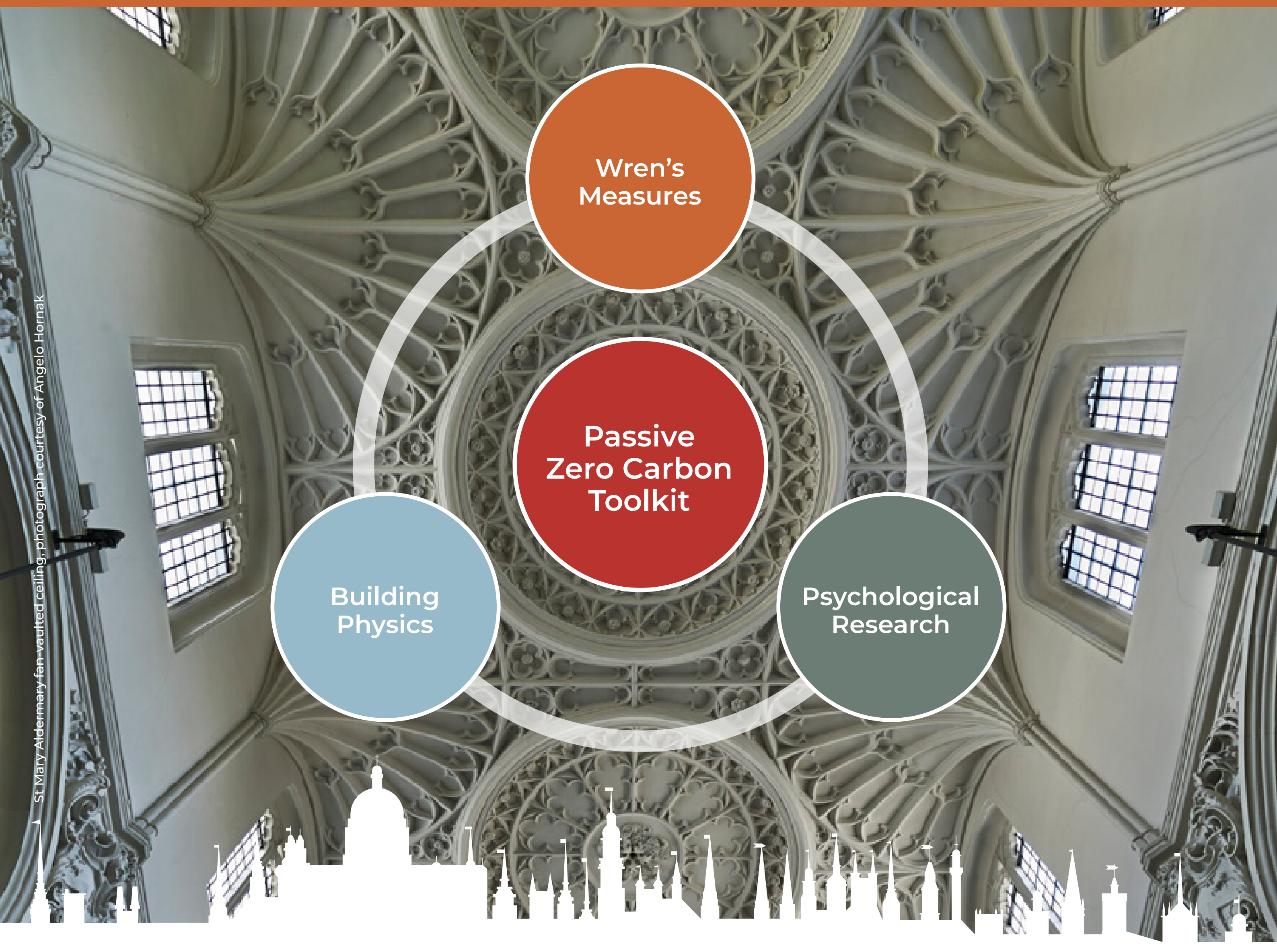
WREN 300

THE SQUARE MILE CHURCHES

TOOLKIT

An Inter-disciplinary Toolkit for Exploring Passive Zero Carbon Transition Pathways for Wren's City Churches



St Mary Aldermary fan vaulted ceiling, photograph courtesy of Angelo Hornak

CELEBRATING WREN IN THE CITY OF LONDON'S CHURCHES

Contents

WREN 300

THE SQUARE MILE CHURCHES

www.squaremilechurches/wren-300

wren300squaremile

@Wren300M

Wren300SquareMileChurches

Made possible with Heritage Fund

Summary

When aiming to reduce the environmental impact of historical buildings, special attention is required concerning the conservation of cultural values, heritage significance as well as the historic building fabric. A holistic approach is necessary to retain heritage significance while implementing sustainability measures.

This holistic toolkit demonstrates how passive measures may improve the energy performance of Wren's City of London churches, whilst fully respecting their cultural heritage, significance and architectural design.

The toolkit is intended for church managers, vicars, or other individuals who are interested in balancing human thermal comfort and church conservation.

The key aim of this guide is to offer an interdisciplinary framework exploring , their history, their psychological impact on churchgoers, and their effectiveness at regulating building temperature.

The refurbishment of historical buildings is of key importance in meeting the climate goals of achieving net zero by 2050 in the UK and EU. The Church of England has set a target to reach net-zero carbon emissions by 2030[1]. This goal involves all parts of the church working together to significantly reduce their annual emissions. Zero-carbon buildings are defined through various frameworks considering energy efficiency, renewable energy usage or carbon offsetting.

Fossil fuels are finite resources, we must move away from gas boilers which are commonly used in churches.

The electrification of heating systems is promising, but the zero-carbon transition is a process which cannot rely solely on a single product. Energy demand reduction and behavioural changes are critical to achieving zero carbon. Passive measures are often overlooked regarding this process and so we have employed historical research to reintroduce them to the modern eye as an alternative method to electric devices. To ascertain the cultural impact of Wren's churches we conducted psychological surveys. Finally, we amalgamated various building surveying techniques into an approach which allowed us to understand the complex needs of Wren's churches.

Once the churches are fully electrified, on-site energy generation can be considered, combined with opting for a green tariff. Of course, churches could opt to rely solely on green energy tariffs derived from renewable sources such as solar, wind or tidal; however, these renewable energies do not improve the energy efficiency of the sites, nor contribute to their preservation. Implementing passive measures to reduce energy demands on-site is a critical step towards zero-carbon buildings.

[1] Church of England, 2022, Net Zero Carbon Routemap, https://www.churchofengland.org/about/environment-and-climate-change/net-zero-carbon-routemap

www.britishmuseum.org (License type: Non-Commercial)

Charles Robert Cockerell, Tribute to the Memory of Sir Christopher Wren (1841)

The research underpinning this toolkit is based on data collected from participating Wren city churches namely: St Edmund, King and Martyr, St James Garlickhythe, St Mary Abchurch, St Mary Aldermary, St Margaret Pattens and St Martin Ludgate, including a more in-depth case study of St Mary Aldermary.

While this toolkit is focused on Wren's City churches, most of the results of the research are equally applicable to all other type of churches as well, though local context and considerations will apply.

This Passive Zero Carbon Toolkit is an ongoing project. So far, we have established a diverse interdisciplinary team from history, psychology, architecture and building physics backgrounds to conduct a thorough investigation of this issue and create a roadmap whilst creating educational content and applicable methods for readers to utilise.

PART 1: Historical Research

The changing character of the City from residential to commercial and financial in the 19th century had a large impact on the City churches, both due to shrinking congregations and new development (Jeffery, 1996). The Second World War and the Blitz brought further radical change to the area, with further Wren churches destroyed and the face of the City radically changed and redeveloped in the years after the war. Of the fifty-one parish Churches rebuilt by Wren's office after the Great Fire of London, only twenty-three remain today.

