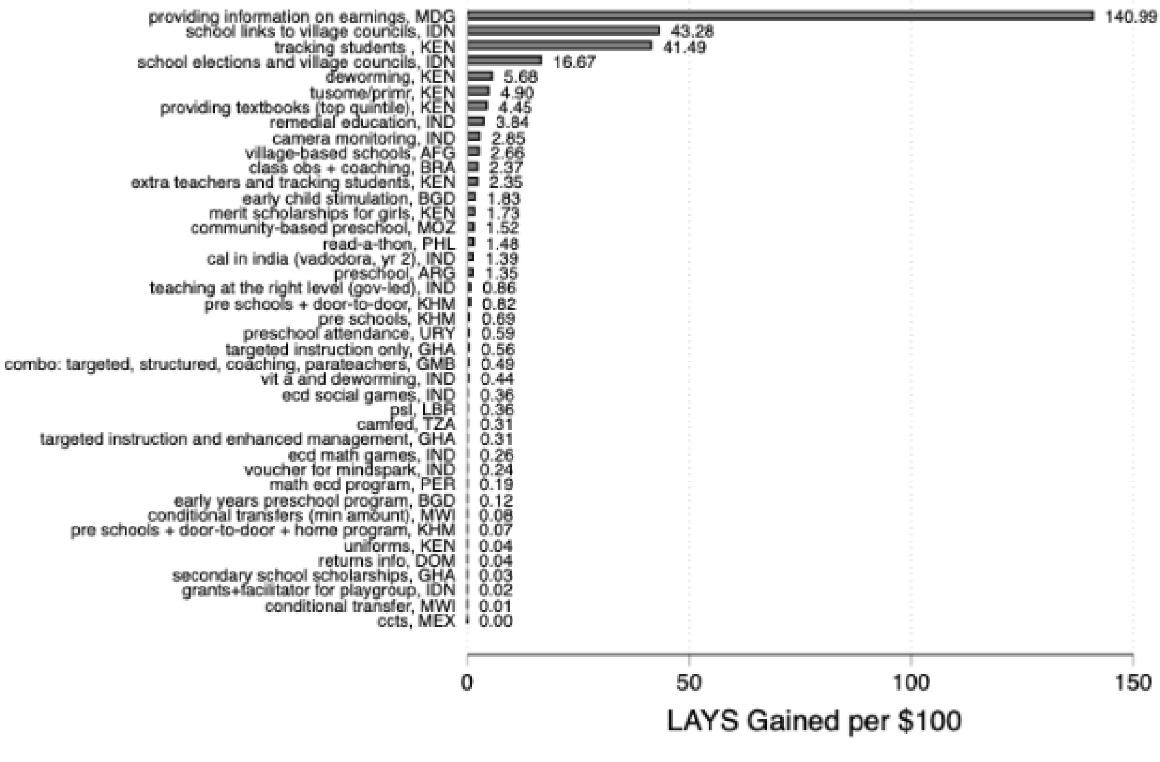


Figure 3: Learning Adjusted Years of Schooling (LAYS) per US$100 spent for various interventions.

Source: (Angrist *et al.*, 2020)

This section of the paper has shown there is an evidential need for improved learning in schools in Tanzania. Further, the implications of poor learning outcomes are wider than the education sector and underscore any demographic dividend. To be considered an education intervention, the proposal to reduce classroom temperature will need to demonstrate a pathway to improvement in learning, rather than simply improving student comfort. Therefore, the next section will review the linkages between temperature and learning.

2.1.2. Temperature and Learning

Question addressed:

- *What is the evidence that links temperature and learning?*

Research into temperature and classrooms goes back to at least the early 1900's. The New York Commission on Ventilation included a view on temperature, highlighting that classroom temperature should be 20℃ or at least between 19.4℃ and 22.8℃ (New York Commission on Ventilation, 1932; Earthman, 2002). However, little of this research is experimental in design, and often focuses on thermal comfort or health outcomes, rather than learning as the outcome. For example, a study by Shamaki (2015) looked at the impact of classroom infrastructure (including temperature) on student experience, but limited data collection to student perception. Therefore, it was not possible to assess the impact on student learning from the study findings. The two most important papers in relation to temperature and learning focus on experimental data: a 2019 meta analysis on the topic and a 2020 retrospective analysis of 10 million students' Preliminary Scholastic Aptitude Test (PSAT) results (Wargocki, Porras-Salazar and Contreras-Espinoza, 2019; Park *et al.*, 2020).

The Wargocki *et al.* (2019) meta analysis reviews data from 18 experimental studies, mainly from the Global North. Their work predicts that students' performance in psychological tests and school tasks can be expected to increase on average by 20% if classroom temperatures are reduced from 30°C to 20°C. This is strong evidence of the link between learning outcomes and temperature. The Park *et al.* (2020) study retrospectively analysed data from 10 million students who retook the PSAT examination in the USA. The study demonstrates that the relationship between temperature and learning is causal. It goes on to suggest that the cumulative learning impacts caused by heat may be mitigated by school air conditioning. The study suggests that reducing temperature by 1°C increased learning by 2% for the average student (Park *et al.*, 2020).

The weakness in the existing research, in relation to learning outcomes in Tanzania, is that most studies use data from the Global North and not from LMICs. The classroom temperatures assessed in these studies have been much lower than would be expected in Tanzania - with the vast majority of studies assessing temperatures between 20℃ and 30℃ (Bidassey-Manilal *et al.*, 2016; Wargocki, Porras-Salazar and Contreras-Espinoza, 2019; Proctor, 2021). Whereas, temperatures in Tanzania and similar regions have been recorded at over 40℃.

From the Global South, a 2016 review of Temperature Extremes and Human Capital in LMICs asserts that "ambient temperature as well as the heat generated by the brain itself, can impede mental processes, thereby creating the potential for heat to hinder learning" (Zivin and Shrader, 2016). However, the paper goes on to note that there is limited direct evidence to support this link and, since this paper was published in 2016, little new research has been produced during the intervening period to date (Zivin and Shrader, 2016). It is interesting to note that a 29-page paper looking at the impact of climate change on children in LMICs, dedicated only 4 lines to learning outcomes, focussing instead on the health impact of climate change on human development. This focus may be explained by the health-centric approach of some donors, such as USAID which in 2020 in Tanzania spent US$281 million on health and US$14 million on education initiatives (USAID, no date).

Whilst health outcomes are relevant to learning outcomes, particularly the impacts of Early Childhood Development (ECD), which have been illustrated effectively by Grantham-Mcgregor, they can miss the importance of education, leading to a gap in the literature around the impact of temperature on learning (Grantham-McGregor *et al.*, 2007; Global Education Evidence Advisory Panel, 2020; Grantham *et al.*, 2020).

However there is good reason to believe that the effects of temperature on learning outcomes apply in LMICs. Firstly, the physiological impact of temperature has been shown extensively, including in LMICs (Abbasi *et al.*, 2019). Fig. 4 shows the limits of human core body temperatures, with death occurring from 42℃. The body uses multiple mechanisms to keep core temperatures low when exposed to higher temperatures (Kuht and Farmery, 2014). Despite this mitigation, temperatures above 30°C have been shown to impact heart rate, accuracy of brain executive functions and response time to stimuli (Abbasi *et al.*, 2019).

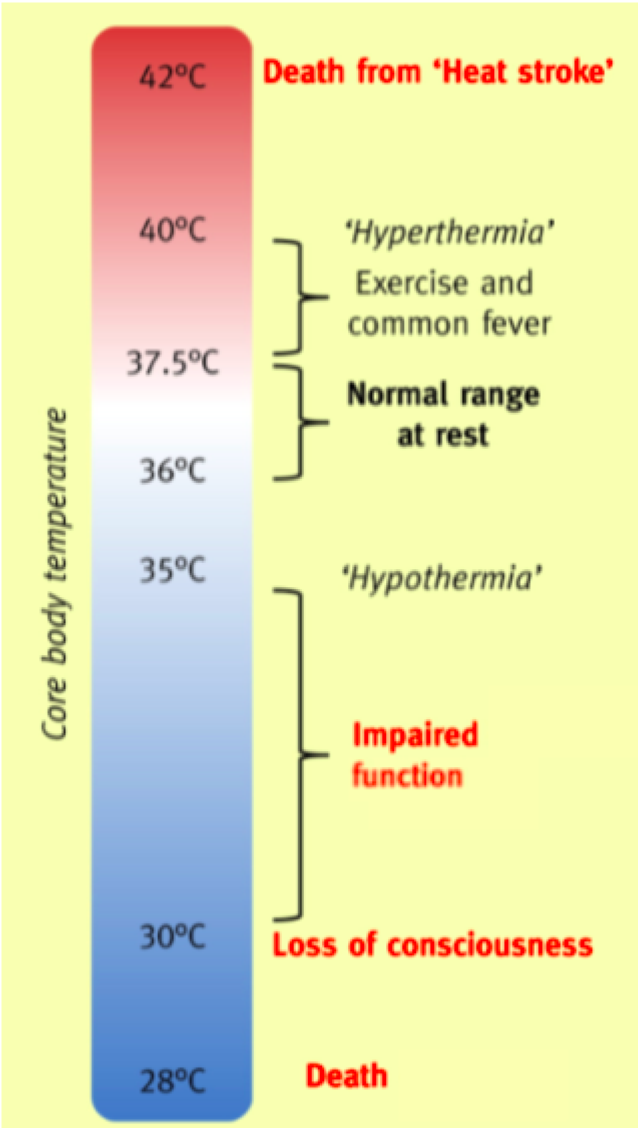


Figure 4: Normal range of core body temperature, and the impact of temperature changes. Source: (Kuht and Farmery, 2014)

Secondly, work to understand thermal comfort has been conducted, which shows that although thermal comfort in the region is higher, it is not very significantly higher (Malama *et al.*, 1998; Eyre *et al.*, 2016). This is discussed further in Section 2.2.2.1.5. Finally, the temperatures in the Global South are likely to be higher than those investigated in the Global North. For example, classroom temperatures in South Africa were recorded up to 53.8℃ and a model predicting temperatures in the region identified temperatures upwards of 37℃ (Bidassey-Manilal *et al.*, 2016; Proctor, 2021). These temperatures are also likely to increase due to climate change (IPCC, 2021). Given that temperatures are higher than in the Global North, it is unlikely that the impact on learning will be lower. Using Global North estimates on learning impact as a benchmark for the intervention in the Global South seems reasonable, but only up to temperatures around 40℃, before additional physiological impacts are introduced (Kuht and Farmery, 2014).

In order to address high temperatures, Park *et al.* (2020) suggest using air conditioners to reduce classroom temperatures. However this is unimplementable at scale in Tanzania, due to financial implications. Proctor (2021) reviewed options for temperature reduction, which are sufficiently low cost to be taken forward in Tanzania. This analysis suggested roof painting presents the most cost-effective option (discussed further in Section 2.2.3.1). Therefore, this paper will build on the work by experimentally testing an option to reduce temperature which is more contextually appropriate for Tanzania than air conditioning (detailed further in the section on retrofit intervention options).

2.2. Building and Infrastructure

2.2.1. Classrooms in Tanzania

Answering the question:

- *What classroom designs and classroom policy currently exists in Tanzania?*

There are around 125,000 primary school classrooms in Tanzania, across a primary school age population of 10 million children (UNICEF Tanzania, 2018; PO-RALG, 2019). The Government of Tanzania has developed various documents, plans and strategies to guide classroom infrastructure development. The overarching strategy is outlined in the School Construction And Maintenance Strategy: 2019 - 2028 (MOEST, 2020b). This focuses on what is required at each school, such as the number of classrooms, and does not include any technical specifications. Technical specifications for classrooms are laid out in the Primary School Design Guidelines (MOEST, 2019). These technical specifications are then costed (at a very high level) in the School Construction And Maintenance Costed Plan: 2020 - 2024 (MOEST, 2020a).

A key point to note in the plans is that corrugated metal roofs have replaced vernacular thatched roofs (Tusting *et al.*, 2019; Carrasco-Tenezaca *et al.*, 2021). This change has introduced increased internal temperatures in classrooms (Carrasco-Tenezaca *et al.*, 2021). However, as metal roofs are cheaper to construct and last longer, they have become the status-quo, as reflected in the government strategy and designs (MOEST, 2019, 2020a; Carrasco-Tenezaca *et al.*, 2021).

The technical specifications are very detailed, with a specific Bill of Quantities (BOQ) (Fig. 5), construction plans and architectural diagrams (Fig. 6). There are three different classroom and office designs detailed. The BOQ specifically highlights that roofing panels should be high quality and be factory resin coated, as shown in Fig. 7. However it does not specify the colour to be used.

C.	**ROOF STRUCTURE & COVERING**				
1	**Roof Structure -** Provisional (5.2m long)				
	Timber 2 " X 2" Purlins	66	PC'S		
	Timber 2" X 4" King Post, wall plate and struts	73	PC'S		
	Timber 2" X 6" Rafter and Tie beam	75	PC'S		
	Fascia board 1" X 10" (5.2m long)	14	PC'S		
	Nails -5"	75	Kgs		
	Nails -4"	50	Kgs		
	Nails -3"	25	Kgs		
	NOTE: The above softwood timber structure should be pressure impregnated treated				
2	**Roof Covering -as per ALAF or equal and approved**				
	28G IT5 resincoated sheet	257	M^2		
	Hips/Ridge and valley - 28 G (3m long)	13	PC'S		
	Roofing Nails	26	Packet		
	TO COLLECTION			**C/F**	

Figure 5: Extract from BOQ for Classroom Construction, showing the requirement for resin-coated, high quality (IT5 28G) corrugated steel roofing.

Source: (MOEST, 2019)

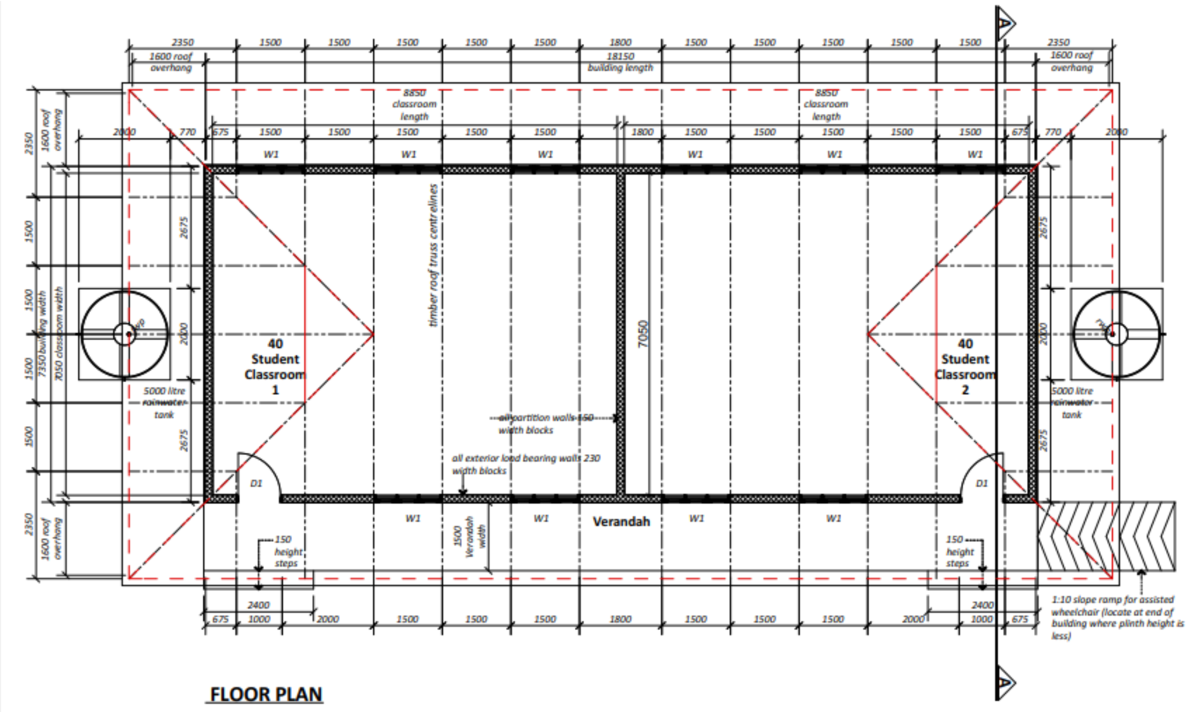
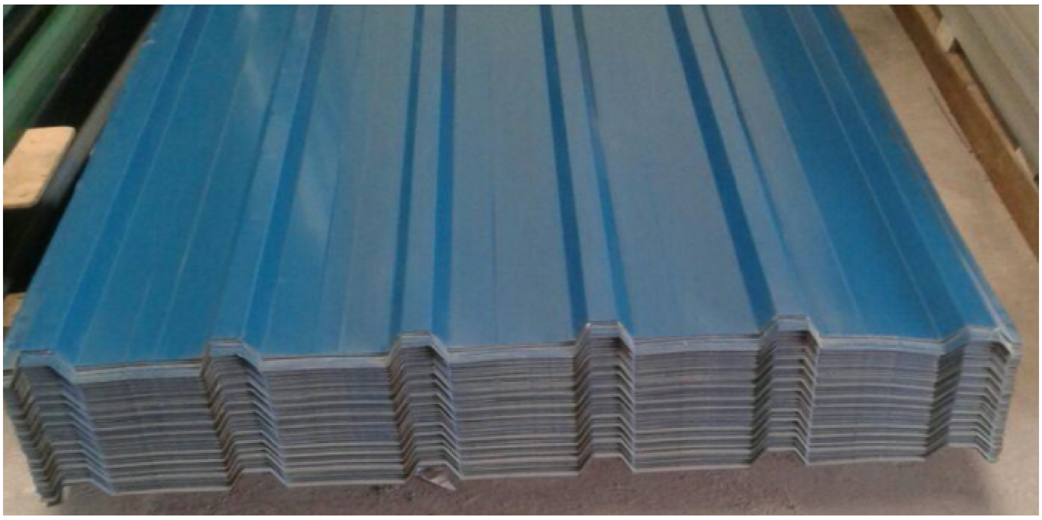


Figure 6: Floor plan of a standard two classroom block construction.