Why historical research?

Historical research can tell us about how our churches were used in the past, how people experienced them and how they adapted to changes in the climate. By looking back, we hope to learn how to regulate our church temperatures with techniques used before we relied on space heating techniques which use fossil fuels. These techniques are called passive methods, they maximise the use of 'natural' ambient energy sources. This includes harnessing environmental conditions such as solar radiation, cool night air and air pressure differences to create a comfortable internal environment without the need for mechanical or electrical systems.

Research also helped to shed light on passive methods Christopher Wren incorporated into the City of London churches. The passing of time can sometimes lead to the modification or even removal of original features, that once worked as effective passive measures to regulate the internal environment of these buildings.

The historical research framework

How do we do historical research? It starts with setting a research question. Our research question was: '*Which passive thermal comfort features can be conserved in the zero-carbon transition?*' Once our research question is established, we identify useful primary sources (original historical documents) by conducting archival searches as detailed in the diagram in Fig 1 (overleaf). We then analyse those primary sources to identify historical examples of passive thermal comfort methods as well as evidence of how people interacted with churches in the past and how they reacted to temperature changes using such passive methods.

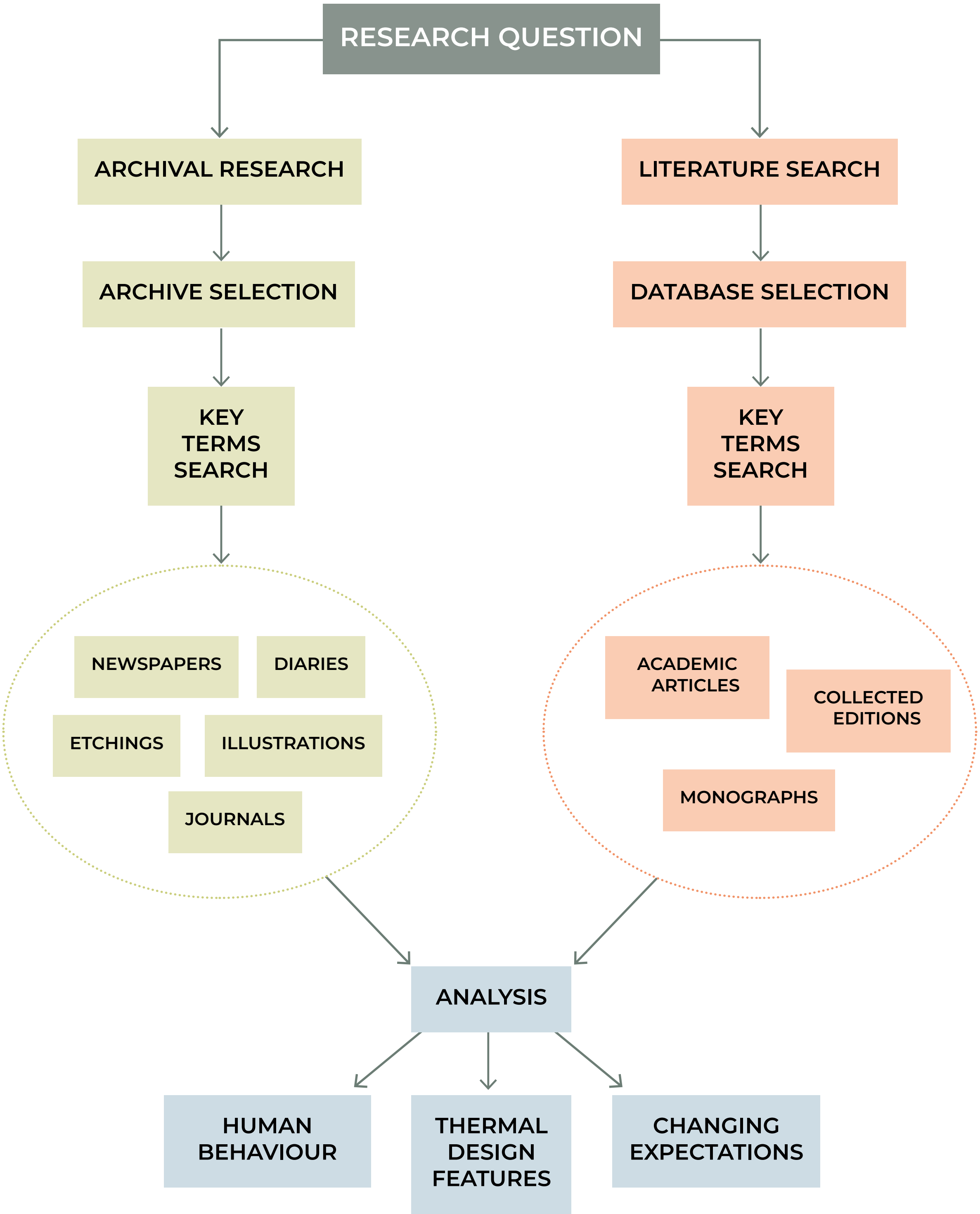


FIGURE 1: Research Method Diagram

www.jstor.org (Public Domain)

Wenceslaus Hollar (1647) 'Muffs, Gloves, Collars and Other Articles of Toilet', The Seasons

An etching by Wenceslaus Hollar from 1647 demonstrates the kinds of additional thermal comfort garments Londoners may have worn to church in Wren's day. This supports a notion from Pepys that churchgoers took extra garments to warm themselves during services.

Thermal comfort design features in the churches of Sir Christopher Wren

To understand historic passive measures, we investigated what already exists and how it has been used in the past. In essence, *are there features built into Wren's churches which could be better utilised before the addition of invasive solutions to thermal comfort and energy efficiency?* To answer this question, we conducted archival searches to assess images of historic Wren churches through the ages and determine which churches had which features built into them, perhaps by Wren, perhaps through later modifications by the Victorians or following World War II when many of Wren's churches were heavily damaged in The Blitz.

Identifying the location and function of each thermal design feature allowed us to conduct targeted simulations and thermography assessments of each church to determine its individual heating needs. The tables overleaf highlight the location of Wren's thermal comfort features across a variety of City churches. We intend for this to inform preliminary investigations of each church, with knowledge of the available architectural features, the possibility emerges to create a more favourable tailored approach which could help us maintain and learn about the heritage of the sites we wish to preserve.

Table 1 (below) highlights four different thermal comfort design elements heavily featured in Wren's City of London churches. The purpose of this table is to signpost the location of said features. The following pages explain each feature and its application in a thermal comfort context. Given Wren's lack of access to modern technologies, all of these thermoregulatory techniques are passive. This means they do not require an active energy source to assist in the temperature regulation of the churches.

	ROUND-HEADED & OPENING CASEMENTS	BOX PEWS	WALL PANELLING & DRAFT LOBBIES	THERMOREGULATORY CHURCH TOWER DESIGN
NO. OF CASE STUDIES	7	7	5	9
NAMED CASE STUDIES	St Benet Paul's	Christ Church Greyfriars	Christ Church Greyfriars	St Antholin
	St Bride's	Royal Chapel, Whitehall	St James's, Piccadilly	St Bride's
	St Edmund King and Martyr	St James's, Piccadilly	St Margaret Lothbury	St Edmund the King
	St James's, Piccadilly	St Margaret Patterns	St Margaret Pattens	St James's, Piccadilly
	St Mary-le-Bow	St Mary-at-Hill	St Mary's Abchurch	St Magnus the Martyr
	St Mary Magdalen	St Mary's Abchurch	-	St Mary Abchurch
	St Nicholas Cole	St Stephen's Walbrook	-	St Mary-le-Bow
	St Mary Abchurch	-	-	St Mary's Aldermary
		-	-	St Michael, Crooked Lane

Table 1: Wren's Thermal Comfort Design Features – No. of case studies

Note: 'No. of case studies' indicates the number of selected Wren churches exhibiting said feature, as found via extant features or documentary evidence

www.sjp.org.uk (Public Domain)

Box pews fill St James's Piccadilly, (1857)
Unknown Author

Round-headed windows and opening casements

Round-headed and opening casements were a glazing style characteristic of Christopher Wren. His windows were large and used clear glass; often semi-circular at the top of rectangular frames. One purpose of this design was to allow as much natural light as possible to enter and warm the buildings in winter using the greenhouse effect.