Source: (MOEST, 2019)



Industrial trough (IT5) sheets

Available Gauges are: 28G & 26G for IT5 and are: 30G & 28G for IT4

Category	Overall width (mm)	Cover width (mm)	Pitch (mm)	Depth (mm)	Coating class (g/m^2)
IT5	985	925	190	32	AZ 111.65

Figure 7: Picture and details of the specific resin covered, 28 Gauge, IT5 corrugated roofing sheet, as outlined in the school designs.

Source: (Waja Mabati, no date)

In practice, it is clear that many of the specifics of the plans and drawings are not widely used. Tanzania's National Audit Office (NAO) undertook a review and found that "Primary schools, particularly public schools have poor, dilapidated and insufficient infrastructure" (National Audit Office, 2017, p. 65). The reasons for these deviations is likely to do with how the construction is procured and delivered. The construction strategy directs that procurement should be delegated to individual School Management Committees (SMCs), who work with the community to deliver the buildings (MOEST, 2020b). This approach has been shown to be much cheaper than national or international procurement processes, as shown in Table 1 (Theunynck, 2009; Bonner *et al.*, 2010; Proctor, Forthcoming). However, this delegated approach does mean that technical changes to designs are left up to SMCs and therefore will be specific to each school.

Procurement Route	Av. Cost per classroom (US$)	When likely useful?
Delegation to Communities from NGOs	5200	At scale, low complexity, primary school infrastructure development
Delegation to Communities from Local Government	6175	At scale, low complexity, primary school infrastructure development
Delegation to Communities from Ministry	6695	At scale, low complexity, primary school infrastructure development
Local Government - National or Local Competitive Bidding	11180	Higher specification and complexity buildings, such as two-storey secondary schools
Delegation to NGOs acting as Contractors	11700	Higher specification and complexity buildings, such as two-storey secondary schools
Central Ministry - National Competitive Bidding	12285	Higher specification and complexity buildings, such as two-storey secondary schools
Delegation to Project Implementation Unit/Contract Management Agency	12350	Where there are specific issues with delegation to government, and there are no NGO options
Central Ministry - International Competitive Bidding	17485	Very high spec projects where there is not the capacity available in country

Table 1: Showing the main routes to procuring classroom construction, their associated costs (averaged from previous projects) and analysis of where the different procurement routes are most suited.

Source: (Theunynck, 2009; Bonner *et al.*, 2010; Proctor, Forthcoming)

Furthermore, there is specific provision in the construction strategy allowing schools to deviate from the plans where cheaper local materials are available (MOEST, 2020b). In Tanzania there is a huge shortage of school infrastructure with an average of 81 students per classroom in Government primary schools (PORALG, 2018 cited in UNICEF, 2020). In practice, this means in some parts of the country class sizes can often exceed 100. Given the shortage in classrooms it is unsurprising that, in practice, classroom construction does not meet the quality specifications detailed in the approved designs. Instead, budgets are used to deliver a larger number of cheaper classrooms. Specifically, this includes buying cheaper unpainted corrugated steel roofing. Anecdotally, the author visited five schools during the duration of the research, none of which had a single classroom with a painted roof (examples shown in Fig. 8).

Figure 8: Examples of classroom blocks visited by the author over the course of the research.

Therefore, it can only be assumed that the general outline of the building plans is adhered to. This general outline is referenced in all of the relevant documents - the strategy, cost plan, designs and other government documents - however the detail of design is likely not implemented (National Audit Office, 2017; MOEST, 2019, 2020a, 2020b). The result is that most classrooms are a double or triple classroom block; these classrooms are usually built from the cheapest materials (locally burnt bricks and mortar); and the roofs are timber framed with corrugated iron cover, as shown in the classroom in Fig. 8.

2.2.2. Factors affecting Building temperatures

Question assessed:

- *What are the key factors that influence classroom temperatures?*

Table 2 shows some of the key factors that affect the interior air temperature and perceived temperature in a classroom. By examining the key factors that affect temperature, the most relevant options to reduce temperature and therefore improve learning can be explored. This section will therefore cover the areas from the table above which are linked to air temperature: weather, building design, heat from people and factors affecting thermal comfort. This analysis will focus on the two or three classroom blocks outlined in the previous section.

Category	**Factor**
Weather	**Solar Irradiance**
	Temperature
	Humidity
	Windspeed
Building Design	**Movement of heat through roof and wall: through radiant absorptivity, emissivity, conduction**
	Roof, wall and floor thermal mass
	Ventilation
Heat from people and factors affecting thermal comfort	**Heat from people**
	Clothing
	Positioning (particularly whether on chairs or floor) and posture
	Acclimatisation

Table 2: Key factors that affect the interior air temperature and perceived temperature in a classroom.

2.2.2.1. Building Design and Heat from People

It has been observed that large temperature differences can occur in buildings of different architectural styles. For example, in Burkina Faso, Pohl *et al.* (2021) found temperature differences exceeding 10℃ between houses built with different materials. These findings demonstrate the complexity of internal temperatures, and how important the impacts of heat may become, especially exacerbated by climate change (Pohl *et al.*, 2021). Even though classroom construction tends to follow a broadly similar design in Tanzania, variances in material selection, window placement and positioning can significantly affect temperatures.

There are very few published datasets of recorded classroom temperatures in Tanzania or the surrounding countries, which limits further investigation and analysis without field studies to gather additional primary data. For example, von Seidlein *et al.* (2017) measured housing temperatures and mosquito prevalence in a rural part of Tanzania's Tanga region. Given that the focus was on acceptability and mosquito reduction, very little data was published on temperatures, other than annual mean temperatures.

Bringing the factors outlined in the previous section together into a model may allow the prediction of temperatures inside a classroom block in other locations in Tanzania using existing weather data. This modelling was undertaken by the author in 2021. The novel model was built from base equations, using Google Sheets, rather than existing software. [The model is available here]() (Proctor, 2021). Other researchers have used software to predict temperatures inside buildings in the region. Eyre *et al.* (2016) used the Integrated Environmental Solutions Virtual Environment software to analyse housing designs in Tanzania, and Kalua (2016) used the Energy Plus software to improve the envelope thermal design of residential buildings in Malawi. The benefit of this type of software is that more complex features, like thermal bridging, can be incorporated into the model, as well as reducing primary data gathering efforts. Modelling is clearly a helpful tool to develop research and identify areas of improvement. However, real world experimental data is also required to test these models. Otherwise seemingly small discrepancies, such as the reflectivity of aged corrugated steel roofing, which varies from 0.1-0.36 dependent on source, can have a large impact on the recorded temperatures (Bretz *et al.*, 1992; CIBSE, 2006; Eyre *et al.*, 2016; Turner J and Parisi Av, 2018).

The important heat flow processes for this type of building are solar irradiance and subsequent solar gains, absorption of heat by thermal mass, ventilation and heat from occupants. These processes are detailed in the following subsections, with the key factors drawn out and described mathematically. Fig. 9 and Table 3 show the modelled heat transfer for a classroom in Malawi, and suggest the majority of heat transfer comes through the solar gains and ventilation (Proctor, 2021). Heat from people and conduction are shown to be much lower, and the implications of this are discussed in the subsequent section.

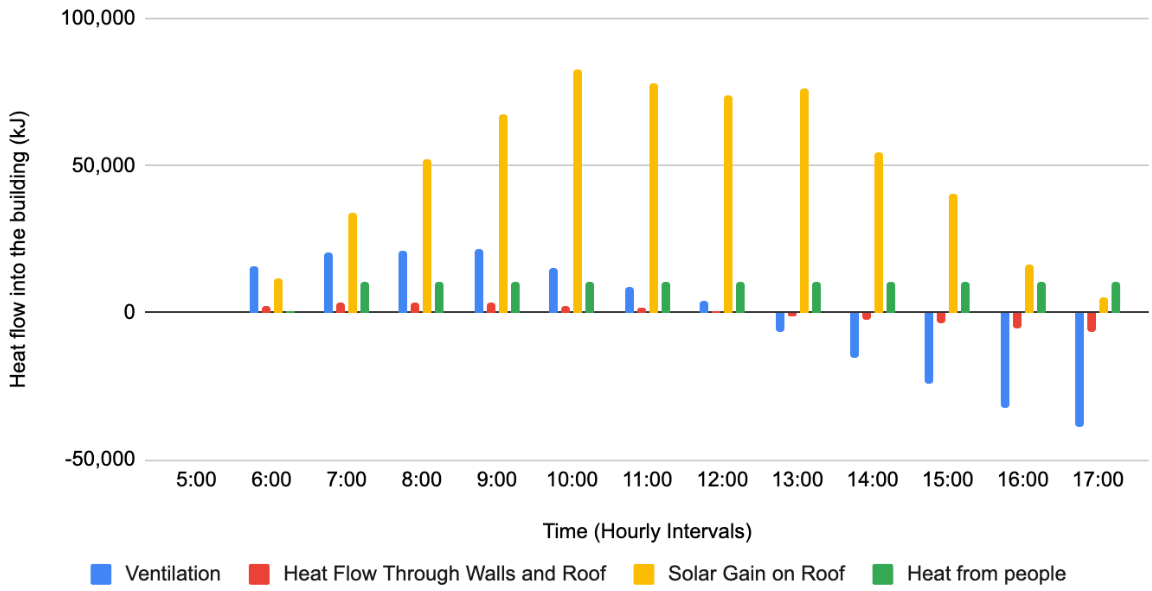


Figure 9: Heat flow into the building at hourly intervals - extracted from a proposed model for a classroom block in Malawi.

Source: (Proctor, 2021)

	Ventilation	Conduction - heat flow through walls and roof	Solar gain on roof	Heat from people
Absolute heat flow total (kJ)	116,634	18,810	525,338	82,944
Absolute heat flow as a percentage of total	15.68%	2.53%	70.64%	11.15%

Table 3: Heat flow through a classroom block - split by different factors, each showing the absolute total of heat flow. The data was analysed using an online classroom block temperature model published by Proctor (2021).

Data Source: (Proctor, 2021)

2.2.2.1.1. Solar irradiance, radiant heat transfer and reflection

Solar rays hitting the roof are initially reflected or absorbed. The ratio of rays reflected compared to absorbed is known as the albedo (ρ). Once the solar rays are absorbed, the heat is either transferred as conduction through the building, transferred as radiation, or transferred by convection, as shown in Fig. 10.

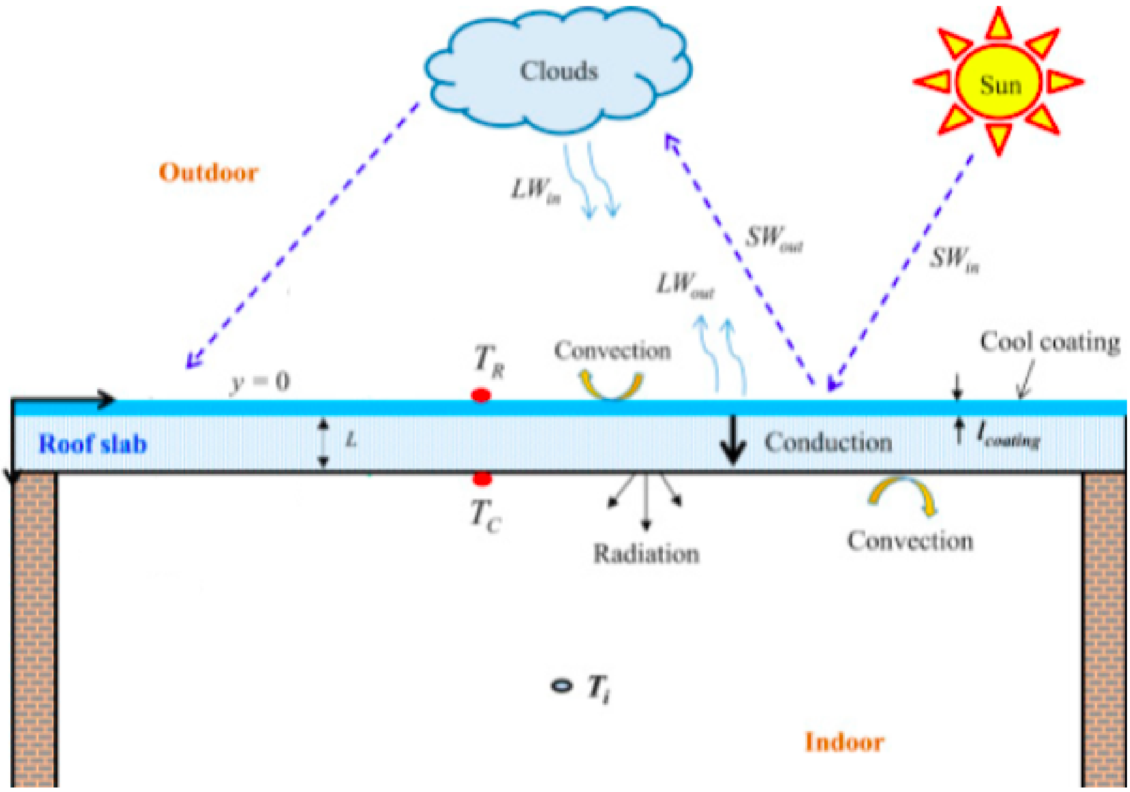


Figure 10: Showing the movement of heat through a roof. The roof shown here is a flat roof, but the same heat flow processes apply to a sloped roof on a classroom block. The Incident (I) radiation on the roof is given by assessing the short wave radiation (SW) radiation directly from the sun and the longwave radiation (LW), reflected from clouds and the atmosphere. Equation (2) governs the radiation absorbed by the roof. Equation (3) gives the relationship of the heat transfer across the roof, accounting for emittance and reflectivity.

Source: (Zingre *et al.*, 2015)

$$I = (SW_{in} + LW_{in})$$

Where:

$I = Solar\ irradiance\ (W/m^2)$

$SW_{in} = Short\ wave\ radiation\ hitting\ the\ roof\ (W/m^2)$

$LW_{in} = Long\ wave\ radiation\ hitting\ the\ roof\ (W/m^2)$

(Equation 2)

(Zingre *et al.*, 2015)

The following equation determines the heat flow into a classroom from solar irradiance. The same applies to the sun's rays hitting the walls, which will absorb energy using the same equation, but with different coefficients.

$$Q_{sr} = I.A.(1 - \rho).E_c.\ t$$

Where:

$Q_{sr} = Heat\ through\ roof\ (J)$

$I = Solar\ irradiance\ (W/m^2)$

$A = Area\ of\ roof\ (m^2)$

$\rho = Solar\ Reflectivity\ (Albedo)$

$E_c = Coefficient\ of\ emittance\ into\ classroom$

$t = Time\ period\ (s)$

(Equation 3)

(Qin *et al.*, 2017)

Heat absorbed by the roof is emitted into the classroom and upwards away from the roof. The biggest factor affecting the emissivity into the classroom is whether there is an insulating layer below the roof. As previously discussed, there are few ceilings or insulation in classrooms in Tanzania. In the case that the corrugate is unpainted, then it can be assumed that absorbed heat is equally emitted up into the sky and down into the classroom (Proctor, 2021).

To summarise, in order to stop heat transfer into the building, it is required to either increase the albedo (solar reflectance) or reduce the emittance into the classroom (and increase the emittance away from the classroom). Fig. 9 and Table 3 suggest that the solar heat gain is the most significant mechanism in moving heat into the building, accounting for 71% of the heat flow. Furthermore, this heat flow is only increasing heat gains, whereas ventilation for example has both a heating and cooling effect at different parts of the day.

2.2.2.1.2. Ventilation

Ventilation is a very significant factor in classroom block temperatures (Proctor, 2021). The movement of heat is dependent on the flow of air through the building, measured in air changes per hour. This variable is dependent on the wind speed and the permeability of the building envelope. Given that school buildings tend to have windows without glass (shown in Fig. 11), there is a high level of permeability.

Figure 11: Shows the unglazed windows, which are common across classroom blocks in Tanzania.

At the start of the day, the air temperature is lower outside the classroom than inside, therefore the ventilation will have a heating effect. However, at some point in the morning, the air temperature in the classroom becomes higher than the air temperature outside, meaning that the ventilations shifts to having a cooling effect. This suggests that reducing ventilation in the morning would delay the classroom heating up, and then increasing ventilation in the afternoon would have a cooling effect. The heat flow can be estimated using Equation 4 below.

$$Q_v = N.V.\frac{T_1 - T_2}{3}.t$$

Where:

$Q_v = Heat\ change\ from\ ventilation\ (J)$

$N = Number\ of\ air\ changes\ per\ hour$

$V = Volume\ of\ the\ classroom\ (m^3)$

$T_1 = Temperature\ inside\ (K)$

$T_2 = Temperature\ outside\ (K)$

$t = Time\ period\ (s)$

(Equation 4)

(OpenLearn, no date)

2.2.2.1.3. Heat conduction through walls and roof

Heat energy will move through the roof and walls, from higher temperature to lower temperature, through conduction. The heat flow can be estimated using Equation 5.

$$Q_U = (\Sigma(A.U.(T_1 - T_2)).t$$

Where:

$Q_U = Heat\ movement\ through\ walls\ and\ ceiling\ (J)$

$U = Heat\ flow\ through\ material(s)\ (w/m^2.K)$

$A = Area\ walls\ and\ ceiling\ (m^2)$

$T_1 = Temperature\ inside\ (K)$

$T_2 = Temperature\ outside\ (K)$

$t = Time\ period\ (s)$

(Equation 5)

(Gorgolewski, 2007)

The heat flow can move in either direction, or stop if the temperature inside and outside is equal. The conduction rate (U) is dependent on the materials used in the roof or wall in question. The conduction properties of particular materials have been tested and outlined in documents such as CIBSE Guide A (CIBSE, 2006).

Although this equation is useful to estimate heat conduction, it does have a number of limitations. First, thermal bridges are normally present and are not easy to account for in a model. Even when a thermal bridge is accounted for with a separate U value, the bridge changes the dynamic heat transfer characteristics of the envelope (Ge, McClung and Zhang, 2013; Ge and Baba, 2015). It is possible to try and account for thermal bridges with more complex modelling.