In some of his churches, Wren also installed opening casements, small panels of glass set into the centre of the windows on hinges which could be opened to allow for greater airflow or closed to prevent drafts from entering the building. This allowed Wren's churches to 'breathe' and for their occupants to control, to some degree, the passage of warm or cool air through the building. Some of Wren's churches that were lucky enough to survive the Victorian restoration and The Blitz with windows intact still have this feature, namely St Benet Paul's Wharf and St Nicholas Cole Abbey. Some have been substantially rebuilt, but have retained this feature. Table 1 highlights churches that were designed with these opening casements in mind.

We suggest that a restoration of the original window style could improve thermal comfort in the summer as well as aid in retaining the heritage of these churches. Consideration could also be given to reinstating blocked windows, if possible, to utilise natural daylight as well as the greenhouse effect.

Box pews

Box pews were a highly efficient method of draft exclusion and featured heavily in many of Wren's original church designs. A surviving example are the pews at St Mary Abchurch. These pews feature large wooden panels boxing the inhabitant in from all sides and preventing cold drafts from wicking away body heat. Box pews varied, some featured sides so tall that church-goers would have to stand up to view the altar and pulpit. Sometimes these pews would have featured cushions or even fabric backings. Whilst these pews did use a lot of space, they were highly effective at draft exclusion. Reinstating box pews may reduce the need for heating methods such as under-pew heaters.

Wall panelling and draft lobbies

Wooden panelling at first glance may not appear to be a thermal comfort feature. However, in the context of Wren's designs, it was used to absorb and release heat from the sunlight permitted into the building by the large clear windows and create a thermal break from the walls. Wren favoured dark woodwork precisely because it trapped more heat than lighter applications.

Almost every internal furnishing was fashioned of wood from the reredos to the pews. Wren also incorporated draft lobbies which were lined with wooden panelling and designed to prevent drafts from entering the church via a two-door system. Many of Wren's churches have maintained this feature despite heavy restoration efforts. Some have exchanged Wren's original wooden doors for glass like in St Vedast, Foster Lane.

With a restoration of the clear windows, the full thermic potential of Wren's woodwork could be realised and incorporated into the zero carbon transition. Draft lobbies where lost could be re-instated, and existing draft lobbies made more effective by repairing the joiner and introducing draftproofing.

Thermoregulatory church towers

Wren's church towers are complex and magnificent. Many of Wren's spires were not completed until years after the construction of the main church and tower of their churches. Many of Wren's towers and spires boast features that were likely born out of necessity for thermoregulation and the application of a Grecco-Roman design philosophy that Wren had been refining since 1660, perhaps even earlier.

Wren's towers feature ventilation panels often on the upper levels, as well as open belfries. The rooms in his towers were airy, as wooden planks were used to create the floor, warm air was almost unrestricted to rise up and out of the towers through the upper, well-ventilated parts. Wren's philosophy for the towers likely dated back to his 1660 ventilation system for the House of Commons.

© Jim Linwood

The Tower of St Bride's Church (2010)

Inspired by the Grecco-Roman method of creating openings at the highest point of a roof to create a convection current, pushing warm air out and drawing warm air in, Wren designed a fume chamber, described in 1889 by the Journal of the Society of Arts the academic publication of the Royal Society of which Wren had been a part of:

> *He calculated that "the breath of the people below, and the steam of the candles, would pass upwards – from the House through these funnels" into the upper chamber provided for the purpose of receiving them before being carried off through the roof.*

Although this initial experiment with convection as a thermoregulator did ultimately fail, it's clear the initial idea developed and influenced Wren's church towers. Table 1 highlights many examples from the past and some still standing, where ventilation may have been used to create cooling convection currents throughout the buildings.

wikipedia.org (Public Domain)

Godfrey Keller, Christopher Wren (1711)

FIGURE 2: Round-headed windows and opening casements, St Benet's, Paul's Wharf.

FIGURE 3: Wall panelling and box pews, windows in round and opening casements removed by Victorians in windows.
Unknown Author (1896) St Mary's Abchurch: Pre-War photograph.

Fabrics in the interior

Fabrics can play a crucial role in sustainable design, serving not only aesthetic purposes but also contributing to thermal comfort and regulation. Curtains, for example, can significantly influence a room's temperature by providing insulation; heavy fabrics can trap heat during winter, while light, airy materials can keep a room cooler in summer. Tapestries, aside from adding visual interest and acoustic benefits, also add a layer of insulation to walls, as well as provide a thermal barrier to cold walls preventing discomfort, and contributing to a room's overall thermal stability. Soft cushions and upholstered furniture (including pews), with its layers of padding and fabric, act as insulators that can reduce conductive heat losses making seating areas more inviting and comfortable. Curtains over doors can provide further draught-proofing. It is difficult to find Wren's original interior schemes, as these would likely have been carried out by the churches themselves, and changed over time. The Victorians used fabrics in their church interiors. Now however, it appears the fabrics in the interior of city churches have disappeared.


CHAPEL HALL, WHITEHALL, 1800

RIBA


BANQUET HALL, WHITEHALL, TODAY

FIGURE 2: Fabrics in the interior.
Wren's Chapel Royal, in the banqueting house in Whitehall, London (1800, and today).

Clear glass, and glazing ratio

Clear glass is a technical innovation from the 17th century. Sir Christopher Wren and Robert Hooke contributed to the development of such innovation and manufacturing capacity in London.

Wren's churches were designed to admit abundant natural light by using clear arched glazed windows. The glazing area functioned both as a site for heat gain and heat loss depending on the external temperature of the building. The glazing ratio is a commonly used parameter in sustainable building design. The glazing ratio compares the total area of the building's exterior with the total area of the windows. Our preliminary research shows that Wren's churches have fairly consistent glazing ratios. However, it is also noted, that many churches don't have openable windows which is a change from the original designs of the Wren's churches as shown in Table 2.

www.londonchurchbuildings.com

St Mary Aldermary, City of London

Glazing area					
Level	Mid level	High level	Glazing Area Total	Wall Area Total	Glazing Ratio
North	28.84	28.98	**57.82**	335.20	**17.2%**
South	36.05	28.98	**65.03**	335.20	**19.4%**
East	7.21	27.65	**34.86**	186.78	**18.7%**
West	14.42	27.65	**42.07**	183.07	**23.0%**
			199.78	1040.25	**19.2%**

Mike Quinn

St Andrew's Church, Holborn

Glazing area	Church					
Level	Mid level	High level	Glazing Area Total	of which openable glazing area (m^2)	Wall Area Total	Glazing Ratio
North	19.10	48.72	**67.82**	**0.00**	305.22	**22.2%**
South	19.10	48.72	**67.82**	**0.00**	305.22	**22.2%**
East	n/a	40.21	**40.21**	**0.00**	217.19	**18.5%**
West	n/a	n/a	**0.00**	**0.00**	n/a	
			175.85	0.00	827.63	**21.2%**