However, the heat flow via conduction is proportionally very small compared to the other factors. Only 2.5% of the absolute heat flow is through conduction. Therefore, when reviewing retrofit options to reduce temperatures, it makes sense to discount the options that focus on reducing conduction.

2.2.2.1.4. Mass

The thermal mass of the building includes the mass in the walls, roof, floor and structure. The thermal mass acts to delay temperature change, by absorbing or emitting heat to the classroom (depending on whether the temperature is going up or down). A higher thermal mass would therefore act in a cooling way during much of the day, as the mass loses heat during the night. Introducing additional thermal mass, is a common method of reducing high temperatures (Braun, 2003; Al-Sanea, Zedan and Al-Hussain, 2012; Beckett and Ciancio, 2012; Wang *et al.*, 2014; Wonorahardjo, Sutjahja and Kurnia, 2019). However adding thermal mass is not effective where there is a significant heat flow into the mass, because the higher the heat flow the shorter time it takes for the heat flow to balance (Al-Sanea, Zedan and Al-Hussain, 2012). The heat required to increase the temperature of thermal mass is given in Equation 6. Given that the solar heat gains and ventilation effects are relatively large, it is unlikely that a thermal mass retrofit would have a significant effect on temperatures.

$$C_B = \sum(mc)$$

Where:
$C_B = Heat\ capacity\ of\ building\ (J/K)$
$m = Mass\ of\ component\ (kg)$
$c = Specific\ heat\ capacity\ of\ component\ (J/kg.K)$

(Equation 6)

(Tro NJ, 2020)

2.2.2.1.5. Heat From People & Thermal Comfort

The heat generated from children is less than from adults. However given the average class size in Tanzania is 81, this heat would still be a non-negligible contribution to temperatures over the course of a school day. The heat from people is split into latent heat and sensible heat as shown in Table 4, with the estimated heat gain from children half of adults (CIBSE, 2006; Proctor, 2021). Both latent and sensible effects would contribute to warming over the course of a school day. Using the classroom temperature model, the temperature in a classroom with 81 children would be on average 2.5℃ higher, with a peak of 3.3℃.

Who	**Degree of activity**	**Rate of heat emission for mixture of males and females (Watts)**		
		Total	**Sensible**	**Latent**
Adults	Moderate office work	130	75	55
Children		65	37.5	27.5

Table 4: Showing estimated sensible and latent heat gains from adults and children.

Source: (CIBSE, 2006; Proctor, 2021)

Thermal Comfort has been previously defined as “the state of mind that expresses thermal satisfaction with the surrounding environment” (Adrian *et al.*, 2008). Thermal Comfort is not solely linked to air temperatures. There is an active debate as to how the different factors come together to affect Thermal Comfort. The likely relevant factors to be considered in relation to classroom temperatures are outlined in Table 3.

Type of Factor	Factor
Physical variables	Air temperature
	Air velocity
	Relative humidity
	Mean radiant temperature
Personal variables	Clothing insulation
	Activity level
Adaptation	Physical adaptation to the thermal environment
	Psychological adaptation to the thermal environment

Table 5: Shows important factors in Thermal Comfort, relevant to this research.

Source: (Macpherson, 1962; Djongyang, Tchinda and Njomo, 2010; Kim, Shin and Cho, 2021)

Thermal Comfort is contextual and is as much about people's perception and experience as it is about measurable building conditions (Kim, Shin and Cho, 2021). The concept of Thermal Comfort is important to consider, because if the Thermal Comfort levels align with classroom temperatures, then it is at least conceivable that classroom temperatures do not impact learning. However, it appears this is unlikely for two reasons. Firstl, previous research shows that Thermal Comfort levels for the region are much lower than expected temperatures. Studies in Malawi and Zambia, which are to some extent comparable with Tanzania, suggest a Thermal Comfort range of 23.5–28.5°C with a mid-point of 24.6°C (Malama *et al.*, 1998; Zingano, 2001). Second, it may be that Thermal Comfort is not linked to learning outcomes in the same way as temperature alone, as shown in Causal Pathway (b) in Fig. 12. One paper has claimed that learning and Thermal Comfort are linked, but only one study with a small sample was identified and this fails to interrogate both causal pathways fully (Jiang *et al.*, 2018). There are few Thermal Comfort studies conducted in African cities, including Tanzania, so it is likely that limitations to the study will be introduced aligned to the identified factors above (Yahia *et al.*, 2018).

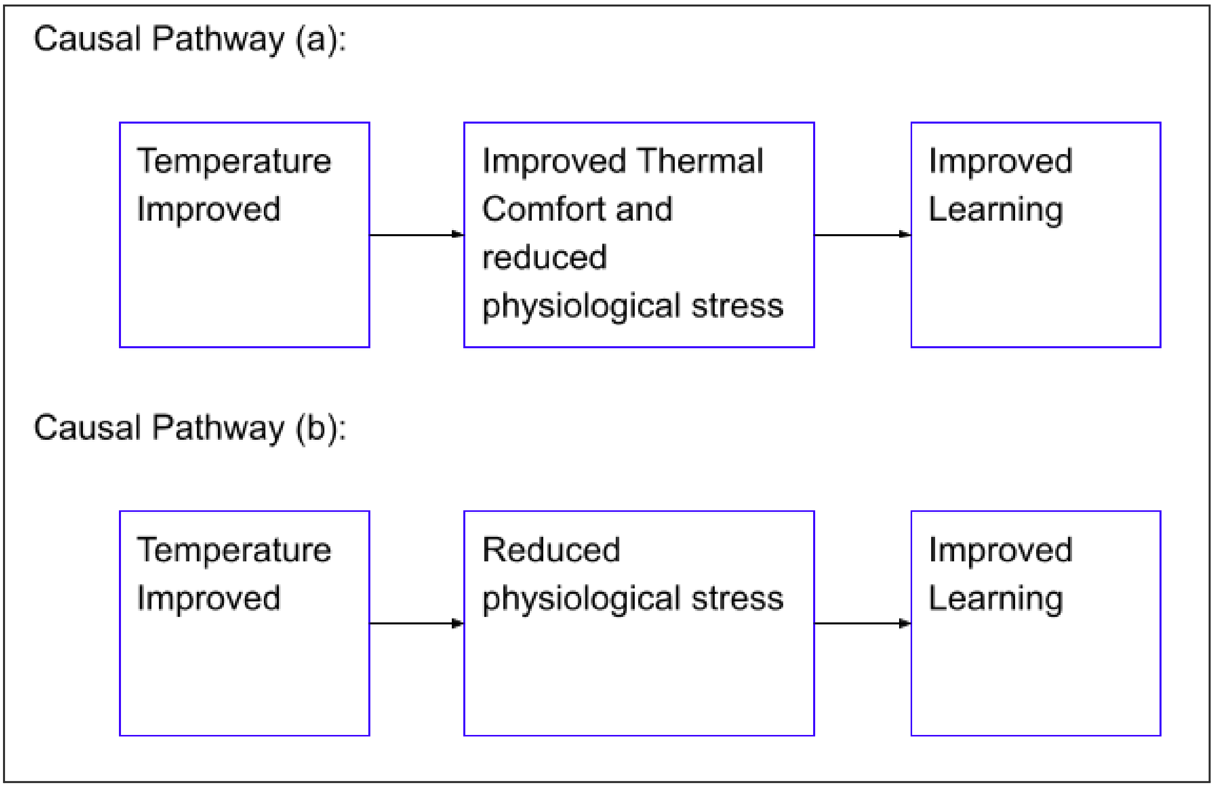


Figure 12: Two causal pathways showing the link between temperature and learning. Causal Pathway (a) includes Thermal Comfort and Causal Pathway (b) does not.

2.2.2.1.6. Heat conduction through walls and roof

Heat energy will move through the roof and walls, from higher temperature to lower temperature, through conduction following Equation 7.

$$Q_U = (\Sigma(A.U.(T_1 - T_2)).t$$

Where:

$Q_U = Heat\ movement\ through\ walls\ and\ ceiling\ (J)$

$U = Heat\ flow\ through\ material(s)\ (w/m^2.K)$

$A = Area\ walls\ and\ ceiling\ (m^2)$

$T_1 = Temperature\ inside\ (K)$

$T_2 = Temperature\ outside\ (K)$

$t = Time\ period\ (s)$

(Equation 7)

(Gorgolewski, 2007)

The heat flow can move in either direction, or stop if temperatures inside and outside are equal. The conduction rate (U) is dependent on the materials used in the roof or wall in question. The conduction of particular materials has been tested and outlined in documents such as CIBSE Guide A (CIBSE, 2006).

Although this equation is useful to estimate heat conduction, it does have a number of limitations. First, thermal bridges are normally present and not easy to account for. Even where a thermal bridge is accounted for with a separate U value, the bridges change the dynamic heat transfer characteristics of the envelope (Ge, McClung and Zhang, 2013; Ge and Baba, 2015). It is possible to try and account for thermal bridges with more complex modelling. However the conduction heat flow is likely to play only a very minor role in the temperature of the building, accounting for only 2.5% of heat flow as outlined in Table 3. Therefore, it makes sense to discount the overall effect when considering retrofit options.

2.2.2.2. Weather and weather data in Tanzania

The weather drives the heat flow in Tanzanian classrooms, so understanding and predicting weather conditions is a vital component of understanding internal temperatures. As outlined in the previous section, the overall shape and dimensions of classrooms are likely to be comparable across the country. However, the precise building specifications are likely to vary significantly. Furthermore, very variable weather conditions will compound the heterogeneity of classroom temperatures. This section will focus on weather variability and the availability of weather data.

The weather in Tanzania is highly variable by both location and changing patterns over time (Waniha, 2018; Walker *et al.*, 2019; Msemo *et al.*, 2021). There are two distinct seasonal patterns: in the North there are two rainy seasons per year (bimodal) and only one rainy season each year (unimodal) in the rest of the country, as shown in Fig. 13 (Lahunga *et al.*, 2016; Walker *et al.*, 2019). Furthermore, Tanzania is highly vulnerable to rainfall variability across both of the seasonal patterns (TMA, 2019; Walker *et al.*, 2019).

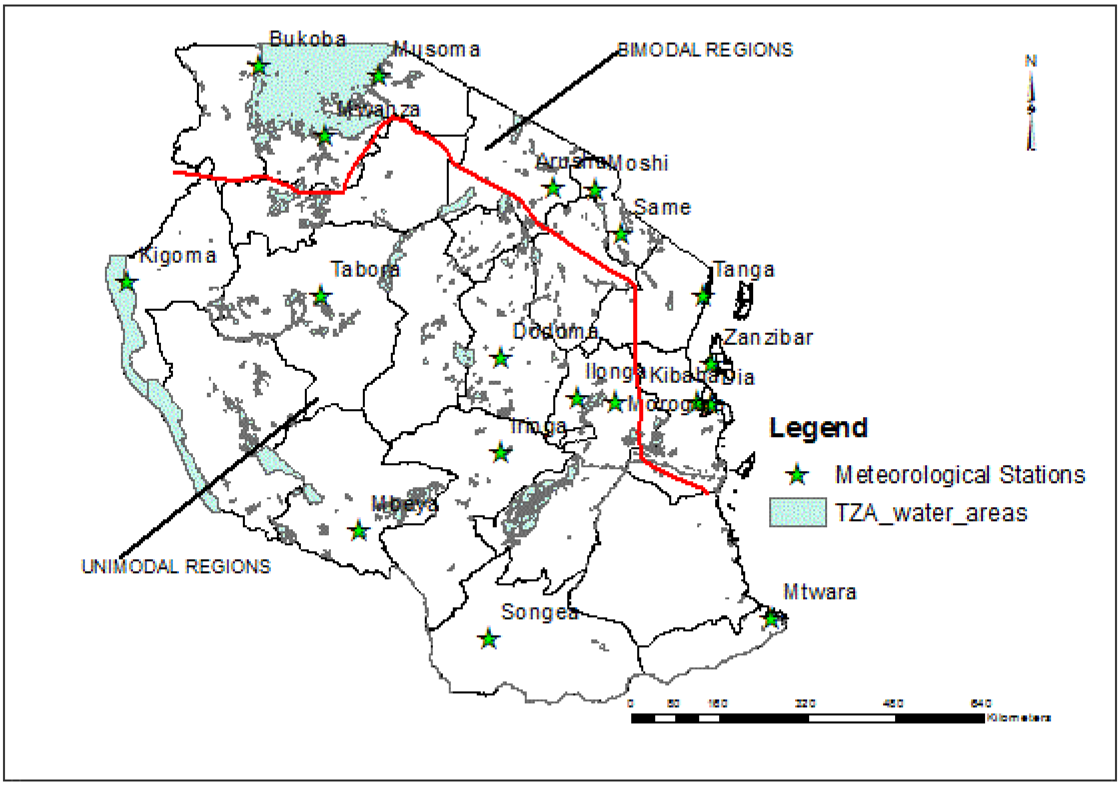


Figure 13: Map showing the unimodal and bimodal regions and some of the meteorological stations in Tanzania.

Source: (Lahunga *et al.*, 2016)

As shown in Fig. 14, the Tanzania Meteorological Authority (TMA) has attempted to establish a number of meteorological stations in Tanzania. However the data collected does not appear to be published online. Furthermore, in some places it seems to be an entirely paper-based process (shown in Fig. 15), and an International Data Rescue project highlighted the need to move to digital systems (TMA, 2016). The TMA created an online portal for data called the 'MAP-ROOM'. The MAP-ROOM software and analysis was researched in 2019, and found to be accurate, but limited in value due to the relatively small number of working weather stations (Luhunga *et al.*, 2019). However the MAP-ROOM website now appears to be permanently offline and could not be reached. Therefore, Government generated weather data is not available for this study, because seeking permission to collect data from the Government for this research is not feasible in the given time frames.

S/N	STATION TYPE	EXISTING	GAP
1	SYNOPTIC	29	15
2	AUTOMATIC WEATHER STATIONS (AWS) (Target 0.75sq.deg)	49	111
3	AGRO-METEOROLOGICAL STATIONS	13	7
4	CLIMATOLOGICAL STATIONS	150	100
5	RAINFALL STATIONS	2056	-
6	AUTOMATIC RAINFALL STATIONS (20km x 20km)	0	2500
7	MARINE STATIONS (BUOYS)+ HF RADAR	0	12+9
8	UPPER AIR STATIONS	1	3
9	PILOT BALOONS STATIONS	1	5
10	RADAR STATIONS	2	5
11	LIGHTING DETECTORS	0	10

Figure 14: Screenshot from a Tanzania Meteorological Agency presentation, showing the existing weather stations and data collection, as well as the perceived 'gap' of what is required.

Source: (Waniha, 2018)

Figure 15: Photo of weather data being rescued as part of the International Data Rescue project.

Source: (TMA, 2016)

There is little non-Government weather data that is recorded in Tanzania and published online. Indeed, in Dar Es Salaam, the biggest city in Tanzania, the only major weather station recording data and publishing online is at the international airport. This data is published on the National Centers for Environmental Information and the European Centre for Medium-Range Weather Forecasts (ECMWF) databases. It is also accessible through many other websites through live interfaces (ECMWF, 2022; NOAA National Centers for Environmental Information, 2022). There are observed gaps in data, which are likely due to frequent power cuts experienced in Dar Es Salaam (Mirondo, 2021). The airport weather station unfortunately does not record solar irradiance data, which will be a useful component of classroom temperature modelling. The closest weather station with solar irradiance data recorded was a personal weather station linked to the Weather Underground network in Dodoma (approximately 400km from Dar Es Salaam) (Weather Underground, 2022). The difficulty in accessing weather data in Tanzania introduces a level of uncertainty with predicted temperatures and hence the intervention effect over time. Using the available weather data does allow estimates to be made, as shown in Table 6, but the limitations must be acknowledged.

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual average**
Monthly average temperature (°C)	27.6	27.9	27.4	26.2	25.6	24.8	24.4	24.5	25.2	26.1	26.7	27.3	**26.14**

Table 6: Average monthly temperatures in Dar Es Salaam using data from 1999 to 2019.

Source: (Climate-Data.org, no date, citing ECMWF, 2022)

2.2.3. Options to reduce temperature

Questions Answered:

- *What are the options for retrofit interventions to reduce temperatures?*

2.2.3.1. Option analysis

There are many options to improve temperatures in a building, and various methodologies to consider when assessing retrofit options that make most sense (Ma *et al.*, 2012). However, in the context of working with Government schools in Tanzania, there are significant constraints on the options that are viable. Contextually appropriate options for an intervention to reduce temperatures were assessed by Proctor (2021), which have been expanded in Table 7. The higher costs associated with solar panels or additional roofing interventions ruled them out of this research, for two reasons. First, the costs of research were higher than the budgets available. Second, the higher capital costs make the interventions much less cost effective in achieving a similar expected cooling effect. The result is that it makes the intervention less likely to be comparable with traditional interventions in terms of cost effectiveness, especially at scale

Design Options	Papers which propose or research this option	Estimated initial cost per classroom	Contextually appropriate? Particularly in terms of cost effectiveness?	Environmental impact
Air conditioning	(Schoer, 1973; Wargocki and Wyon, 2007; Porras-Salazar *et al.*, 2018; Park *et al.*, 2020)	US$5000+	**Contextually inappropriate**. Most schools do not have electricity, and the cost associated with running an air conditioning machine are a different order of magnitude to Government budgets available in Tanzania. The costs attached to maintenance and energy would be unmanageable, and likely lead to the intervention stopping shortly after installation.	**Poor environmental impact**. There is a significant negative environmental impact linked to air conditioning. Given the high permeability of air through the buildings, especially in light of unglazed windows, would mean that the energy input required would be very high. Furthermore, there is not reliable grid energy, so carbon intensive diesel backup generators would likely be required. If an off grid option was put forward, the embodied energy of the set up would be significant, and difficult to justify in isolation.
Cool roof or painting roof with reflective paint	(Cheng, Ng and Givoni, 2005; Amer, 2006; Pisello, Santamouris and Cotana, 2013; Dias *et al.*, 2014; Proctor, 2021; Song *et al.*, 2021)	US$250+	**Contextually appropriate**. Roof painting is common across the country, and the cost is within the affordability range of education sector budgets. Many public sector buildings have painted roofs and the Government plans for education suggest this should be the case.	**Low-medium environmental impact.** In previous studies it has been shown that the carbon impact of reducing cooling load outweighs the carbon emissions of paint production (Papasavva *et al.*, 2002; Shittu *et al.*, 2020). However in this case, it is not reducing a heating load, so the environmental impact cannot be discounted. Furthermore, there would be emissions linked to transporting the paint by lorry to school locations. In addition to carbon emissions the paint releases volatile organic compounds (VOCs) when drying (Porwal, 2015). These VOCs can contribute to smog creation and local pollution impacts. This is more of a concern in urban environments, than rural environments and care should be taken by those selecting and applying the paint.
Purchasing new solar panels - which	(Dias *et al.*, 2014; Wang *et al.*, 2020)	US$5,000+	**Contextually inappropriate.** The costs of solar panels, and associated electrical systems for all schools are far higher than	**Unable to assess environmental impact.** Given that the primary goal of electrification is not shading, it is difficult to assess the overall

are roof mounted for shading			budgets available. It would not make sense to drive an electrification programme based on the shading potential.	environmental impact, because it depends on how the energy is used. As previously discussed, it would not be appropriate if linked solely to air conditioning.
Mounting existing solar panels on the roof to act as shade	(Dias *et al.*, 2014; Wang *et al.*, 2020)	US$400+ (Only for mounting existing panels on roof - not for purchasing the panels)	**Contextually appropriate**, **but only for a limited number of schools.** The benefits of roof mounting solar PV have been shown in previous studies (Dias *et al.*, 2014; Wang *et al.*, 2020). If a school already has solar panels, then it may be contextually appropriate to mount them on the roof to benefit from shading. However, given the budget constraints in schools, it is unlikely that many schools have the required number of solar panels to mount to cover a classroom. Therefore, whilst it may be appropriate for specific schools, it is not appropriate for an at-scale intervention, given the lack of schools with sufficient panels to take part in any initiative.	**Low environmental impact.** Given that this intervention assumes the solar panels are in place, it is unlikely to have further significant environmental impact. If the panel positions are moved, and become less efficient as a result, then the total life cycle of the solar panels will become more damaging to the environment.
Additional roof erected over the existing corrugated roof	(Kadri, Bouchair and Laafer, 2022)	US$2000 for labour and materials	**Contextually <u>in</u>appropriate**. This type of roof construction is not common across Tanzania, and the cost is too high to be adopted within the education sector.	**Medium environmental impact.** The materials for this type of roofing are likely to be wood for the frame and either corrugated iron or local thatch for the roofing. The local environmental impacts linked to deforestation are damaging (Luhunga *et al.*, 2019). Furthermore, if corrugated iron is used, then there is embodied carbon emissions.
Roofing insulation	(Amer, 2006; Song *et al.*, 2021)	US$600+	**Contextually <u>in</u>appropriate**. The costs attached to the intervention would be significantly higher than education budgets available. Furthermore there would be real concerns about the longevity of the intervention. Given high rainfall, and humidity during the rainy season, damp would be a concern. There is also a risk	**Low-medium environmental impact.** The environmental impact of insulation depends on which insulation is used (Richman, Pasqualini and Kirsh, 2009; Llantoy, Chàfer and Cabeza, 2020). Given the risk of termite damage to natural materials, it is assumed that higher impact materials would likely be used.

			from bats nesting in the insulation.	
Horizontal ceiling	(Amer, 2006; Song *et al.*, 2021)	US$600+	**Contextually appropriate.** Introduction of horizontal ceilings is widely used in buildings across Tanzania. Furthermore, it is also a feature that is relatively common in secondary school classrooms visited by the author. There exists risks of termite damage and bat infestations, but given the widespread usage, there are known strategies to address the difficulties. The main challenge is the costs attached to the intervention, and the potential risks of collapse if the quality is low.	**Low environmental impact.** The ceiling would likely be made of plywood or fibreboard. The impact of this would likely be from carbon emissions, given that this type of board is often imported and often uses resin to set the board (Barata *et al.*, 2016).

Table 7: Contextual and environmental assessment of different retrofit interventions to reduce classroom temperature in Tanzania.

The two most feasible options from the analysis are roof painting and horizontal ceilings. Given previous research that suggests adding a horizontal ceiling would be difficult to implement in practice in Tanzania, and the budget and timing constraints of the research, this option was discounted (Proctor, 2021). Therefore, in relation to the classroom blocks, the most feasible option to reduce temperatures is to reduce the heat absorbed in the first place, by increasing the albedo of the roof (Proctor, 2021). The next section will look at the literature in relation to this topic.

2.2.3.2. Roof Painting and Cool Roofs

Cool roof technology is not a new concept, and the biggest meta analysis identified is from 2004, where 72 papers were analysed (Haberl and Cho, 2004). Since then, a significant amount of literature has been produced on cool roofs, which demonstrate the effectiveness at reducing building temperatures (Haberl and Cho, 2004; Akbari, Levinson and Rainer, 2005; Cheng, Ng and Givoni, 2005; Amer, 2006; Synnefa, Saliari and Santamouris, 2012; Pisello, Santamouris and Cotana, 2013; Dias *et al.*, 2014; Gao *et al.*, 2014; Song *et al.*, 2021). Therefore, it is not contentious to suggest that adding a reflective coating to a building reduces the solar heat gain, as shown in Fig. 16 (Santamouris, Synnefa and Karlessi, 2011). Researchers have previously demonstrated that cool roofs can reduce internal temperatures by up to 4℃ (Italy), 5℃ (Portugal), 5℃ (Hong Kong) and 6.5℃ (location undisclosed, but likely Egypt) (Cheng, Ng and Givoni, 2005; Amer, 2006; Pisello, Santamouris and Cotana, 2013; Dias *et al.*, 2014; Song *et al.*, 2021).

A key limitation of painted roofs is longevity, as outlined by Mastrapostoli *et al.* (2016). Their research shows that the reflectance drops by 25% in the four years after the application of the paint. Including a coefficient of this degradation will be vital in any method predicting efficacy over time.

Whilst the data from other countries is encouraging, it is less clear how effective a painted roof intervention would be in Tanzania in reducing internal building temperatures. This is because there is not much research that assesses buildings with corrugated iron roofs, and even less literature that looks at classroom blocks. The level of temperature reduction is vital to understand if the intervention is to improve learning in a cost effective way.

Material	Solar reflectance	Infrared emittance	Solar reflectance index
Coatings			
White	0.70–0.85	0.80–0.90	84–113
Aluminum	0.20–0.65	0.25–0.65	–25 to 72
Conventional black	0.04–0.05	0.80–0.90	–7 to 0
Cool black	0.20–0.29	0.80–0.90	14–31
Conventional dark colored coatings	0.04–0.20	0.80–0.90	–7 to 19
Cool dark colored coatings	0.25–0.4	0.80–0.90	21–45

Figure 16: Measures Solar Reflectance, Infrared Emittance and Solar Reflectance Index values.

Source: (Santamouris, Synnefa and Karlessi, 2011)

3. Methods, Methodology & Results

This section is divided into two parts. Firstly a short section covering the pilot phase, followed by a review of the main experiment.

3.1. Pilot

3.1.1. Pilot Methodology

As outlined in the literature review, there is a wide range of paints available that could be used to reduce building temperatures. However, for the intervention to be practical, the paints considered for the experiment needed to be easily available for purchase in Tanzania. There is limited information about the paints that are locally available. Therefore, a level of iteration was introduced to reduce the resulting risk, by answering these unknown questions on a small scale, before progressing to the main experiment. The pilot also provided an opportunity to test the measuring instruments used.

The key questions addressed in the pilot were:

- *What paints are available locally in Dar Es Salaam?*
- *Which paint would be most appropriate for the intervention?*

The pilot was divided into two parts. The first part investigated what paint is available for purchase, and the second tested the paints on a small-scale model of a school block, built specifically for the purpose.

3.1.2. Pilot Methods

Four hardware stores in Dar Es Salaam were visited to review what paint was available at different price points. The prices and types of paint were recorded. Two of the most appropriate paints were then selected, to be tested on a small model of a classroom.

Figure 17: Pictures of the four different hardware shops visited. (a) Africab Hardware, Kinindoni, (b) Tronic Hardware, Masaki, (c) Asha Hardware, Kinondoni, (d) Al Nasser Paints Center, Kisutu.

An experiment was set up by creating three identical model classrooms, located in a car park in Oyster Bay, Dar Es Salaam. The models were made of bricks and corrugate, similar in design to classroom blocks. Two sets of corrugated iron were painted with the two most widely available / cost effective paints. An unpainted new corrugated roof was used as a control. A thermometer data logger was placed in each model and they were left in the car park of a four-floor apartment block for three days.

a b

Figure 18: Showing the model classrooms which were built. (a) shows the bricks and (b) shows the models with roofing sheets.

The resulting temperatures, recorded each minute, produced 4320 data points that were uploaded to Google Sheets. Google Datastudio was used to visualise the data .The results were analysed by examining the average temperature difference between the models during school day times. The corrugated roofs were then visually inspected to give a view on the reliability of each paint for use on classroom blocks.

3.1.3. Pilot Results

3.1.3.1. What paints are available locally in Dar Es Salaam?

The variety of roofing paint was found was limited, especially in the ranges offered by normal hardware stores. Each major brand typically produces one variety of roofing paint. The colours available as standard were red, blue and green. Other colours (including white) were only available by special request from the factory and were slightly more expensive.

The cost of roofing paint is higher than paint marketed for external walls. Both were purchased to see if the cheaper paint would be usable for the experiment. A summary of the shops visited and costs is shown in Table 8.

Paint Shop	Paints Available and Costs
Asha Hardware, Kinondoni	Coral paints only: - Roof PVA paint in blue - 140,000 TZS (£47) for 20L - External wall paint in white - 120,000 TZS (£40) for 20L
Africab Hardware, Kinindoni	Coral and Goldstar paints: - No roof paint available - External wall paint in white - 110,000 TZS (£37) for 20L
Tronic Hardware, Masaki	Coral paints only: - Roof PVA paint in green - 150,000 TZS (£50) for 20L - External wall paint in white - 120,000 (£40) TZS for 20L
Al Nasser Paints Center, Kisutu	Goldstar paints: - Roof paint in blue and green - 130,000 TZS (£43) for 20L - Roof paint in white - 140,000 TZS (£47) for 20L - External wall paint in white - 110,000 TZS (£37) for 20L

Table 8: Showing the paint shops visited and the key findings at each.

3.1.3.2. Which paint would be most appropriate for the intervention?

In the experiment, a significant difference was not detected between the models in terms of the temperatures recorded. Fig.19 shows the recorded temperatures for the three models. This was expected, as the thermal mass in the walls and floor was proportionally higher than in a full-size classroom. Given the pilot questions were focused on paint selection, rather than temperature reduction, it does not have an impact on the overall study. There was significant learning from the visual inspection, which showed that at least two coats of roof paint are required. The key points from the visual inspection are recorded in Table 9.

Paint	Coats	Remarks on applying the paint	Remarks on visual inspection at the end of the process
Red roofing paint	Two	After one coat, the paint had run down the corrugate, and was blotchy. It needed at least two coats to ensure that the corrugate was fully covered.	The paint did not degrade or 'run' during the experiment.
White exterior paint	Two	The paint was universally covering the corrugate after one coat. A second coat was applied to keep alignment with the red roof paint.	The paint was almost entirely washed away during the period when it rained.
Unpainted	-	-	No change.

Table 9: Key points from applying the paint and on visual inspection at the end of the process.

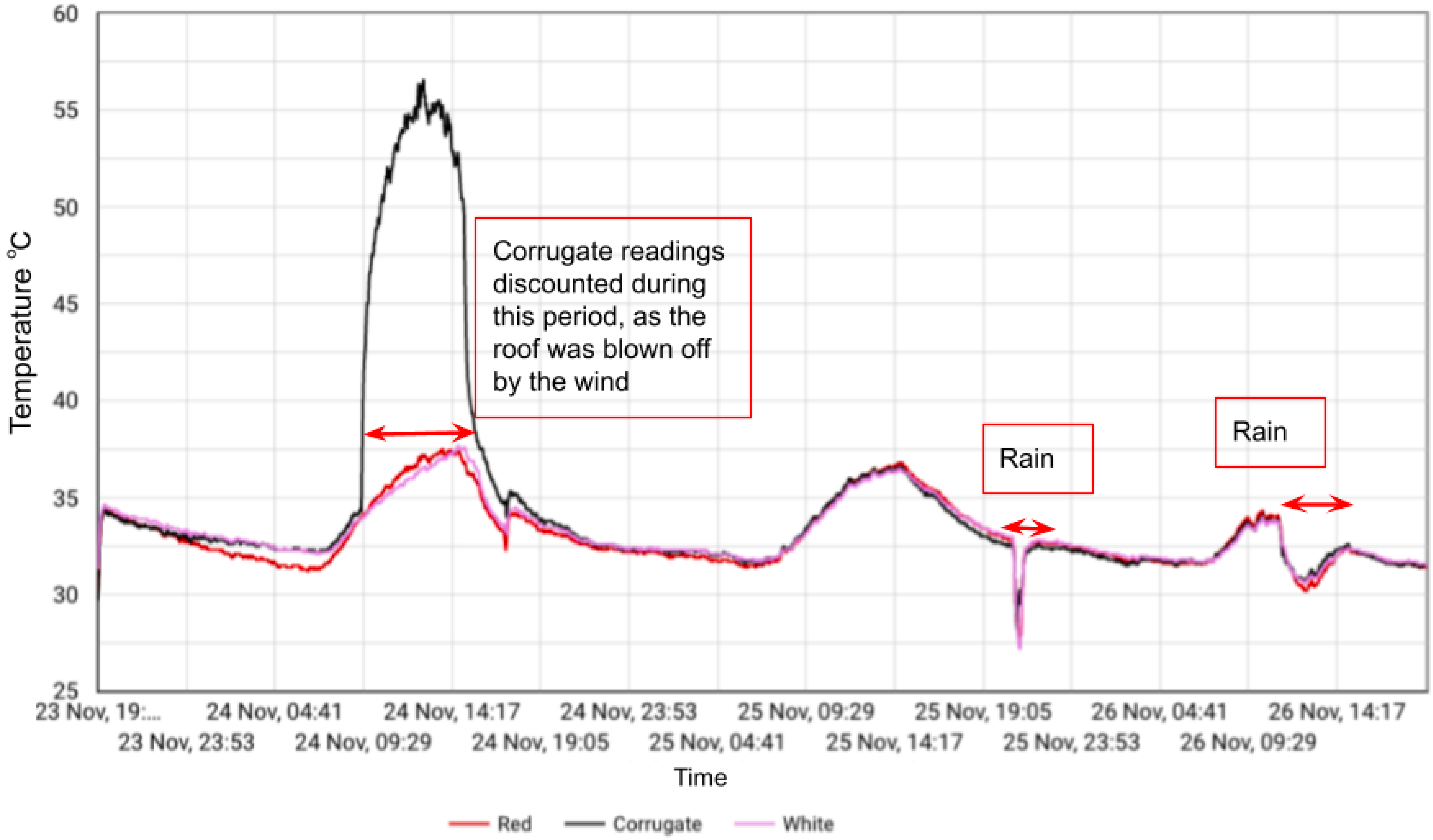


Figure 19: Showing the temperature recorded in each of the model classrooms over the course of the three days.

Key learnings from the pilot to be taken forward to the main experiment were as follows:

- The use of a bespoke roofing paint is required, as the other paint tested rapidly degraded when applied to corrugate.
- The only brand of white roofing paint available was Goldstar roof paint. This was selected for the experiment - with a 20 litre bucket costing 130,000TZS (£43) in blue or 140,000TZS (£47) in white. Multiple hardware shops advised that roughly 1 litre of paint would be required per coat for a $10m^2$ area of roof. This aligned with the Goldstar paint technical specifications available online (Goldstar Paints, 2017)**.** Further, that three coats of paint would be required, meaning that a single $100m^2$ classroom would need approximately 30 litres of paint costing approximately £70.
- At least two coats of the paint to be used, given the issues of the paint cracking and failing to provide good coverage of the corrugate.

3.2. Main Experiment

3.2.1. Experiment Methodology

Previous studies looking at classroom temperature and learning follow one of three distinct different methods: field studies, cross-sectional studies, and controlled laboratory experiments (Wargocki, Porras-Salazar and Contreras-Espinoza, 2019). Table 10 shows the studies from 1973-2019 reviewed in the 2019 meta-analsis. Given that the experiment required primary data, a controlled lab experiment methodology was discounted.

In order to run a cross-sectional study using existing data, it would require analysis of data for existing school painted roofs together with classroom-level learning data. Using both datasets, a regression could then be run over time to see if a statistically significant effect was apparent in a similar process to Park *et al.* (2020). Within the education sector in Tanzania, the mandate for collecting and publishing education data sits with the President Office for Regional Administration and Local Government (PO-RALG). However, in reviewing the published Tanzania education data, it was found these datasets were unavailable (PO-RALG, 2019, 2020). Furthermore, given the difficulty in monitoring temperature differences across locations, it is unlikely that a meaningful effect would be identified without a very large sample size. Facilitating such data collection would require significant engagement with the Government of Tanzania, as well as significant travel to visit and record roof conditions. Collecting this type of data was unrealistic in the time available. The next section covers field studies, which was selected as the methodology.

It was decided therefore to run a field study experiment with two classrooms, following similar methodology in four of the previous field studies outlined in Table 10 (Schoer, 1973; Wargocki and Wyon, 2007; Bakó-Biró *et al.*, 2012; Porras-Salazar *et al.*, 2018). However, unlike the previous studies, which attempted to understand student performance, this study will focus solely on temperature changes. This decision was made to avoid direct interaction with children, and the subsequent ethical implications and lengthened research timeline.

Undertaking a field study still introduces challenges in terms of access, ethics and consent. In order to run the experiment, a school needs to be identified and permissions sought from the school headteacher(s) and School Management Committee (SMC). However, it also provides the most real world data, which gives the results significance and transferability.