Simon Knott

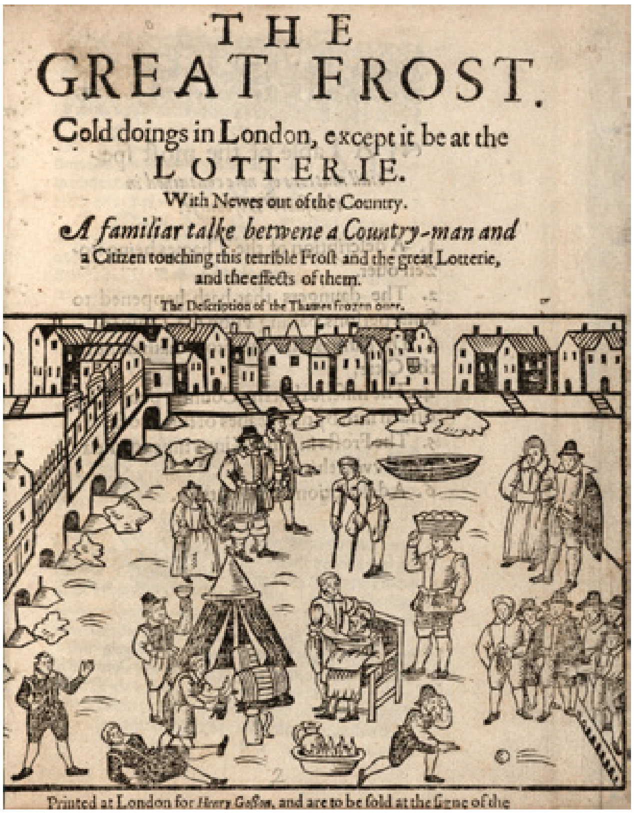
St Nicholas Cole Abbey, London

Glazing area	Church					
Level	Low level	Mid level (m^2)	Glazing Area Total (m^2)	of which openable glazing area (m^2)	Wall Area Total (m^2)	Glazing Ratio (m^2)
North	n/a	46.32	46.32	2.50	188.29	**24.6%**
South	n/a	28.50	28.50	2.10	188.29	**15.1%**
East	n/a	26.58	26.58	1.50	126.94	**20.9%**
West	n/a	5.07	5.07	0.00	126.94	**4.0%**
			106.47		630.46	**16.9%**

TABLE 2: Glazing ratios

How people in the past adapted

In the following section, we will explore various historical documents that demonstrate how people in the 17th century adapted to cooler climate conditions in churches. Primarily through the works of English diarists like Samuel Pepys and John Evelyn. The works of Bohemian artist, Wenceslaus Hollar also indicate how people in the past adapted their clothing to match their surroundings.



wikimedia.org

Henry Gosson (1608) 'The Great Frost' Printed leaflet

Wren was building in a time of great environmental change known as the Little Ice Age. The Little Ice Age spanned from 1303 to 1850 during which London and indeed England experienced several major freezing events. These events were known at the time as 'Great Frosts', the river Thames would freeze over and individuals would take to the ice with stalls, games and skates to enjoy the novelty of the Frost Fairs. Other 'Great Frosts' were recorded in the following years 1683, 1684, 1709, 1894 and 1895.

A change of clothing

Samuel Pepys was a prominent member of British society in Wren's day. He was an MP, a naval administrator and a prolific diarist. A few of his diary entries shed light directly upon behavioural adaptations to temperature changes made by people in the past. One such entry discloses that the people of Wren's time brought their personal thermal comfort items to the church, blankets in particular. In the burnt wreckage of St Paul's Cathedral in 1666, an old man was found dead after attempting to retrieve his blanket, 'there were several dogs found burned among the goods in the churchyard, and but one man, which was an old man, that said he would go and save a blanket which he had in the church'.

On Christmas day, 1668, Pepys donned his waistcoat to church to ward off the winter chill, 'Up, and continued on my waistcoat, the first day this winter, and I to Church'. These two extracts imply that clothing changes were a core part of 17th-century churchgoing behaviour. This notion is consolidated by the etching collection *The Seasons* by Wenceslaus Hollar, a bohemian artist living in London in the 1640s who created a series showing various clothing styles changing with the seasons. Muffs, Gloves, Collars and Other Articles of Toilet, belonging to said series illustrates the variety of thermal comfort clothing items used in the 17th century when Wren was working.

A change in expectations?

There's no doubt that our expectations for thermal comfort have risen over the past few centuries. In 1889 Dr G. Hoey delivered a paper to the Royal Society in which he stated that a room temperature between 15.5-17.2°C was ideal for comfortability and 'freshness'. In 2014 Public Health England recommended a room temperature of 18°C for 'a sedentary person, wearing suitable clothing'. In reality, most people nowadays prefer a higher temperature range between 19°C and 26°C.

Wren's buildings were designed and built at a time when temperature expectations were much lower. This change in expectation may be for good reason, the aforementioned public health inquiry argued their recommendation for health reasons, not necessarily thermal comfort. The two it seems aren't always aligned. In the past, churchgoers brought their own thermal comfort items to church with them.

Very few parishes could afford curtains, rugs, cushions and blankets for their churches for all the worshippers, the only historical example of a Wren church with such lavishness is the Royal Chapel at Whitehall.

The diaries of Samuel Pepys and John Evelyn show that clothing was the first line of defence against inhospitable church temperatures. When the donning of a 'waistcoat' by Pepys wasn't enough to ward off the chill, he simply decided not to attend. After all, if the building was too hot or too cold, why go in the first place?

These historical revelations throw up some complicated questions. Are our expectations too high for the temperature of these historic buildings? Is it our duty to ensure every churchgoer is comfortable despite historic temperatures being far lower than they are today? Perhaps thermal comfort should give way to prioritising the preservation of the materials of Wren's churches.

Once that criterion has been reached, might it be the responsibility of those visiting to bring their own thermal comforts in the form of blankets or extra clothing as it was in the past? The impetus is now to be open and welcoming to as many people as possible, and providing a comfortable environment has become synonymous with welcoming. That said, is 26°C comfortable, welcoming or sustainable? The rule of thumb suggests that 10% of energy is saved by lowering

National Portrait Gallery

'...landed in Southwarke, and to a church in the street where we take our water beyond the bridge, which was so full and the weather hot that we could not stay there.'
(Summer 1667)

FIGURE 3: Samuel Pepys, by John Hayls, 1666

A diary entry from 1668 tells us that churchgoers in Wren's time brought their own thermal comforts to church. During the Great Fire, an old man was described as having returned to St Paul's cathedral to retrieve his blanket.

the temperature by 1°C. And perhaps space heating is not the only way to provide thermal comfort to the occupants.

Thinking about summer as well as winter

Most people tend to concentrate on winter, and space heating when thinking about sustainability. That is indeed the most pressing concern. Usually, church buildings tend to have high thermal mass, high ceilings and other aspects of traditional design, which result in them being cooler in Summer. As global heating results in higher temperatures, churches could become a refuge and a haven in the heat, a form of 'cool banks' for the public. That said, if the thermal mass of the building is impeded from working correctly, such as via the loss of openable windows to allow the cool night air to flush out the heat, the thermal mass may retain too much heat and cause the occupants to overheat even when the external temperature is cooler. Heatwaves occurred even in Wren's time, as evidenced by Pepys diary entry describing a day so hot that they could not stay inside a church in Southwark. This may explain why Wren included ventilation and passive cooling measures in his designs.

THOUGHTS FOR YOUR CHURCH:

- Commission historical research for your church, to understand key thermoregulatory passive features used in the past
- Consider if any historic passive measures can be used again more effectively
- Consider if any lost passive features can be reinstated
- Consider if any historically relevant passive features from other churches of a similar design can be introduced sensitively in your church

PART 2: Psychological Research

Why psychological research?