Some previous studies take repeated measures with students before and after a change, in order to create a control and an intervention (Porras-Salazar *et al.*, 2018; Wargocki, Porras-Salazar and Contreras-Espinoza, 2019). In this case, a classroom will be assigned as the intervention and the other as a control. This will ensure only one factor changes across both sets of readings. To ensure that the classrooms in the experiment are identical, other than the intervention, it will be vital to record temperature in advance and ensure that temperatures are aligned. To make sure classroom conditions are held constant, a classroom block with multiple classrooms will be used where only part of the block roof is painted.

Within the field of buildings research, using an experimental design to understand the effects of an intervention is common (Akbari, Levinson and Rainer, 2005; Santamouris *et al.*, 2007; Ma *et al.*, 2012; Synnefa, Saliari and Santamouris, 2012; Tahsildoost and Zomorodian, 2015; Garay Martinez, Benito Ayucar and Arregi Goikolea, 2017; Guerrini *et al.*, 2021). Many experimental research designs take measurements before and after an intervention ('pre and post'), with the control being the state of the building before the intervention. Given the changeable weather conditions in Dar Es Salaam, it was decided to run the intervention concurrently in two classrooms within the same classroom block. This reduces the complexity and uncertainty in the analysis. It follows the same method as the Guerrini *et al.* (2021) experiment investigating building seismic resilience and the Gao *et al.* (2014) experiment measuring the effect of a cool roof in China.

In many previous experiments measuring the effect of roof painting, the designs have focused on roofing temperature, heat conduction, energy use and modelled temperatures, rather than recorded air temperatures (Akbari, Levinson and Rainer, 2005; Synnefa, Saliari and Santamouris, 2012; Gao *et al.*, 2014). This is because the studies wanted to assess effects over a full year, or the buildings are being actively used, with internal heating and cooling systems affecting air temperatures. Furthermore, these experiments have been looking at much more complex building designs, which are common in the US, European and Chinese contexts where the studies were undertaken. Given the relatively heterogeneous nature of classroom design in Tanzania, recording the direct effect on air temperature presents a simpler and more reliable approach.

Author	Year	Country of Study	Study Type	Population (classrooms)	Population (pupils)	Age of pupils	Temperature range examined (°C)	Learning Assessed
Schoer & Shaffran	1973	USA (Iowa)	Field intervention: Air conditioners	2 classrooms in an elementary school	22	10	22.4, 24.9 & 22.6, 26.1 & 22.3, 25.4	School tasks
Johansson	1975	Sweden	A controlled laboratory study in a climate chamber	N/A	36	10	23, 30, 36	School tasks and psychological tests
Wyon. Andersen and Lundqvist	1979	Denmark	A controlled laboratory study in a climate chamber	N/A	72	17	20–29	School tasks
Wargocki and Wyon	2007	Denmark	Field intervention: Air conditioners	2 classrooms in an elementary school	44	10–12	20, 23.6 & 21.6, 24.9	School tasks
Bakó-Biró et al.	2012	England	Field intervention: slightly cool outdoor air was introduced into the classrooms through a mobile ventilation equipment	2 classrooms in an elementary school	36	9–10	23.1, 25.3	Psychological tests
Haverinen-Shaughnessy and Shaughnessy	2015	U.S.A (Southwest)	Cross-sectional study	140 classrooms in 70 elementary schools	3019	10	20–25	National tests examining progress in learning

Park	2016	U.S.A. (New York)	Cross-sectional study	947 high schools	1 million	17–18	<u>15.5–35</u>	National tests examining progress in learning
Goodman et al.	2018	U.S.A.	Cross-sectional study	N.A.	10 million	14–17	<u>N.A.</u>	National tests examining progress in learning
Porras-Salazar et al.	2018	Costa Rica	Field intervention: Air conditioners	2 classrooms in an elementary school	37	10–12	25.0, 30.0	School tasks

Table 10: Temperature and learning papers published from 1979-2018, from Wargocki et al. (2018) meta-analysis. It should be noted that Park et al. (2016) and Goodman et al. (2018) are both working papers, which lead up to the Park et al. 2020 paper that is discussed in more detail in the literature review.

Source: (Wargocki, Porras-Salazar and Contreras-Espinoza, 2019)

3.2.2. Experiment Method

3.2.2.1. School and Classroom Selection

Various head teachers at schools in Dar Es Salaam were approached to understand their interest in participating in the research. The headteacher at St Peter's Primary School confirmed interest. A site visit was undertaken and a school block was identified as appropriate for the intervention and the research. The three classrooms were of a similar size and were named C1 (10.4 metres by 11.5 metres), C2 (9.2 metres by 11.5 metres) and C3 (9.8 metres by 11.5 metres). The location is shown in Fig. 20, and the aerial view in Fig. 22, as well as pictures of the classroom in Fig. 22 and Fig. 22.

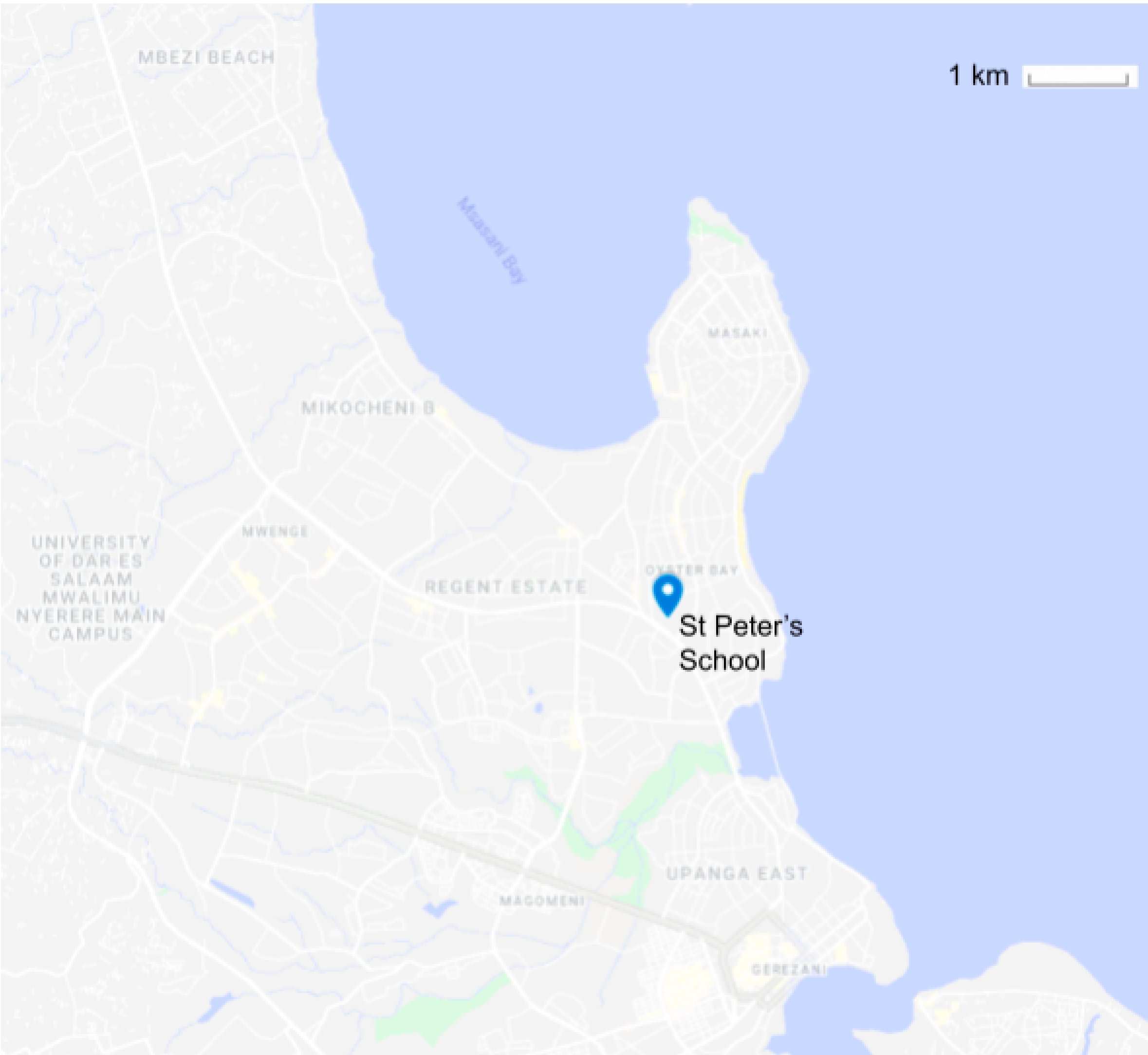


Figure 20: A map of Dar Es Salaam, showing the location of the school where the research took place. The scale is shown in the top right corner.

Source: (Google Maps, 2022)

Figure 21: Aerial picture of the classroom block that was used for the experiment (in the centre of the picture).

Source: (Google Maps, 2022)

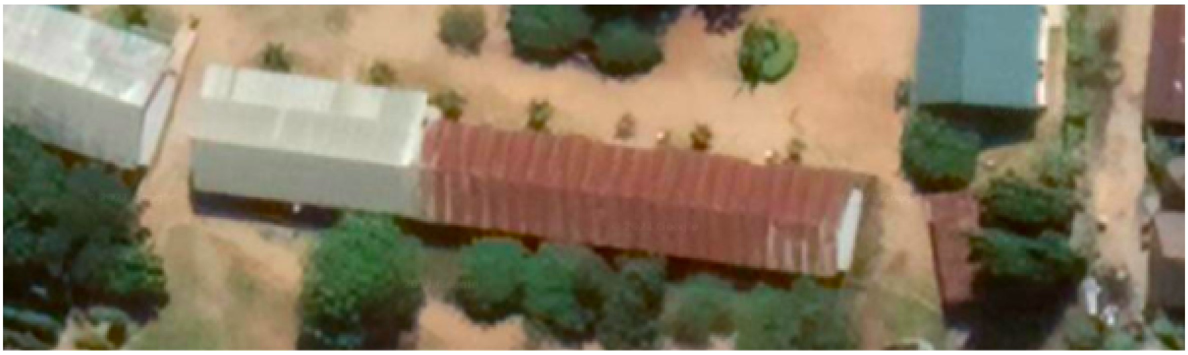
Figure 22: Author's picture of the three classrooms in the block (classroom C1, classroom C2 and classroom C3), which were used for the experiment.

Figure 23: Author's picture of the three classrooms in the block which was investigated.

A meeting was established with the School Management Committee (SMC), to request their support and permission for the research. During the meeting with the SMC, the research was explained as well as the theory behind the intervention. Whilst supportive, the SMC expressed a strong preference to have a roof colour that is ‘UNICEF light blue’, instead of white. The ‘UNICEF light blue’ is shown on their logo in Fig. 24. In order to meet this request, it was agreed that the full roof would be painted in light blue following the completion of the research. In order to avoid impacting the school day, it was agreed that the research would take place during the Christmas school holiday period, when the classrooms were unused. The SMC members and the headteachers were paid a travel allowance for attending the research meeting. Following agreement of the SMC, building contractors were approached and contracted to undertake the work.

Figure 24: UNICEF logo from the UNICEF Tanzania contact page. This is the 'UNICEF light blue' colour the SMC expressed a preference for.

Source: (UNICEF, no date)



(a)

(b)

Figure 25: Aerial picture of the classroom block before (unpainted) and after (painted 'UNICEF Blue' at the SMC request).

Source: (Google Maps, 2022)

3.2.2.2. Measurements

Three thermometer data loggers were used to collect data throughout the experiment. The data loggers were from the brand Elitech and were the RC-5+ model. The specification outlines they have a 0.1°C resolution and ±0.5°C accuracy (Elitech, no date). Three other data loggers from Easy Log (model EL-USB-2) were also tested, but failed due to rain exposure.

The data loggers were located in Classroom 1 (C1), Classroom 3 (C3) and outside under a tree. In the classrooms, the loggers were located in the centre of the classroom on a chair raised approximately 30 cm from the ground. The data logger outside was attached to a tree at around one metre above the ground, and shaded with a piece of cloth (ensuring it was only shaded from direct sunlight and not insulated by the cloth). Pictures in Fig. 26 show the locations.

(a) (b)

Figure 26: Author's pictures of the thermometer location (a) inside the classrooms and (b) outside the classroom under a tree.

To calibrate the experiment, the temperature inside each classroom was recorded over the course of two days, to understand the similarity and differences. The thermometer's location was switched between the days, to ensure that any systematic bias was uncovered. As shown in Fig. 27 and Table 11, the temperatures recorded were almost identical with just 0.17℃ difference recorded (averaged across the two days).

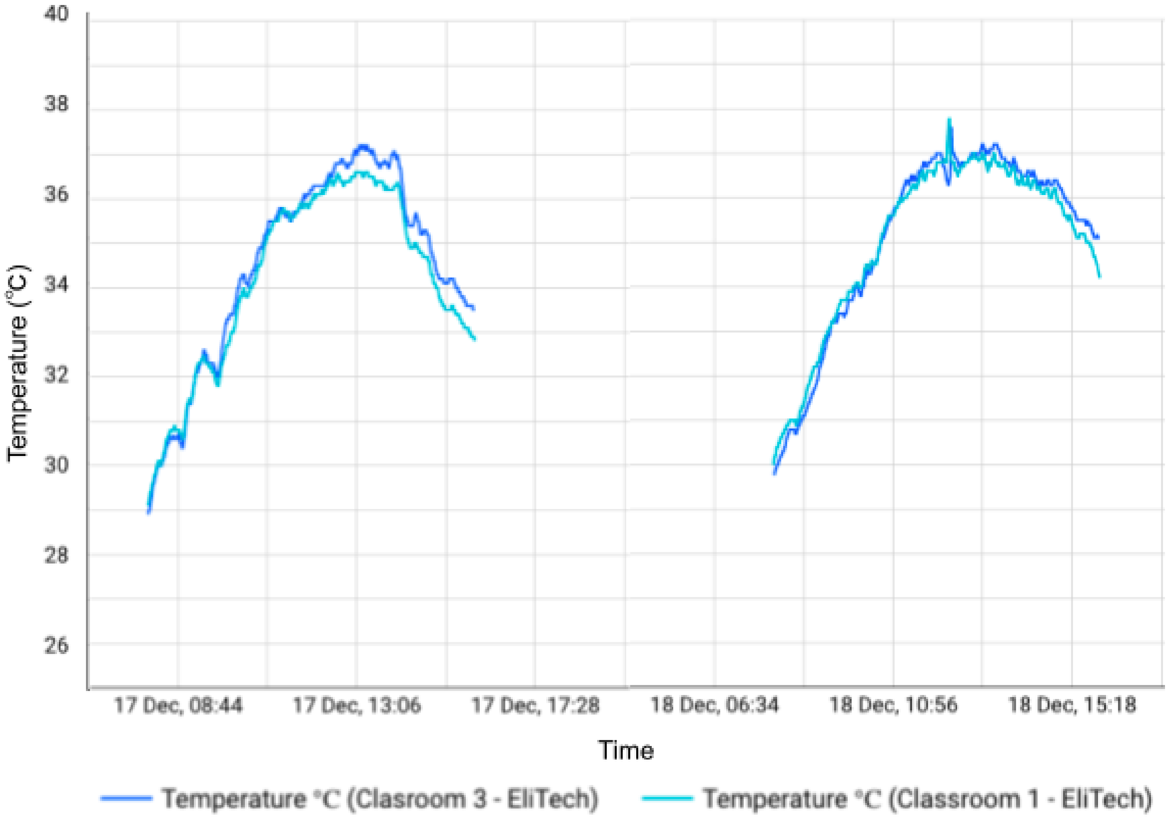


Figure 27: Graph showing the calibration temperatures recorded over the course of two days, during school hours, in Classroom C1 and Classroom C3.

	Day 1	Day 1 difference (C1-C2)	Day 2	Day 2 difference (C1-C2)
Classroom 1 (℃)	35.09	0.05	34.49	0.29
Classroom 3 (℃)	35.04		34.2	

Table 11: Average temperatures during the calibration process in Classroom C1 and Classroom C2.

3.2.2.3. Data Collection Process

Given the strong SMC request for a blue-coloured roof, the method was adjusted to investigate a White Paint Intervention (WPI) and a Blue Paint Intervention (BPI). To apply the intervention, the roof area was manually sanded to ensure the paint would stick to the corrugated iron. The paint was then applied in two coats. Blue paint and white paint was then mixed, in a ratio of 1 to 5, to produce a ‘UNICEF’ light blue colour.

The decision over which classroom to apply the intervention first was taken with the toss of a coin. The BPI was first applied to Classroom 1 (C1). The temperatures were then recorded for four days in BPI Classroom (C1), the control Classroom (C3), and outside under a tree.

The WPI was then applied to Classroom C3 and the process repeated. The temperatures were recorded for four days in BPI Classroom C1, WPI Classroom C3 and outside under a tree (approximately 20m from the classroom, as shown in Fig. 26).

Period	Conditions recorded	Duration	Start date	End date
Period 1	- Classroom 1 - no paint - Classroom 3 - blue paint - Outside under a tree	4 days	19/22/2021	22/12/2021
Period 2	- Classroom 1 - No paint - Classroom 3 - blue paint - Outside under a tree	4 days	30/12/2021	02/01/2022

Table 12: Showing the two periods of the intervention and the different interventions.

Figure 28: Showing a picture of the classrooms during Period 1, with the BPI and control.

Figure 29: Due to a technical error with the photo taken by the contractor, the pictures for Period 2 are not available. Instead the figure shows what Period 2 would have looked like, with the WPI and BPI, using photo editing software to adjust half of the roof colour.

The data was then uploaded to Google Sheets. Given the significant amount of data points to analyse, the data was visualised through Google Data Studio, a software which is designed to process large amounts of data. The school day runs from 07:30-15:30. Given that there are assemblies and other activities taking place outside at the start of the morning, it was decided to analyse the temperature from 08:00 after children are more likely to be in the classroom. So the analysis focuses on the period from 08:00-16:00.

3.2.2.4. Temperature Data Analysis

First, the average hourly temperatures were plotted for both Period 1 and Period 2 (shown in the results Section 3.2.3.1 in Fig. 30 and Fig. 31). However, this analysis alone does not allow a direct comparison between the WPI, BPI and control. Therefore, in order to produce a graph overlaying the WPI, BPI and the control, the outside temperature was used as a benchmark across the eight-day period of the experiment. To achieve this, a number of steps were followed, using Equations 8 and 9.

First, the percentage deviation from the outside temperature was calculated for each of the conditions. This was calculated across the four-day Period 1 for the control and across Period 2 for the WPI. It was calculated across both Period 1 and Period 2 for the BPI, and the results combined. This percentage difference between the classroom temperatures and the outside temperature was then averaged for each minute reading across the respective four- or eight-day period. The percentage difference was then multiplied by the minute by minute average outside temperature, across the eight-day period. This gives a modelled single-day temperature difference across a single day. These resulting graphs are presented both with minute level recordings and hourly averaged recordings, as Fig. 33 and Fig. 32 in the results section (Section 3.2.3.1). For the WPI at 08:00 (or any given minute), the modelled temperature is given by:

$$T_{WM_{(t)}} = \frac{\sum_{D1}^{D4} \frac{T_{W_{(t)}}}{T_{O_{(t)}}}}{4} \cdot \frac{\sum_{D1}^{D8} T_{O_{(t)}}}{8}$$

Where:

$T_{WM_{(t)}}$ = Temperature for the White Paint Intervention - post modelling

$T_{W_{(t)}}$ = Temperature for the White Paint Intervention

$T_{O_{(t)}}$ = Temperature outside

D = Days

t = Time (data recorded each minute

(Equation 8)

For the Control (no paint) at 08:00 (or any given minute), the modelled temperature is given by:

$$T_{CM_{(t)}} = \frac{\sum_{D1}^{D4} \frac{T_{C_{(t)}}}{T_{O_{(t)}}}}{4} \cdot \frac{\sum_{D1}^{D8} T_{O_{(t)}}}{8}$$

Where:

$T_{CM_{(t)}}$ = Temperature for the control classroom - post modelling

$T_{C_{(t)}}$ = Temperature for the control classroom

$T_{O_{(t)}}$ = Temperature outside

D = Days

(Equation 9)

As the BPI was in place in Classroom C1 for the full eight days, no temperature modelling was required. Instead the results were simply averaged for each minute across the eight-day period.

3.2.2.5. LAYS Calculation

The WPI results were used to give a LAYS improvement estimate for the learning impact of the intervention.

In order to determine a LAYS value, it is first required to estimate the school temperatures over the course of a full year. This was estimated by assuming that the temperatures recorded in the experiment in December are representative of the month of December. Further, it was then assumed that the average temperature reduction from the intervention was proportional to the average monthly temperature (previously shown in Table 6). This was recorded in a table, then averaged to give an average annual temperature reduction from the intervention (shown in the results section, Table 17).

The average annual temperature reduction was then used to calculate a percentage improvement in learning, using the 2% improved learning per 1℃ estimation proposed by the Wargocki *et al.* (2019) meta-analysis, which concurs with the later Park *et al.* (2020) study. The degree of learning improvement is also linked to the number of students in the classroom. The national average of 81 students per class was used (PORALG, 2018 cited in UNICEF, 2020). The length of the interventions was estimated at five years, given the high levels of environmental exposure and the bimodal rainy season (Lahunga *et al.*, 2016). However, cool roofs do also degrade in their effectiveness over time. Hence a coefficient of degradation was estimated at 5% per year, shown as compound reduction in Table 13, using the analysis on cool roof degradation from Mastrapostoli *et al.* (2016).

Degradation	Effectiveness reduction %	Compound effectiveness %
Year 1	0%	100.00%
Year 2	5%	95.00%
Year 3	5%	90.25%
Year 4	5%	85.74%
Year 5	5%	81.45%
Average reduction (a)	-	90.49%

Table 13: Showing predicted degradation of the reflectiveness of paint, using data from previous studies.

Source: (Mastrapostoli *et al.*, 2016)

$$S_{Intervention} = I\ .\ aT\ .C\ .\ L$$

Where:
$S_{Intervention} =\ Improved\ Learning\ in\ Years\ of\ Schooling\ due\ to\ the\ intervention$
$I\ =\ Improvement\ in\ learning$ %
$T\ =\ Length\ of\ the\ intervention\ in\ years$
$a\ =\ Coefficient\ of\ degradation\ of\ the\ effect\ of\ cool\ roof$
$C\ =\ Number\ of\ children\ in\ the\ classroom$

(Equation 10)

$$LAYS_{Intervention}\ =\ S_{Intervention}\ .\ \frac{L_{Tz}}{L_N}$$

Where:
L_{Tz} = Average learning-per-year in Tanzania
L_N = Average learning-per-year in country N (often where where country N is the globally top performing country)

(Equation 11)

The learning co-efficient $\frac{L_{Tz}}{L_N}$ was calculated, at 0.62, using the Expected LAYS and the Expected Years of Schooling figures predicted by the World Bank using published Government data and previously shown in Fig. 2 (World Bank, 2020).

3.2.2.6. Cost Effectiveness Analysis

3.2.2.6.1. Cost Measurement

The costs of the intervention were recorded throughout the research process. The costs of the materials, the SMC engagement and the labour were detailed. Recording costs in relation to education interventions is a non-trivial activity, and guidance for this is outlined in a Costing Guidance Note from the Building Evidence in Education (BEE) group (Walls, Tulloch and Holla, 2020). The research specific inputs (as opposed to intervention inputs) were excluded.

The measured costs were calculated using the BEE Guidance Note suggested format, and an estimated ‘General Management and Overhead cost’ was introduced, given that this would be a requirement if the intervention were to scale (Walls, Tulloch and Holla, 2020). The General Management and Overhead cost figure was estimated at 39.6%, using the Makhalidwe Athu Expenditure Data case study outlined in the BEE Guidance Note (Walls, Tulloch and Holla, 2020).

3.2.2.6.2. LAYS per US$100

In order to compare the cost effectiveness against other interventions, the LAYS per $100 spend was calculated using the following equation:

$$LAYS\ per\ US\$100_{Intervention} = (LAYS_{Intervention}\ /\ Estimated\ Cost)\ x\ 100$$

(Equation 12)

3.2.2.7. Method Constraints, Assumptions and Limitations

The following sections correspond to the previous Experiment Methodology sections, detailing the key limitations and assumptions for each. It must be noted that the limitations linked to the final learning calculations are significant. The high-level limitations of the research are set out in the conclusion, but the detailed limitations linked to the method are outlined in this section. Further research options are detailed in the conclusion, in order to suggest how to reduce the cited limitations in any future research.

3.2.2.7.1. School and Classroom Selection

There were three major constraints around the selection of the classroom. First, the classroom needed to be within close proximity of Oyster Bay in Dar Es Salaam. This was required in order to give sufficient researcher access in the time available. Second, there was limited time available to approach different schools to find suitable classrooms for the intervention. Finally, a school needed to be identified where the school leadership and SMC fully support the intervention and the research.

These school selection constraints introduced the following key limitations into the study. As the school needed to be in close proximity to Oyster Bay, it is unlikely to be typical of schools in the rest of the country, in terms of education, human capital and economic outcomes (Wodon *et al.*, 2019). Furthermore, the coastal weather and climate in Dar es Salaam is not representative of much of the country. However, it should be noted that the diversity of climatic conditions across Tanzania, spanning across the bi-modal and unimodal rainy seasons, presents a challenge whichever site was selected. These limitations are less relevant in terms of the empirical results of the intervention. They are, however, crucially important in relation to the broader applicability of the research.

The requirement for SMC and school leadership support was a significant limitation on the research design, following the clear request to paint the roof blue. Rather than simply using the WPI, the additional BPI was required. Therefore, the data needed to be modelled to show comparison, leading to the assumptions laid out in the section on temperature data analysis (Section 3.2.2.7.4).

3.2.2.7.2. Measurement

The constraints around the measurements were largely practical constraints. First, it was challenging getting reliable data loggers and other data collection devices to be sent in time to Tanzania. This meant that there was minimal time to test the devices ahead of the pilot and the experiment. In order to mitigate potential risks linked to this constraint, two sets of data loggers were sent from the UK. In order to ensure greater calibration, it was decided to use one type of temperature data logger, rather than a 'mix and match' approach. During the calibration, one of the Easy Log data loggers failed, following a period of heavy rain. Therefore, the Elitech data loggers were taken forward to the main experiment. The limitation for the data loggers is the listed ±0.5°C accuracy. However in practice the calibration test showed much less deviation, so although the absolute temperature accuracy is ±0.5°C, the relative temperature accuracy appeared to be higher (but specification data was not available to corroborate this).

Furthermore, due to cost constraints, it was only possible to purchase air temperature thermometers and not globe thermometers. This meant data could only be collected on air temperature, and not radiant or dry bulb temperatures. The result is that perceived temperatures may be systematically lower than reality, given the amount of potential radiative heat through metal corrugated roofs. This is examined further in the discussion (Section 4.1.1).

3.2.2.7.3. Data Collection Process

The data collection process was carried out as described, and the temperature data loggers responded as expected. Although the school and classrooms were not in use for schooling at the time of the experiment, the headteacher and deputy headteacher did access them throughout. Although it was requested that the classroom doors remain closed, this could not be guaranteed at all times and this is therefore a constraint. There is an implied assumption that any opening and closing of doors, or the effect of individual people entering the classrooms, did not significantly impact the results. Given that the classrooms had open windows, and that it would only have only occured for a small time period, it seems reasonable to assume any impact from this was negligible.

3.2.2.7.4. Temperature Data Analysis

The constraint introduced by the SMC to use blue-coloured paint led to a set of assumptions around the final results. The goal was to produce a graph that showed the WPI, against a control (unpainted) classroom. However, there were only two classrooms suitable for the intervention, which led to the staggered approach outlined in the method. The method uses the percentage of classroom temperatures of the outside temperature as a way to overlay the different results. This method assumes the relationship between the outside temperature and the indoor temperature is the same for each intervention, at all temperatures recorded. Although this is unlikely to be precisely true in practice, it is likely to hold at the level of uncertainty introduced by the thermometers.

3.2.2.7.5. LAYS Calculation

The most significant assumptions are introduced in order to perform an estimated LAYS calculation of the intervention. First, there is a crude assumption that the weather in December is comparable to that experienced during other times of the year based on average temperatures. In practice, other factors, such as cloud coverage, rain, humidity and changes in solar radiation would likely impact these findings. Furthermore, as noted in the literature review, access to reliable weather data in Tanzania is very limited. This means average temperatures cover a large range, and in practice were likely recorded at the airport, which is 12.5km from Oyster Bay. Secondly, there is an assumption that the days of weather recorded in December are representative of the rest of the month. Given that there is a level of variability of weather in December, this is unlikely to be precisely the case. However, the variability is not so great that it would likely have a major impact on the results.

Third, there are a set of assumptions linked to the learning calculations. The method relies on the assumption, inferred from the literature, that a 1℃ reduction in temperature results in

2% improved learning (Wargocki, Porras-Salazar and Contreras-Espinoza, 2019; Park *et al.*, 2020). However, this inference comes from data investigating lower temperature contexts, and it is not clear if this linear relationship holds true at the higher temperatures experienced in Tanzania. So it is possible that the learning impact is both lower or higher (examined further in the discussion section).

Fourthly, much store is placed on the World Bank Expected LAYS figure for Tanzania, which is estimated using examination data at specific years, then applied across all years of primary education. It is likely that some year groups have a higher figure and some lower. However, LAYS is the best metric currently available to assess learning, rather than years of school attendance.

These learning assumptions significantly limit these results, and makes a clear case for further research to corroborate the findings and is examined further in the discussion section.

3.2.2.7.6. Cost Effectiveness Analysis

The cost effectiveness analysis gives a clear cost of the trialled intervention. However, the main limitation is that costs of painting the roof of a small number of classrooms will vary significantly from the cost of painting at scale. In some ways the costs could reduce at scale, such as through economies of scale linked to bulk paint purchases. However, in other ways the costs could increase, such as through the costs attached to general management, overheads and monitoring. Therefore, in order to account for the significant researcher time, and to make the costs more reflective at scale, a 39.6% increase in costs was applied to cover general management. This is a crude assumption, but one that gives more realistic results than without such a cost estimate added. This is a further significant limitation of the work, and one which needs corroboration through further research.

3.2.3. Experiment Results

3.2.3.1. Recorded Temperature Results and Reduction

3.2.3.1.1. Period 1: Control and Blue Paint Intervention

During the first four-day period, the BPI reduced internal classroom temperatures compared to the unpainted control classroom, across all of the school day. The temperature reduction began at around 1℃ and increased to a peak of around 2.5℃, as shown in Fig. 30. The average temperature reduction between the control and BPI classrooms was 2.0℃ over the period, as shown in Table 14. The highest recorded temperature in the control classroom was 37.9℃, whereas the highest in the BPI was 35.0℃ (a 2.9℃ reduction at the peak).

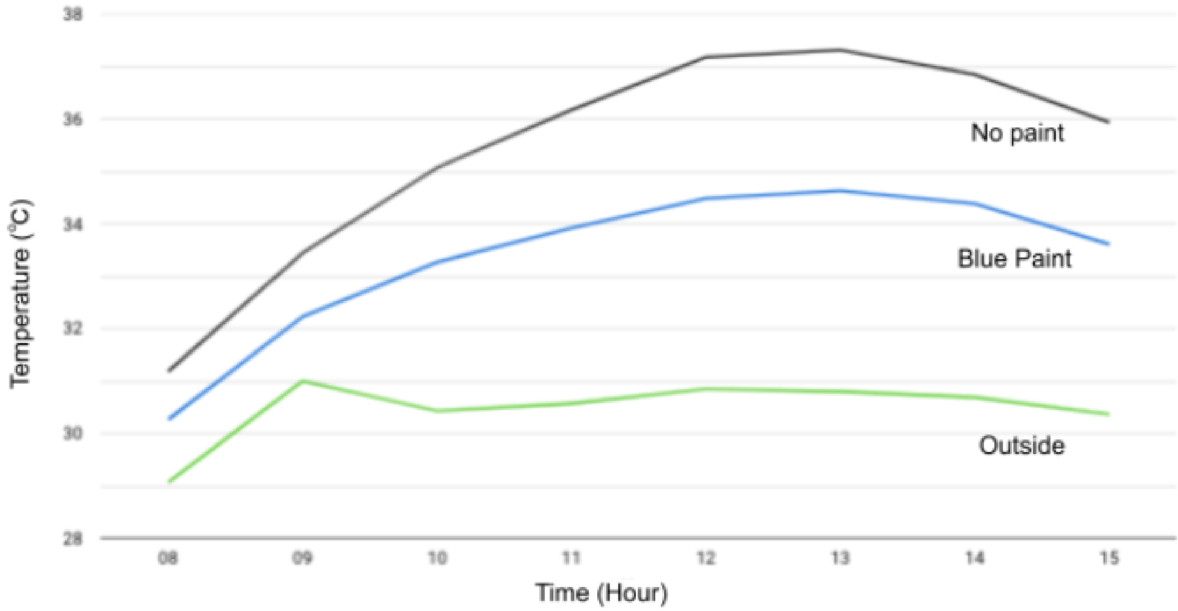


Figure 30: Minute by minute temperature recordings averaged across the four days and averaged hourly, from 19th December 2021 - 22nd December 2022 for the Blue Paint Intervention Classroom, Control Classroom and Outside under a tree.

Thermometer location	Average school day temperature (℃)
Control (Classroom 1)	35.4
Blue Paint Intervention (Classroom 3)	33.4
Outside under a tree	30.5

Table 14: Average temperature recordings in each classroom during the first four-day recording period.

3.2.3.1.2. Period 2 - White Paint Intervention and Blue Paint Intervention

During the second four-day period, the white painted roof was found to reduce internal temperatures more than the blue painted roof across all of the school day. The temperature reduction began at around 1℃ and increased to a peak of around 2℃, as shown in Fig. 31. The average temperature reduction between the BPI and WPI was 1.6℃ over the period, as shown in Table 15. The highest recorded temperature in the WPI was 33.1℃, whereas the highest in the BPI was 35.1℃ (a 2.0℃ reduction at the peak).

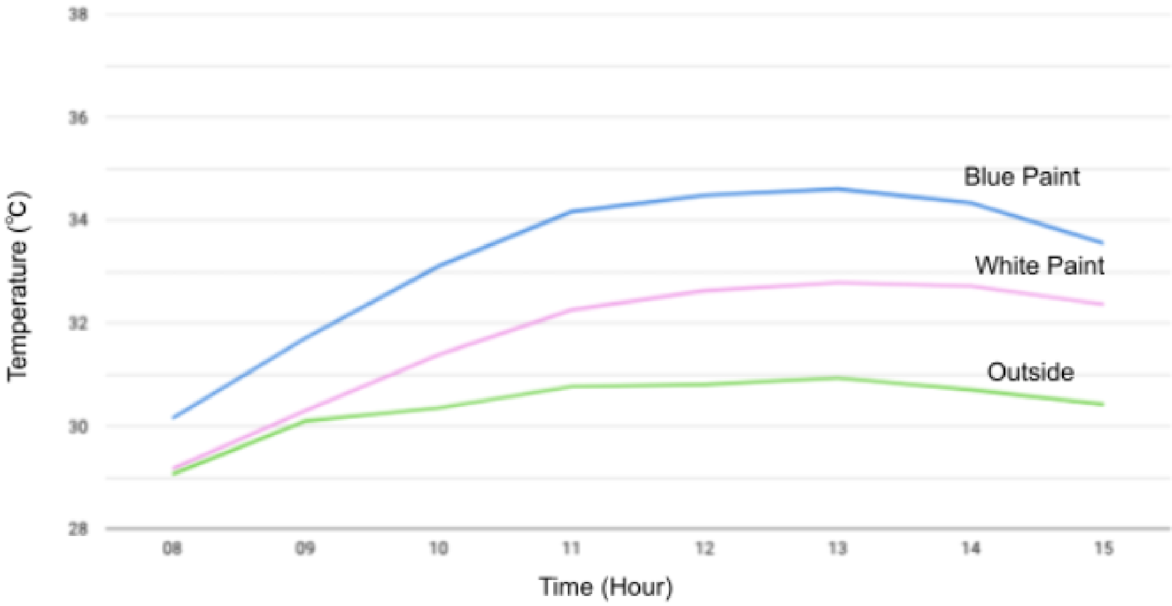


Figure 31: Minute by minute temperature recordings averaged across the four days and averaged hourly, from 30th December 2021 - 2nd January 2022 for the Blue Paint Intervention Classroom, White Paint Intervention and Outside under a tree.