Psychology research can help us understand how the modern churchgoer experiences Wren's buildings. Our expectations for room temperature have changed, and so have our churchgoing behaviours. Churches are no longer solely religious sites, they also welcome London's students and workers who use the spaces to work, tourists interested in their historical significance, and religious groups who host a variety of events.

Churches not only embody the zeitgeist of its times, but are irreplaceable cultural resources, and architectural gems that are designed to imbue a sense of wonder to visitors. Given our commitments to warmer buildings, net zero, and heritage, it is important to establish what the users of our churches need and how they feel. To understand this better, we conducted some psychology-based surveys to understand the interplay between thermal comfort and spirituality in a church environment. In essence: *how do people experience Wren's churches now?*

The psychological research framework

To understand the modern churchgoer's needs we utilised two psychological research methods. These are Psychometrics (an assessment of human abilities, attitudes, traits, and education), and Qualitative Interviews (interviewing churchgoers one-to-one to understand how people experience space and place). Our psychometric survey measured four different variables: thermal comfort, emotions, spirituality and a sense of awe. We asked participants to complete a 10-minute online survey using their mobile devices. They were seated on a pew on the north aisle in the nave of St Mary Aldermary to ensure every participant had a similar view of the church. Half of the participants were asked to sit on a heated pew, whilst the other half sat on a non-heated pew. The pews were heated with thermal seat pads. In our results participants from the first group were called the 'heated condition' and those from the second the 'neutral condition'. Alongside their answers, we recorded the age, gender, ethnicity, UK domestic status, English proficiency level, and reason for visiting of each participant. All question responses were optional. Alongside the questionnaires, we also conducted qualitative interviews conducted one-to-one with participants. During which, we discussed their thoughts on the space itself and how they felt it should be heated.

www.metmuseum.org (Public Domain)

Thomas Rowlandson, Auguste Charles Pugin (1809)
St. Stephen's Walbrook

Measuring thermal comfort, emotions, spirituality and awe

We measured the *thermal comfort*, emotions, spirituality, and awe of our participants using the following scales. Each scale corresponds to one of the four experience measures we wanted to record. Thermal comfort was measured using the ASHRAE 55 Thermal Comfort Scale. *Emotions* were measured using the Positive and Negative Affect Scale (PANAS). *Spirituality* was measured through the Importance of Spiritual Beliefs in Life Subscale, derived from the Spirituality Questionnaire. Finally, *Awe* was measured through the Awe Experience Scale (AWE-S). Each of these scales was incorporated into the survey via specific sets of questions. The following sections will explain what each scale measures and the types of questions used to measure each metric.

ASHRAE 55 Thermal Comfort Scale

The ASHRAE 55 Thermal Comfort Instrument is a series of questions asking how comfortable and satisfied people are with the present temperature. It aims to record an accurate reading of participants' thermal comfort. It defines thermal comfort as 'that condition of mind that expresses satisfaction with the thermal environment'. Some example questions from this psychological tool are: How do you feel right now? Answers on a scale of -3 Cold to +3 Hot. Right now, would you prefer to be... ? Answers on a scale of -1 Cooler to +1 Warmer. After a participant's answers are taken, their satisfaction level is calculated, and answers in the range between -1.5 and +1.5 are considered "satisfied". Totally satisfied individuals choose answers closer to 0. The closer to 0, the more satisfied the participant.

Marc Gascoigne

All Hallows by the Tower

PANAS Positive and Negative Affect Schedule

For our survey, we took eight items from the PANAS. They were simple questions asking how much participants were feeling certain emotions. In particular, how relaxed, irritable, attentive, fatigued, self-assured, frightened, inspired, and downhearted they felt during their visit to St Mary Aldermary. The PANAS asks participants to rate the extent they are feeling a certain emotion on a scale of 1–5.

1. Not at All
2. A Little
3. Moderately
4. Quite a Bit
5. Very

The scale measures an equal number of positive and negative emotions. Our survey used four of each. At the end, we have a score between 4 and 20 for positive effect and a score between 4 and 20 for negative effect. Higher scores in positive affect indicate an overall positive experience and higher scores in negative affect indicate an overall negative experience.

Spirituality Questionnaire: Importance of spiritual beliefs in life subscale

The Spirituality Questionnaire was developed in 2009 by Nasrin Parsian and Trisha Dunning. It consists of four subscales: *Self-awareness, Importance of Spiritual Beliefs in Life, Spiritual Practices, and Spiritual Needs*. Our questionnaire utilised the second subscale Importance of Spiritual Beliefs. It asks participants four questions about how involved spirituality is in their lives. The questions are as follows:

1. My spirituality helps me define my goals
2. My spirituality helps me decide who I am
3. My spirituality is part of my whole approach to life
4. My spirituality is integrated into my life

Each question is answered on a scale of 1–4.

1. Strongly disagree
2. Disagree
3. Agree
4. Strongly Agree

This subscale helps us to determine how spiritual a participant is. Allowing us to factor that into their answers to other questions, such as those on the awe experience scale.

Awe Experience Scale

We used the AWE experience scale to measure, awe. A scale aiming to capture the complex emotion of awe which is comprised of six facets:

- *Physical sensations* – how people react physically when experiencing awe (e.g. goosebumps, gasping).
- *Connectedness* – the perception that you are connected to the world and other people.
- *Self-diminishment* – the sense of feeling small in the presence of something greater than oneself.
- *Alterations in time* – the feeling that time is moving at a slowed pace.
- *Need for accommodation* – the belief that an experience is too much to fully process; it is too much for your eyes and/or brain to fully handle.
- *Perceptions of vastness* – either physical vastness or perceptual vastness.

Our survey asked participants to respond to statements which indicated their experience of the six facets of awe. For example 'I sensed things momentarily slow down.' Or 'I felt my jaw drop'. These statements are usually answered with a scale of 1–7.

1. Strongly Disagree
2. Disagree
3. Moderately Disagree
4. Neutral
5. Somewhat Agree
6. Moderately Agree
7. Strongly Agree

Each facet of awe is covered by multiple questions of this nature. Once all questions are answered an individual participant's level of awe can be calculated.

PANAS and AWE-S results

The following section will detail some analysis of responses to the PANAS and AWE-S sections of the survey. These results are based on the responses of 32 participants (11 male and 21 female). Their ages ranged between 21 and 69 years, with an average age of 34 years old. The majority of participants (69.87%) lived in the UK. Half of the group were native English speakers with the other half speaking English at an advanced or intermediate level. The majority of respondents identified as white, with the second largest group being Asian. The average participant responded to 75.87% of the survey.