Thermometer location	Average school day temperature (℃)
White Paint Intervention (Classroom 1)	31.7
Blue Paint Intervention (Classroom 3)	33.3
Outside under a tree	30.4

Table 15: Average temperature recordings in each classroom during the second four-day recording period.

3.2.3.1.3. Comparing The Control, White Paint Intervention and Blue Paint Intervention

The temperatures were modelled as described in Equation 8 and 9 (Section 3.2.2.3), and the results are shown in Fig. 32. Additionally, the results are shown in Fig. 33 with the temperatures averaged for each hour, to give a smoother graphical representation.

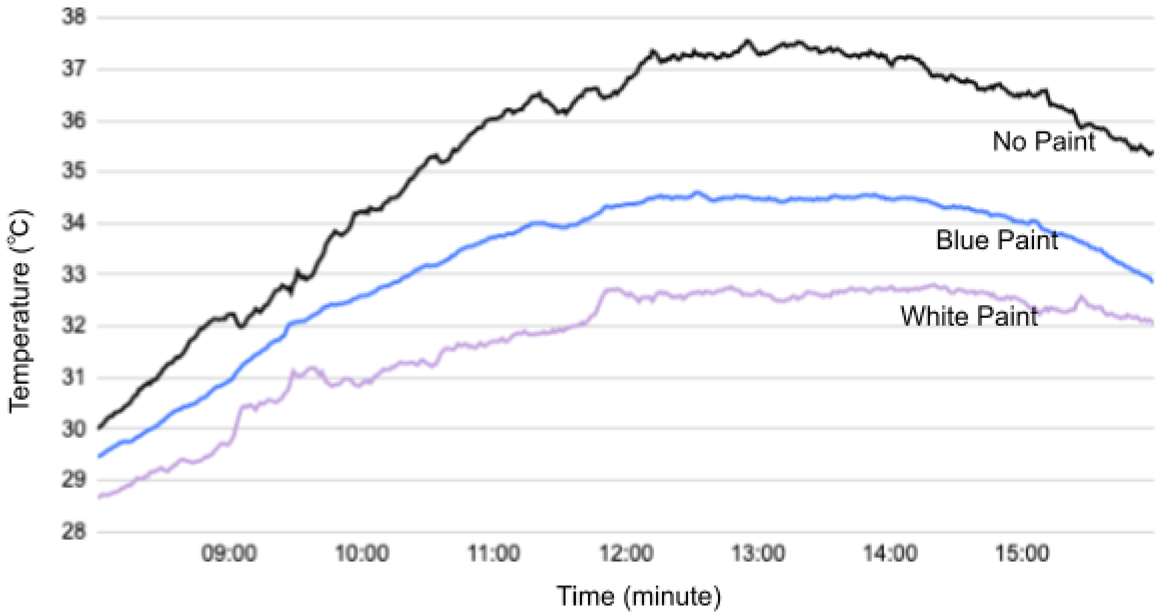


Figure 32: Minute by minute temperature recordings modelled and averaged across the 8 days for the White Paint Intervention Classroom, Blue Paint Intervention and Control Classroom.

The minute by minute data does not show any significant outliers, so all the data was included. This minute level view also provides a level of reliability to the data, as it is very reflective of the hourly averaged data, and shows that insights are not lost through averaging the data.

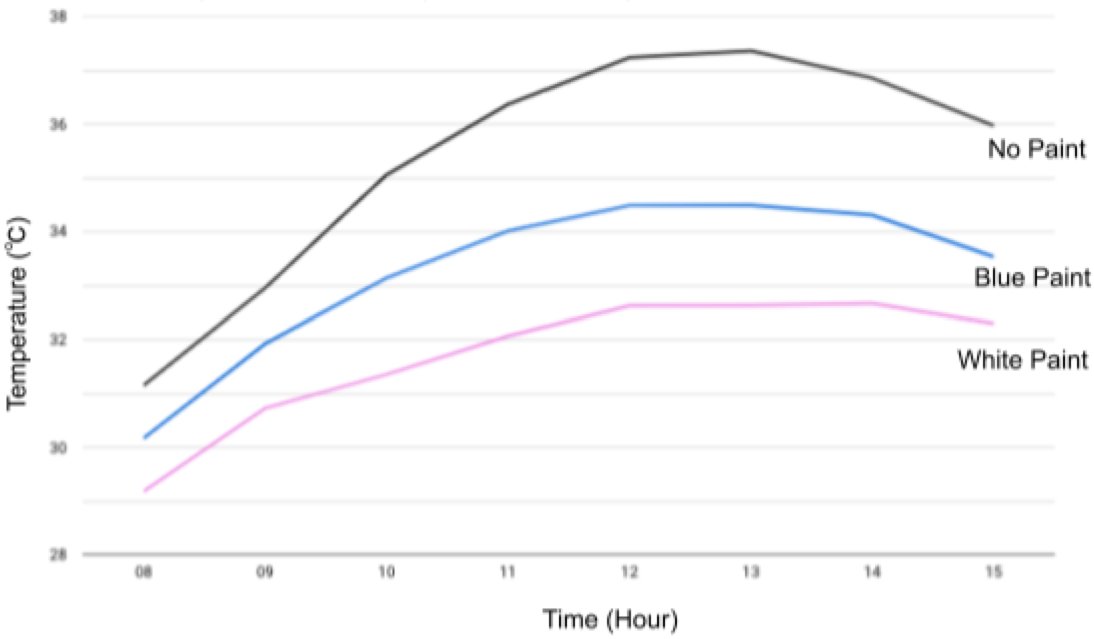


Figure 33: Minute by minute temperature recordings modelled and averaged across the 8 days, then averaged hourly, for the White Paint Intervention Classroom, Blue Paint Intervention and Control Classroom.

The WPI clearly performs best in the experiment in terms of temperature reduction. At the start of the school day, the WPI temperature begins at approximately 1.3℃ below the control. This temperature reduction between the WPI and the control increases up to 5.0℃ (with the difference at respective peak temperatures of 4.8℃). The average temperature reduction between the WPI and the control was 3.7℃ over the course of the school day (Shown in Table 16).

Thermometer location	Average school day temperature - modelled (℃)	Maximum school day temperature - modelled (℃)
White Paint Intervention (Classroom 1)	31.6	32.8
Blue Paint Intervention (Classroom 3)	33.3	34.6
Control	35.3	37.6
Outside under tree	30.4	31.4

Table 16: Average and maximum temperatures modelled across both periods of the experiment.

3.2.3.1.4. Predicting The Results Over The Course Of A Full Year

Extrapolating the data over the course of a full year, using average monthly temperatures (shown in Table 17), it is predicted the WPI will reduce classroom temperature by 3.5℃ on average during the school day throughout the year.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual average
Dar Es Salaam monthly average temperature (°C)	27.6	27.9	27.4	26.2	25.6	24.8	24.4	24.5	25.2	26.1	26.7	27.3	**26.14**
Percentage difference of temperature compared to month of December	+1.10%	+2.20%	+0.37%	-4.03%	-6.23%	-9.16%	-10.62%	-10.26%	-7.69%	-4.40%	-2.20%	0	**-4.24%**
Predicted classroom temperature change (°C)	-3.7	-3.8	-3.7	-3.6	-3.5	-3.4	-3.3	-3.3	-3.4	-3.5	-3.6	-3.7	**-3.5**

Table 17: Monthly average temperatures in Dar Es Salaam, used to predict the fluctuation in average temperatures in classrooms in Dar Es Salaam.

Source: (Climate-Data.org, no date, citing ECMWF, 2022)

3.2.3.2. LAYS Calculation

The LAYS was calculated using the average temperatures across the year, as shown in Table 17, and using the method previously described. Full detailed calculations are available online: https://docs.google.com/spreadsheets/d/1A_AYzLUqkLi2TmaHvCNsH4DHq-9vcj-dtpyZEQIAxDg/edit#gid=820912954.

Using the estimate inferred from the literature, of 2% improvement in learning per 1℃ reduction in temperature, and the predicted 3.5℃ reduction in temperature over the year, the data suggests a 7.1% increase in learning would be achieved from the intervention. Over the course of five years and using the national average class size, this yields 26 Years of Schooling improvement in learning, which is equivalent to 16.1 LAYS. The input data and the results are shown in Table 18 below.

Category	Description	Equation	Unit	Result
Input variables and coefficients	LAYS coefficient in Tanzania	-	LAYS	0.62
	% Improvement per 1℃ reduction in temperature	-	-	2%
	Predicted annual temperature change in classroom	-	℃	-3.5
	Predicted % improvement in learning	-	-	7.1%
	Intervention length	-	Years	5
	Degradation coefficient (average degradation over five years at 5% reduction in efficacy per year)	-	-	0.9
	Class size (average in Tanzania)	-	Number of children	81
Years of schooling improvement	Annual improvement for a class size of 81 (years of schooling)	Class size x degradation coefficient x predicted improvement in learning	Years of schooling	5.2
	% Improvement for a class size 81, over a longevity of intervention five years (years of schooling)	Annual improvement (years of schooling) x length of intervention	Years of schooling	26
LAYS improvement	LAYS annual improvement for a class size of 81 (years of schooling)	Class size x degradation coefficient x predicted improvement in learning x LAYS coefficient in Tanzania	LAYS	3.2
	LAYS improvement for a class size 81, over a longevity of intervention five years (years of schooling)	LAYS annual improvement x length of intervention	LAYS	16.1

Table 18: Shows the inputs and the results from the analysis method used.

3.2.3.3. Cost Effectiveness Analysis

The costs of the intervention are detailed in Table 19. As discussed in the methods section, the 40% General Management cost was not incurred in practice, but was added in order that the research management time could be reflected and to reflect some expected costs of scaling.

BEE cost category	Costs	Description	Total cost (GBP)	Cost per classroom (GBP)	Cost per classroom (USD)
Safe schools and infrastructure	Paint	- 4.5 x 20l drums of white paint at £47 per 20l drum. - 0.75 x 20l drum of blue paint at £43 per 20l drum.	£244	£81	US$102
	Labour and tools	Negotiated through discussion with building contractors.	£250	£83	US$104
	SMC engagement costs	Costs to facilitate travel for SMC to meet	£40	£13	US$17
General operations, management, and reporting	Estimated General operations, management, and reporting at 30%	This is a predicted cost of rolling the intervention out at scale.	£196	£65	US$81
Total			£729	**£243**	**US$304**

Table 19: Shows the recorded intervention costs and the predicted general management costs.

Given that the expected LAYS of the intervention is recorded at 16.1 and the expected cost of the intervention is US$304, the resulting cost effectiveness is predicted at 5.3 LAYS per US$100 spent.

4. Discussion

4.1. Classroom Temperatures sub-RQs

4.1.1. Sub-RQ: What are the daily temperatures in classrooms in Dar Es Salaam?

The results of the experiment show that classroom temperatures are high. During the first four-day recording period, the unpainted control classroom recorded an average temperature of 35.4℃ and hit a peak of 37.9℃. December is the fourth hottest month in Dar Es Salaam, however the temperatures do not vary significantly throughout the year (shown previously in Table 17). This is significantly higher than any thermal comfort ranges recorded in the region (23.5–28.5°C) and higher than results previously recorded in relation to learning (Malama *et al.*, 1998; Zingano, 2001; Wargocki, Porras-Salazar and Contreras-Espinoza, 2019). These temperatures do align with temperature measurements in classrooms elsewhere, such as in South Africa, and are broadly in line with temperature modelling undertaken across the continent (Bidassey-Manilal *et al.*, 2016; Pohl *et al.*, 2021; Proctor, 2021).

Furthermore, the results are likely to underestimate the actual air temperature and the perceived temperature experienced in the classroom for two main reasons. First, the temperatures recorded were without the normal heat gains from the presence of students, which would push up the temperature cumulatively throughout the day. This was unavoidable, because the research needed to take place during the school holidays in order to reduce disruption and avoid ethical implications. Using CIBSE Guide A estimates of 70 Watts per child (combined sensible and latent heat), the presence of 81 children (the average national class size) would introduce 5,670 Watts of heat, which would likely be significant over the full day. Using the previous classroom temperature model, it would suggest the heat gains from students would increase the temperature by an average of 2.5℃ (Proctor, 2021). Therefore, the peak air temperature with children in the class would be over 40.4℃ based on this modelling. Given that this temperature is so far outside the range normally put forward when discussing temperature impacts on learning, it is a significant finding in itself.

The second main reason is because the results only measure the ambient air temperature. This discounts the radiative heating effect that would be expected from an unpainted corrugated roof (as described previously in Fig. 10). Increased radiant heat increases perceived human temperatures, and can have a greater impact than air temperatures (Höppe, 1999; Kántor and Unger, 2011; McMullan, 2017). Given that radiation would travel down from the roof, directly hitting the exposed heads of the children, the perceived temperatures experienced by children would likely be higher than the air temperatures recorded. The radiant temperature could be estimated in future using a globe thermometer, which can measure a combination of air temperature, radiant temperature and air velocity. If air temperature and air velocity are recorded separately, then the radiant temperature (and resulting Mean Radiant Temperature) can be calculated (Aparicio *et al.*, 2016). The Dry Resultant Temperature (referred to as Operative Temperature in ASHRAE and ISO), is a good, but simplified measure of people’s thermal comfort and can be calculated using air temperature, radiant temperature and air velocity (Koch, 1962; Aparicio *et al.*, 2016; Designing Buildings, 2020). This can be calculated at low air speeds using Equation 13. However, given the open nature of the classrooms, it is likely to require the more complex Equation 14.

$$T_{res} = \frac{1}{2}T_r + \frac{1}{2}T_a$$

Where:

T_{res} = Dry resultant temperature

T_r = Radiant temperature

T_a = Ambient air temperature

(Equation 13)

Source: (McMullan, 2017)

$$T_{res} = A.T_a + (1 - A)MRT$$

Where:

MRT = Mean Radiant Temperature

A = Value that is a function of air velocity as: $[< 0.2\frac{m}{s}, A = 0.5]$, $[> 0.2\frac{m}{s} \& < 0.6\frac{m}{s}, A = 0.6]$, $> 0.6\frac{m}{s} \& < 1\frac{m}{s}, A = 0.7]$

(Equation 14)

Source: (Aparicio *et al.*, 2016)

Given the level of temperatures recorded, and the likelihood that the perceived temperature will be much higher, the temperature results recorded in the experiment are significant. From reviewing the literature, it appears that this is the first collection of temperature data in classrooms in East Africa. It provides base data that shows that huge amounts of investment into the education sector may be systematically undermined by sweltering classroom temperatures experienced by students and teachers.

4.1.2. Sub-RQ: What effect does painting a classroom roof have on temperatures recorded?

The results show that a roof painting intervention can reduce school temperatures by 3.7℃ during school hours on the days measured, and by an estimated 3.5℃ on average over the year. Given the relatively low cost of the intervention, this level of reduction is significant. The White Paint Intervention reduced the temperature by 1.7% more than the Blue Paint Intervention. This makes a very clear recommendation that roof painting interventions should be white colour for optimal effect. However, given the potential concerns around the acceptability by SMCs, the White Paint Intervention needs further investigation in terms of acceptability.

The results align with other estimates for white paint cool roofs, which have been cited at 2-6.5℃ (Cheng, Ng and Givoni, 2005; Amer, 2006; Pisello, Santamouris and Cotana, 2013; Dias *et al.*, 2014; Song *et al.*, 2021). Therefore, from a purely building science perspective, the results simply build on the existing orthodoxy, albeit in a region with little prior data collection.

4.1.3. Sub-RQ: Using the existing literature, what is the predicted subsequent effect on learning from the temperature reduction identified?

From the review of the literature, the evidence suggests there is a 2% improvement in learning outcomes, per 1℃ centigrade reduction in temperature. Using the estimated annual school time temperature reduction of 3.5℃, it is trivial to calculate this figure at 7%.

However, there is still considerable uncertainty attached to this figure, related to the significant assumptions outlined in the methods section. There are two key factors contributing to this uncertainty. First, the literature does not adequately cover instances of temperatures above 35℃. It cannot be assumed that temperature and learning impacts continue in a linear relationship as temperature increases. This linear relationship is unlikely to hold true at higher temperatures, as past 50℃ the physiological effects would be so pronounced that it is difficult to envisage any learning taking place (Piantadosi, 2003). Fig. 34 shows how the learning impact might deviate at these higher temperatures.