Awe-inspiring painted dome of St Mary Abchurch

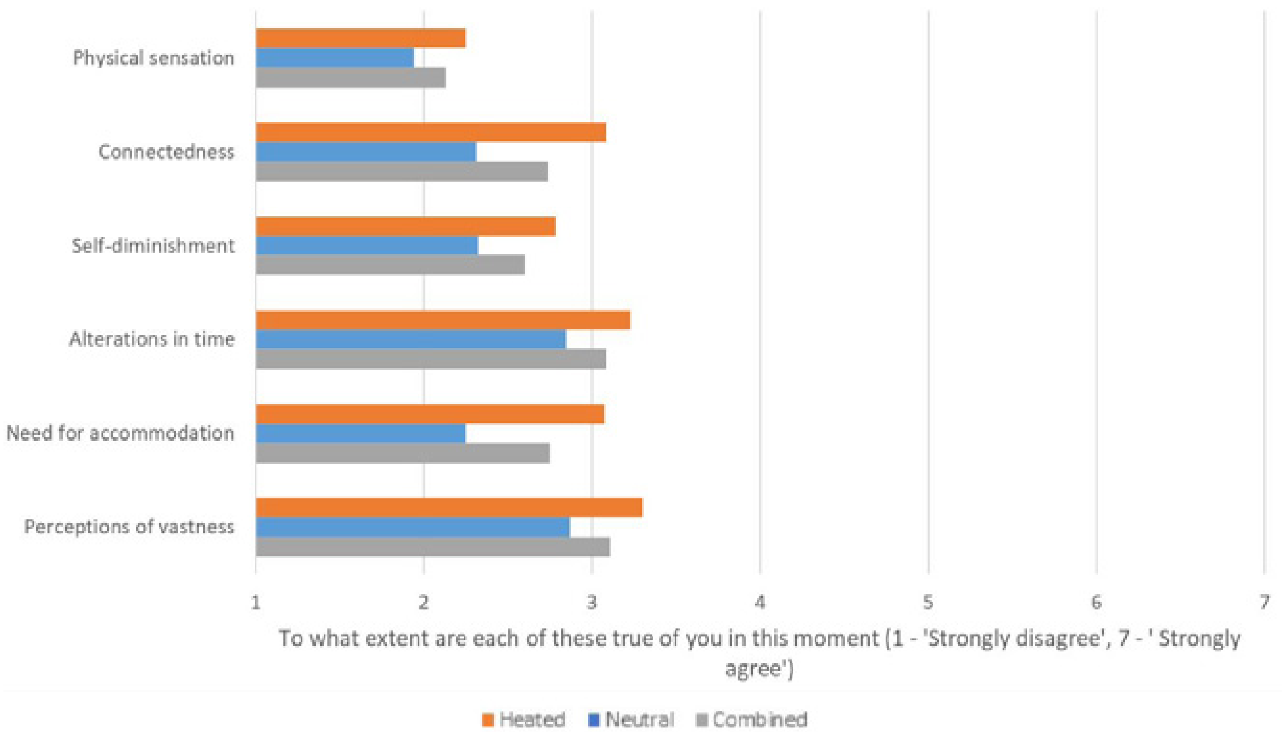


FIGURE 4: PANAS results

The results for each item on the PANAS scale are divided into three measurements. The average score for participants in the *heated condition*, the average score for participants in the *neutral condition* and a combined average of both groups. On average, participants who sat on the heated pews in the *heated condition* reported feeling more relaxed and more fatigued than those who sat on the unheated pews. However, participants in the *neutral condition* did report feeling significantly more self-assured and slightly more inspired, though unfortunately they also felt significantly more frightened and down-hearted, perhaps a sign that they felt more in awe of their surroundings than those in the *heated condition*. However, based on the results of the AWE-S questions in Figure 5. perhaps another factor is at play.

Hannah Spedding

St Stephen Walbrook

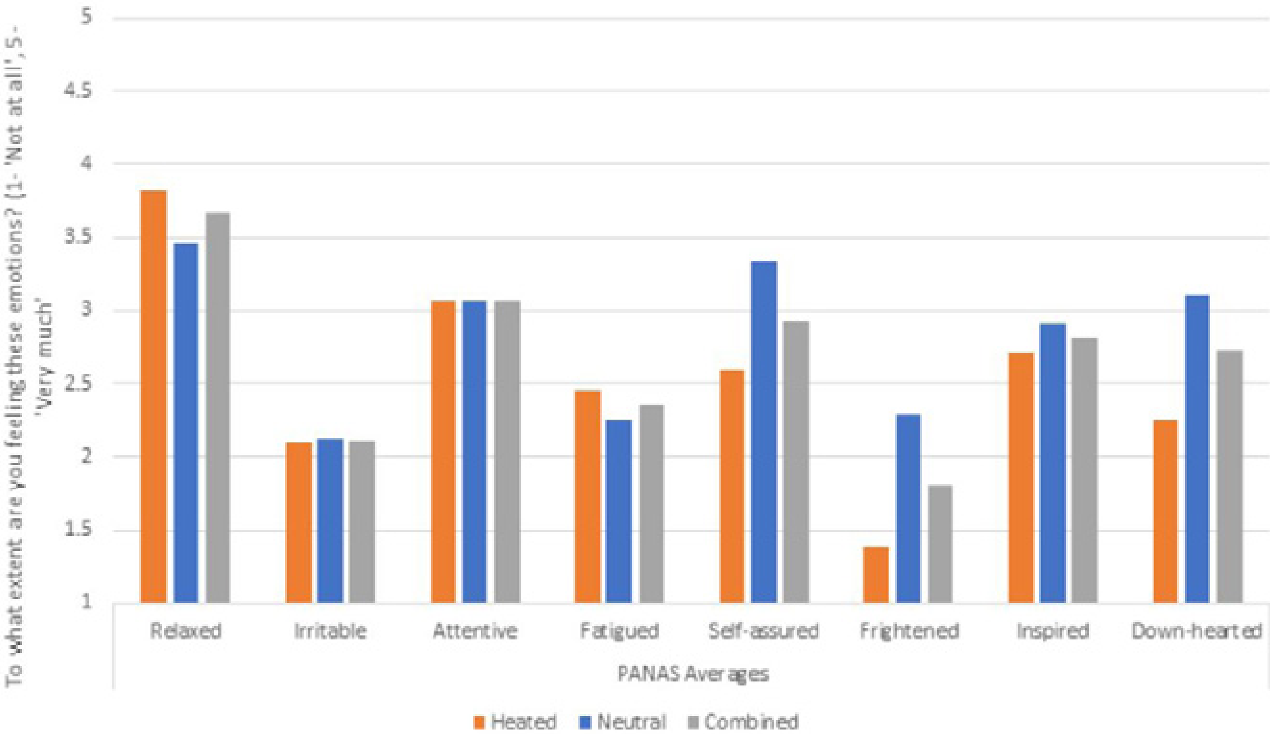


FIGURE 5: AWE-S results

As can be seen from the above graph, participants seated on the heated pews experienced a greater sense of awe on average across its six facets. The most significant difference was in the facets of connectedness and need for accommodation where participants in the *heated condition* felt it more than those in the *neutral condition*.

It is to be noted that these are preliminary surveys, and different results can be expected for different churches and different scenarios.

FIGURE 6: Temporary heated cushions to test user responses for a future under pew heating system

Qualitative interviews

Qualitative interviews were conducted one-on-one and took the form of a more casual conversation. We invited church staff and members of the public to respond and discuss how they felt about certain aspects of St Mary Aldermary. Specifically, what they felt were the most important church features, and their views on the importance of heating.

Identification of important aspects of church architecture

During the qualitative interviews participants were asked to identify what they felt were the most important architectural features of St Mary Aldermary. A sample of their responses mentioning the vaulted ceiling, pews and windows are listed below:

1. "People who don't know the building are often drawn to look up, as they come in, to the ceiling."
2. "They removed the pews, and it doesn't feel like a church anymore... It's like a huge open space because I've been there personally and the idea is great and everything, but it doesn't feel like a church anymore."
3. "It's great to look out when you're in the church, to look out and to get it's not about being in here... it is about the wider world."

Discussion of the importance of heat/thermal comfort

During the qualitative interviews, the interviewer discussed the importance of heat and thermal comfort whilst visiting the building with the participants. Below, we have listed some of the most pertinent responses to said discussion point.

1. "It is warm for a church. It's about 18 and a half degrees. So, unless you end up sitting next to the door that hasn't shut properly, it's a good place to be."
2. "We have customers, they're coming from the offices and they're saying like it's much warmer inside the offices. So, they're always shocked, like how warm is the space, but they love it... I think temperature, it's just enough."

Overall, these responses are positive, indicating that staff members feel the church temperature is appropriate. Some participants mentioned their feelings regarding the thermal seat pads. The response to this method of local heating was reserved. Below we have listed some of those reservations recorded during our qualitative interviews.