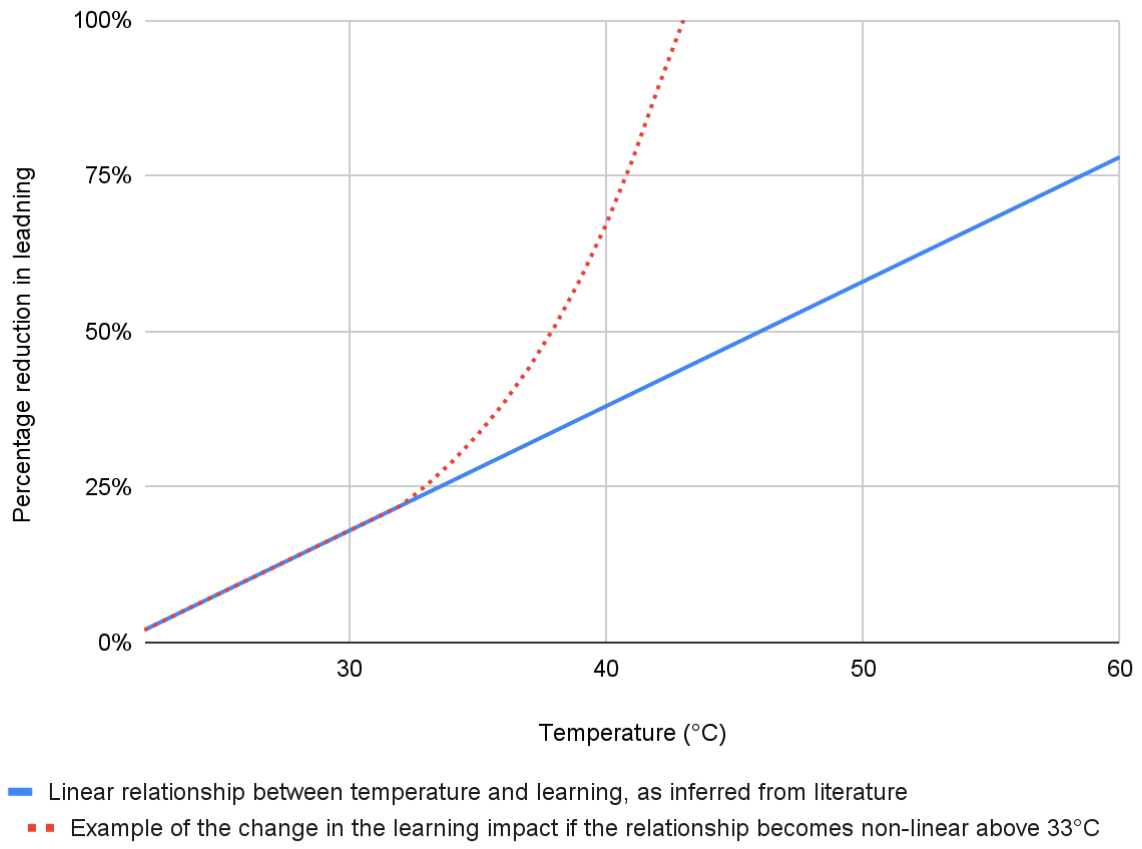


Figure 34: Showing the linear relationship between temperature and learning inferred from the literature. Also showing an example relationship, where this relationship only holds to 33℃.

The second key factor is the lack of understanding of the causal mechanism between temperature and learning. Referring back to the theoretical model in Fig. 35, the step inferred from the literature, from temperature change to learning, is highlighted in red. However, the causal mechanism of this step is not known. For example, it is unclear whether improving Thermal Comfort directly improves learning, or if only particular physiological factors that improve learning. Furthermore, it is unknown which of these physiological impacts are the most important. More investigation is needed in order to understand how temperature affects learning. However, given it is practically much easier to investigate the causal relationship between temperature and learning, it may be beneficial for the further research studies to regard the precise mechanisms as a 'black box' (Nidhra and Dondeti, 2012).

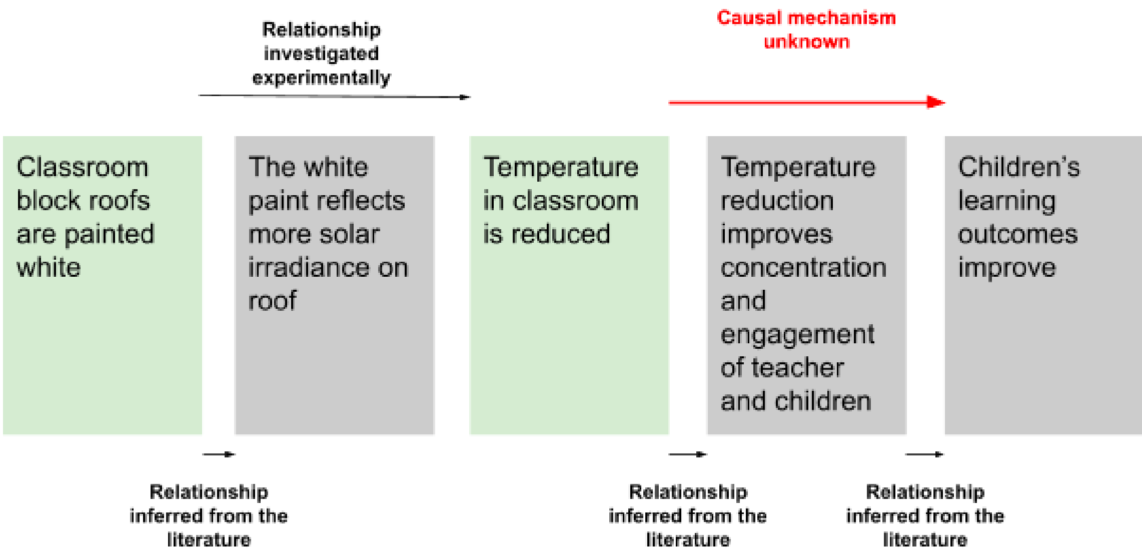


Figure 35: The theoretical model for the relationship between painting classrooms and learning outcomes. In this version the missing causal mechanism between temperature and learning is highlighted.

4.1.4. Sub-RQs: What is the cost effectiveness of the intervention in Learning Adjusted Years of Schooling per US$100 spent? How does the intervention compare to other interventions available?

The estimates predict that the temperature reduction of the intervention can result in 4.8 LAYS per US$100 improvement, when delivered at a greater scale. These results are significant, as the intervention is estimated to be more cost effective than other researched teaching and learning interventions, as shown in Fig. 36. The interventions assessed that were significantly more cost effective were system strengthening accountability programmes (Angrist *et al.*, 2020). The roof painting intervention cost effectiveness is predicted as slightly higher than the hugely impactful and celebrated Tusome intervention, which improved learning outcomes through systemic support to teachers in Kenya (Piper, 2018; Piper *et al.*, 2018; Lysenko *et al.*, 2019).

Temperatures are expected to increase in the region over time due to climate change, and therefore these results are likely to grow in significance and provide greater cost effectiveness (IPCC, 2018). As such, the results provide a firm basis for further investment into researching temperature in classrooms, and possibly wider classroom experience.

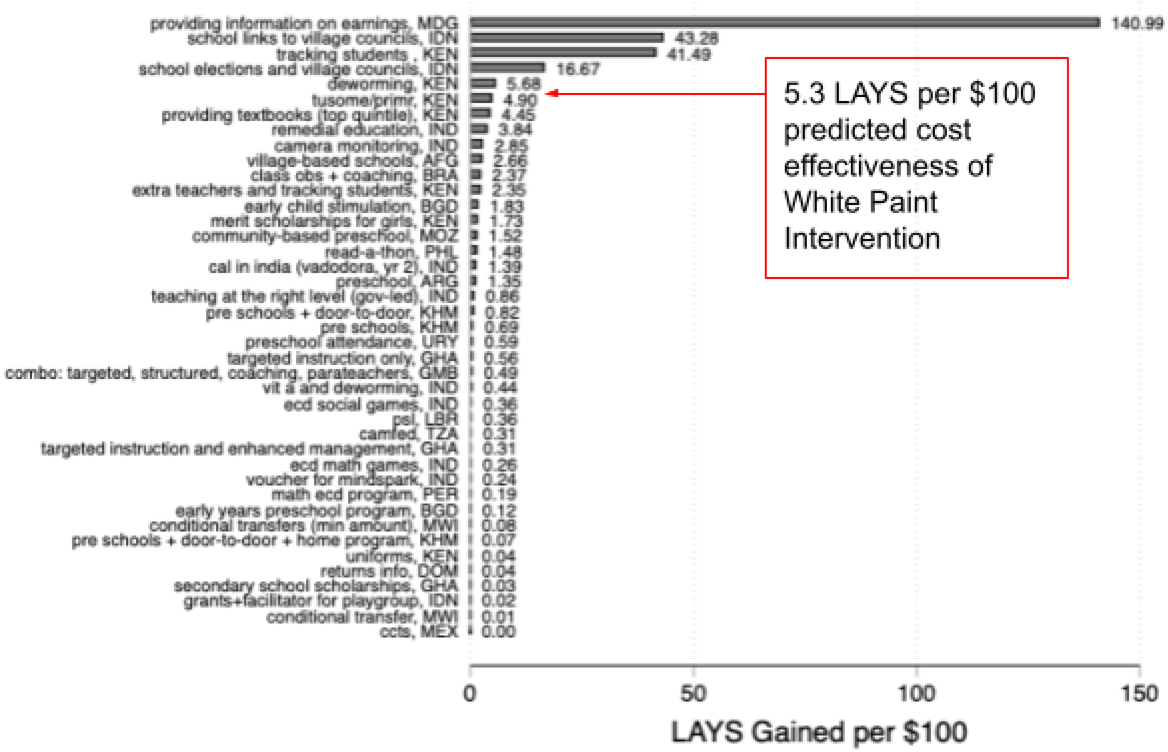


Figure 36: Learning Adjusted Years of Schooling (LAYS) per US$100 spent for various interventions - with the White Paint Intervention highlighted for comparison.

Source: (Angrist *et al.*, 2020)

A key outstanding question remains over the longevity of the intervention, as referenced in the methods section. It is unclear how the intervention will perform over time. Furthermore, it is worth noting the potential for the paint to increase the lifespan of the roofing. The inclusion of a degradation coefficient looks to address this factor, but more research is needed to give assurance to this variable.

An important aspect of the intervention, which was uncovered through the process, is the acceptability of the intervention. Temperature reductions achieved using the White Paint Intervention were significantly less than using a Blue Paint Intervention. However, in the experiment the SMC were clear they didn't want the classroom block to have a white roof, and preferred a light blue colour. This also aligns with feedback from the pilot investigations in paint shops, which suggested colour preference is important. The situation is exacerbated because roof paint producers do not manufacture white roof paint as standard. It is unclear whether with persuasion the SMC would have accepted a white roof, if the recorded temperature difference was presented to them and benefits explained. It is crucial to investigate this acceptability issue further, as the work for a retrofit intervention like roof painting would be decentralised to schools and SMCs to implement. This means that without addressing this concern, there may be issues around future at-scale implementation fidelity.

4.2. Overall RQ: Is painting classroom roofs in East Africa a cost effective intervention for reducing classroom temperatures and improving learning outcomes?

In answering the Sub-RQs concerning classroom temperature, it has been comprehensively shown that classroom temperatures are high in Dar Es Salaam and therefore likely high across the region. It has been predicted that the intervention will be more effective at improving learning than most of the existing teaching and learning interventions. Bringing together the answers to the sub-RQs, the research suggests that painting classroom roofs could be a cost-effective intervention to improve learning outcomes.

However the limitations outlined in the methods sections are very significant and the results need to be viewed through that lens. There is therefore some uncertainty as to whether the intervention would achieve learning outcomes at scale. At the less impactful end of the uncertainty, the intervention might only be cost effective when targeted at the hotter areas. If the predictions were to hold true, then it would likely make sense to roll out the intervention at scale to all schools in the region. Given the uncertainty, the research is not strong enough to call for policy change to deliver at scale a roof painting retrofit intervention across Tanzania or the region. Instead, it is recommended to pilot the intervention in a smaller number of schools, whilst investing in further research. Given the simplicity of the intervention, it would be relatively straightforward to increase the scope and longevity of the research, and to include learning outcomes as a measured variable. Further research options are detailed in the conclusion.

In order to deliver the intervention across to all primary schools, it would need to be rolled out to 126,000 classrooms - costing approximately US$42 million (UNICEF Tanzania, 2018; PO-RALG, 2019). This level of funding would be a stretch for any donor as a specific retrofit intervention. However, given the Government focus on infrastructure, and donor focus on learning, it is conceivable that this could be funded. It is certainly a potentially affordable amount, given the education sector budget of US$1.4 billion and recent World Bank investments of US$500 million in Tanzania over the next five years (UNICEF, 2020; World Bank, 2021). However, for this level of investment, more research would be required to demonstrate effect and reduce the levels of uncertainty presented in this paper.

5. Conclusion

5.1. Summary

The paper has built on the evidence around roof painting interventions in East Africa. A literature review covered the drivers within the education system in Tanzania, as well as the link between temperature and learning. The literature review then goes on to look at classroom design in Tanzania and the prevalence of simple, unpainted two- or three-classroom blocks. The literature also details the difficulties in accessing reliable weather data, which impedes research and particularly the ability to model temperature.

The paper records and publishes classroom temperatures for, what appears to be, the first time in Tanzania and East Africa. The research estimates the impact of a roof painting intervention. Again for what appears to be the first time, the paper calculates the potential education impacts in terms of Learning Adjusted Years of Schooling, allowing the intervention to be benchmarked against other education interventions.

The first finding from the paper is clear: that classroom temperatures in Dar Es Salaam, and likely across the region, are high and reached over 37.5℃ on the days recorded. This excludes the heat input from children in the classroom, which is estimated to push the air temperature over 40°C. The research also suggests that the perceived temperature is likely to be higher once radiated heat is taken into account. These temperatures are higher than those found in the vast majority of previous studies on heat and learning, which mainly focus on the 20-30℃ range. This therefore makes a compelling case for further research into the temperature extremes and the impact of these higher temperatures on learning outcomes.

The second finding of the paper is that a white paint cool roof intervention reduced classroom temperatures by an average of 3.7℃ over the course of the school day, during a four-day measurement period in December 2021. Further, the maximum temperature reduction was 5℃.

The third finding of the paper, concerning the intervention, comes with significant qualification. The paper suggests that a white paint intervention is likely to be cost effective in improving learning outcomes at an estimated cost effectiveness of 5.3 LAYS per US$100 spent. However, although this outcome is likely to hold true in the hottest areas in Tanzania, it may not hold true everywhere. Therefore, the paper does not make a suggestion for policy change, but rather for specific further research that would provide sufficient evidence to make policy recommendations.

5.2. Limitations

There were significant limitations introduced at different stages of the investigation. The initial experiment has fewer limitations than the subsequent learning and cost effectiveness analysis. The high level limitations are covered in this section, but detailed description of methodological limitations are laid out in Section 3.2.2.7.

In relation to the initial experiment results, the key limitation is that only air temperature was measured, which discounts expected perceived impact from radiant heat off of the roof. This may have the effect of systematically reducing the temperatures recorded, especially under the unpainted control roof.

In the temperature analysis the recorded data was extrapolated over the course of a full year, in order to give a view on the intervention efficacy. This introduced a high margin for error, and the experiment needs to be repeated over the course of a full year to reduce this.

The subsequent learning analysis introduced a high level of uncertainty. The analysis assumes a link between temperature and learning that was inferred from a literature base that is predominantly from lower temperatures and from the global north. Furthermore, it is not clear yet what the causal pathway is between temperature and learning. Finally, the learning data used from Tanzania to predict LAYS and LAYS per US$100 are from crude World Bank estimates, and likely include a level of error.

5.3. Implications of the Research

5.3.1. Implications for policy and practice

The key implication of the research for policy is in uncovering classroom temperatures in Tanzania that very likely exceed 40℃. Donors are channelling billions of dollars in funding to the region, focused on learning outcomes. This paper provides evidence that this funding and impact may be undermined by sweltering classroom temperature.

The research goes on to suggest a white paint cool roof intervention may be a cost effective approach to reducing temperatures. However, given the very significant limitations linked to the study, it is not recommended for policymakers to invest in this retrofit intervention without further research. New build design was not the focus of this research, however the evidence is likely strong enough to justify policy makers adjusting new build designs to include a white roof.

5.3.2. Implications for research

There are three key implications for research from the paper. First, the paper builds on work globally, showing the role of temperature in classrooms and provides empirical evidence of temperatures in East Africa. Second, the findings of the white paint cool roof intervention are broadly aligned with findings from other interventions showing a 2-6.5℃ decrease in temperature from white paint cool roofs in hot environments. Finally, the methodological section outlines an approach to experimenting on classroom blocks to understand temperature changes, where half the block is used as intervention and half as the control. This method could be repeated as further research is undertaken.

5.4. Future Research

Three areas of future research are identified and detailed in this section. First is desk based research, using data already collected or available, to model classroom temperatures across Tanzania. The second area replicates the research experiment undertaken in this paper, but with an adjusted scope and over a longer time, and would address the limitations described. The final area suggested is a Randomised Control Trial, which would show any causal link between the intervention, temperatures and learning outcomes. The combination of the three pieces of research would show if, how and where to reduce temperature, allowing recommendations to move quickly into policy and implementation.

More data was collected than has been analysed and proposed in this paper, and has been published online as a supplementary file. This includes wind speeds and solar irradiance data. Using this data, it would be possible to update and refine the classroom temperature model previously proposed by the author. This would give the model a wider applicability and increase the reliability. It would be possible to use the model to analyse weather data across Tanzania, to give a wider insight into classroom temperatures. This could then be used to target interventions, roof painting or otherwise, to address these sweltering temperatures.

Many of the limitations of the research could be addressed through a similar piece of experimental research, covering a full year of readings across multiple sites. This research could follow a similar method, but given the complexity of two separate interventions, it is suggested that only the white paint intervention is used. It may also make sense to broaden the scope, so that it is mixed methods research, including qualitative data collection. This would allow insight into the acceptability of the intervention, and to understand if there are other issues, once implemented. This would also allow investigation to understand the acceptability of the intervention, given concerns raised by the SMC regarding roof colour. Furthermore, it is suggested that this research investigates the impact of radiant heat, as opposed to just air temperature, using globe thermometers.

Finally, a Randomised Control Trial is suggested, where the intervention is applied to a number of classrooms. It is suggested that the design would be a cluster RCT, where the cluster unit of randomisation is the classroom. The participants would be the students, and the measurement could be linked to existing learning assessments. Using the expected learning effect, power calculations could be used to estimate the cluster size required. Given the costs attached to a cluster RCT, it is suggested the two suggested areas of future research are completed beforehand.

6. References

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7. Supplementary Files

The raw data from the experiment is published online as a supplementary file available here: https://docs.google.com/spreadsheets/d/1a-kJ6BDf-JI9Zhb_TWiwMMkTABReezOCCWhh-fuFhes/edit#gid=136982907 .

Tables and LAYS calculations are available here: https://docs.google.com/spreadsheets/d/1A_AYzLUqkLi2TmaHvCNsH4DHq-9vcj-dtpyZEQIAxDg/edit#gid=820912954.