1. "In some churches I know I play the organ in they put the heating under the seat the only trouble is that sort of cooks your behind."
2. "It might just heat up a little bit ... the surfaces might still feel a bit cold. It might be a bit harsh. Yeah, it wouldn't have that same comfort."
3. "I prefer the whole space... It just feels nicer, you know?"

Thoughts for your church:

- Consider using the ASHRAE, PANAS or AWE-S scale questionnaires to understand how people feel about your church
- Consider testing out a particular heating measure to see occupant's thermal comfort response
- Consider lowering the temperature of your church by 1°C and explaining to people how it impacts the environment, and seeing their response
- If using a traditional measure, consider testing out, or showing historic images in questionnaires to see occupant's responses

PART 3: Building Physics

Why building physics research?

Building physics can play a crucial role in church conservation and zero carbon retrofitting by offering a scientific framework to understand and control the environmental impacts on historic structures. It informs the development of strategies to enhance the thermal performance and energy efficiency of churches, minimizing their carbon footprint while preserving their architectural integrity. Through the application of building physics principles, conservation professionals can accurately assess the thermal behaviour, moisture dynamics, and energy demands of these buildings, enabling the implementation of sustainable retrofitting solutions that do not compromise their cultural or architectural heritage.

The building physics research framework

To monitor and assess the internal environment we utilised a holistic building physics toolkit, including non-invasive techniques known as NDIs, indoor temperature and humidity monitoring and building performance simulation. For non-destructive inspection (NDI), we employed thermal cameras to analyse the heat loss profile of the building envelopes; and ground penetrating radar (GPR) to detect structural irregularities. Considering the importance of an internal environment for human comfort and conservation of heritage artefacts, we monitored humidity and temperature fluctuations across six different Wren churches namely: St Edmund, King and Martyr, St James Garlickhythe, St Mary

Thermal Imaging Scanning at St Mary Abchurch with an Infra-red Scanner

Abchurch, St Mary Aldermary, St Margaret Pattens and St Martin Ludgate. Finally, we constructed building simulation models of St Mary Aldermary to explore insulation and microclimate intervention scenarios.

Non-destructive inspection techniques

Non-destructive inspection (NDI) for heritage buildings is a group of investigative techniques used to assess the condition of heritage buildings without causing any damage to them. These techniques allow us to discern valuable information about a building such as the materials, structural integrity, areas of concern and most importantly which intrusive procedures can or should be used. When assessing the condition of two churches, St Mary Aldermary and St Mary Abchurch, we utilised two techniques: Infrared thermography and Ground Penetrating Radar (GDR).

Temperature and humidity monitoring: data from sensors at St Mary Abchurch

Infrared thermography

Infrared thermography is a non-invasive diagnostic tool that captures the infrared radiation emitted from an object's surface. Infrared radiation is beyond the visible spectrum, with wavelengths longer than what human eyes can perceive, it remains invisible to us. This Infrared thermal camera can capture infrared radiation which translates the intensity of infrared radiation into a visual palette of colours or shades of grey, serving as a temperature indicator.

Infrared thermography has numerous applications, such as detecting heat loss through thermal bridging, assessing the extent of damage from moisture penetration, identifying potential condensation issues, and spotting various structural flaws. For accurate interpretation, these thermal images should be analysed in conjunction with a thorough examination of the material's condition and historical background of any previous treatments. This method is especially valued for its ability to reveal underlying issues without disruptive probing.

Emissivity and reflectivity can significantly impact the accuracy of a thermal imaging camera's readings. Objects with high emissivity (e.g. human skin with 0.97–0.999, Limestone, 0.92) emit thermal energy effectively. Conversely, materials with low emissivity (e.g. aluminium foil 0.03) are generally quite reflective and do not emit thermal energy efficiently. This could lead to confusion and inaccurate analysis of the situation if one is not cautious.

Examples of Infrared thermography

Infrared Thermography uses infrared cameras to locate thermal anomalies on the building's surface. Temperature variations can indicate issues like building defects, moisture ingress, voids (empty spaces between solid building elements like walls), delamination, or thermal bridging. We employed this technique to identify areas of heat loss in St Mary's Aldermary and St Mary Abchurch. The following images identify areas of concern at St Mary's Aldermary and St Mary Abchurch. In particular the roof, ventilation openings and doorways, windows floors.

FIGURE 7. Thermal Imaging: St Mary's Aldermary ceiling

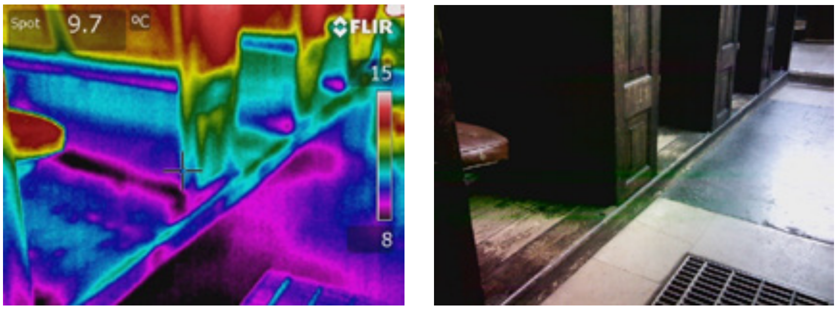


FIG 8A: Floor Temperature St Mary Abchurch

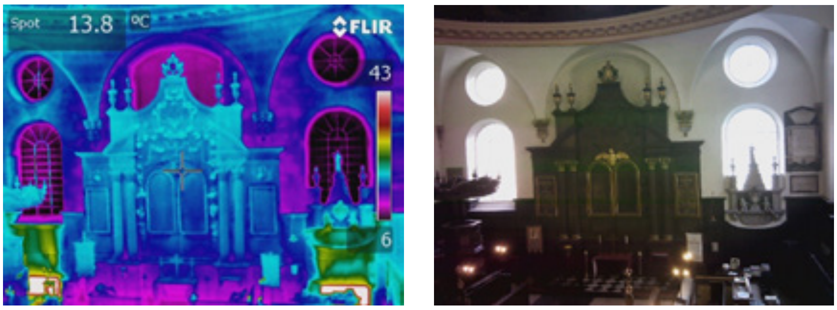


FIG 8B: Walls, Windows, Radiators St Mary Abchurch

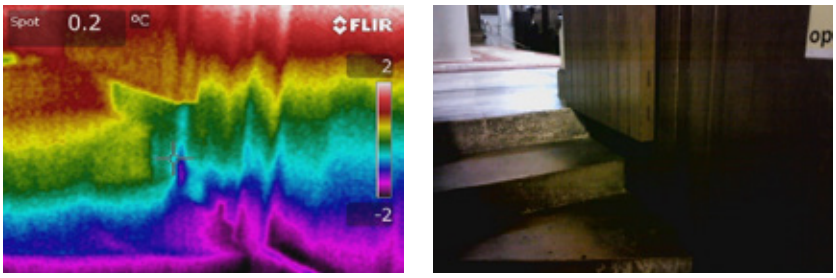


FIG 8C: Drafty Doorway St Mary Aldermary Vestry

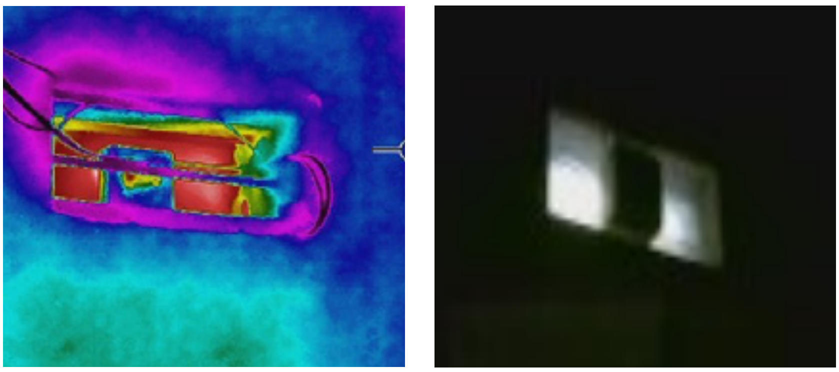


FIG 8D: Ventilation Openings St Mary Abchurch

Ground Penetrating Radar (GPR)

Ground Penetrating Radar (GPR) probes the subsurface layers of a building's components, including walls, floors, and foundations. GPR is adept at detecting the presence of voids, fissures, or other structural irregularities. We used GPR at St Mary's Abchurch to assess the church's structural integrity. The solid brick walls displayed high quality walls which were solid with some voids (as micro-cavities). The micro-cavities in the walls will actually increase the thermal resistance of the walls, as shown by the GPR data in Fig 10 and Fig 11.

This could possibly explain why traditional masonry walls perform better thermally than current thermal models predict. The GPR scan in Figure 12. showed an anomaly which could be an unknown crypt or other buried feature. This demonstrates that GPR could be a useful tool for identifying any unknown underlying features.

FIGURE 9: GPR Scanner in St Mary Abchurch

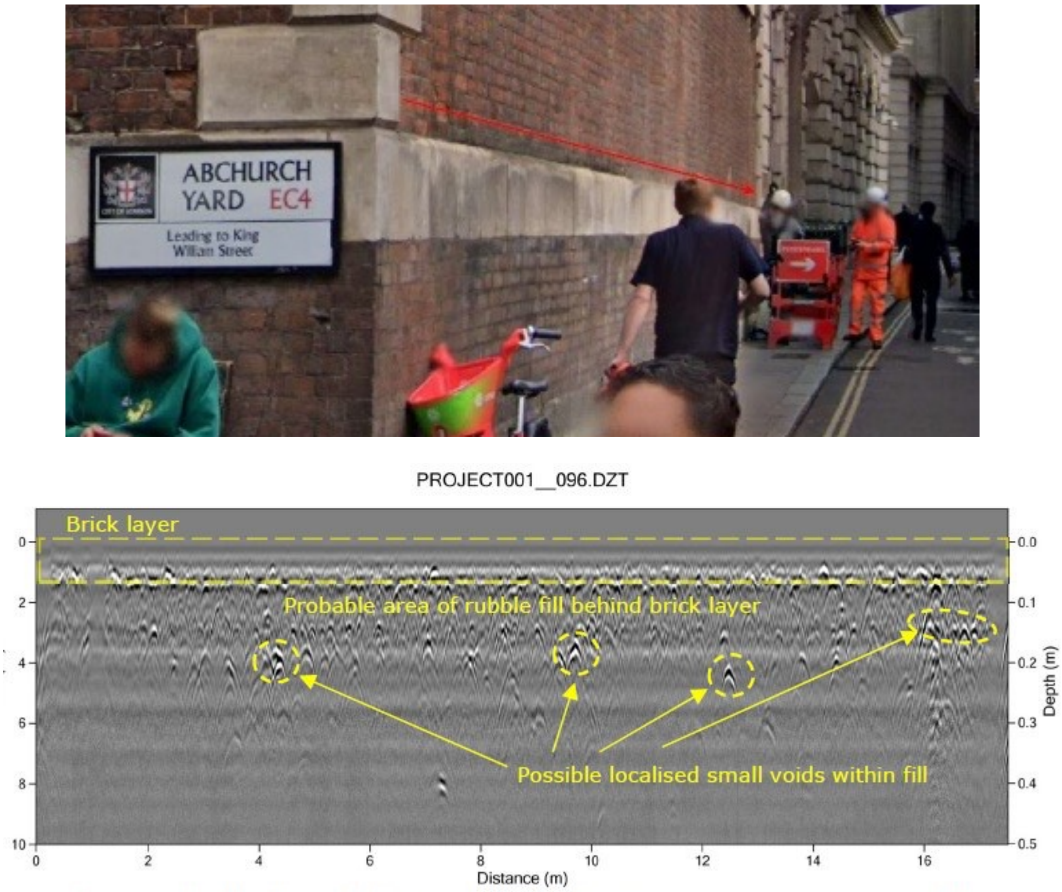


FIGURE 10: Shallow GPR Investigation: St Mary Abchurch Eastern External Wall

Examples of GPR Scanning Results

We employed GPR to investigate the solid brick walls in St Mary Abchurch and the solid stone walls in St Mary's Aldermary. The initial results demonstrated:

- high quality solid walls
- potential air void identified which may indicate better thermal insulation performance of solid walls than the theoretical values, which assume that no such voids (as insulation) exist.

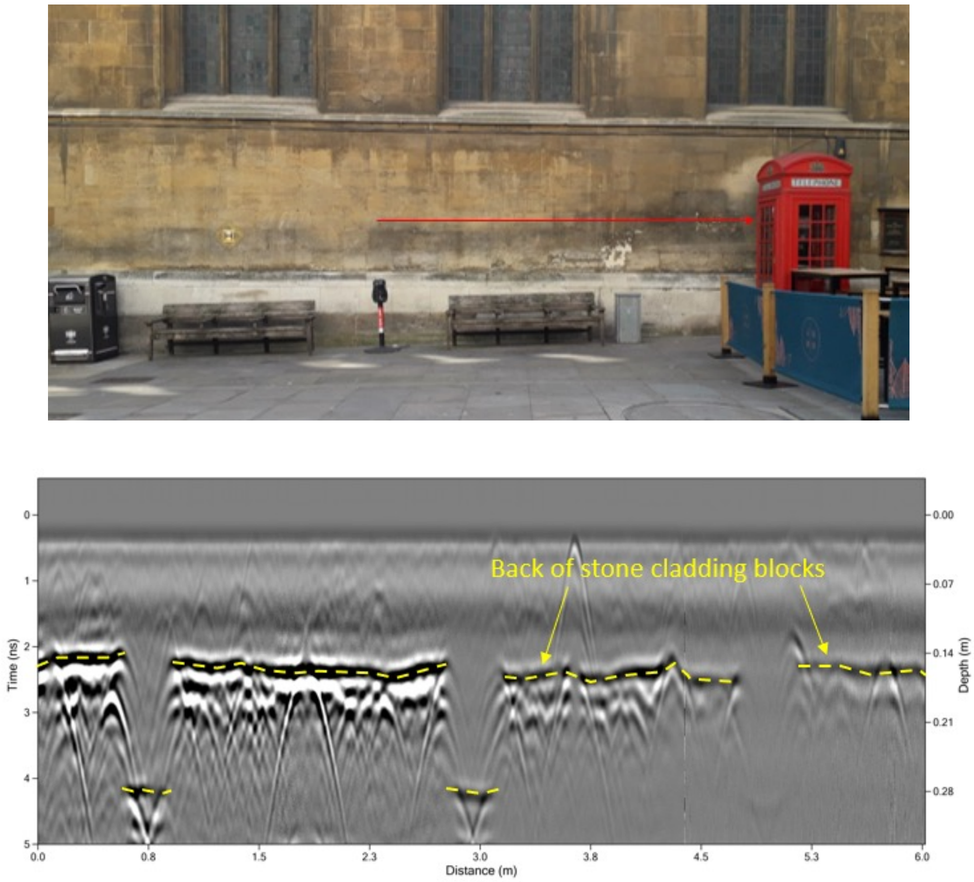


FIGURE 11: Shallow GPR investigation: St Mary Aldermary North External Wall

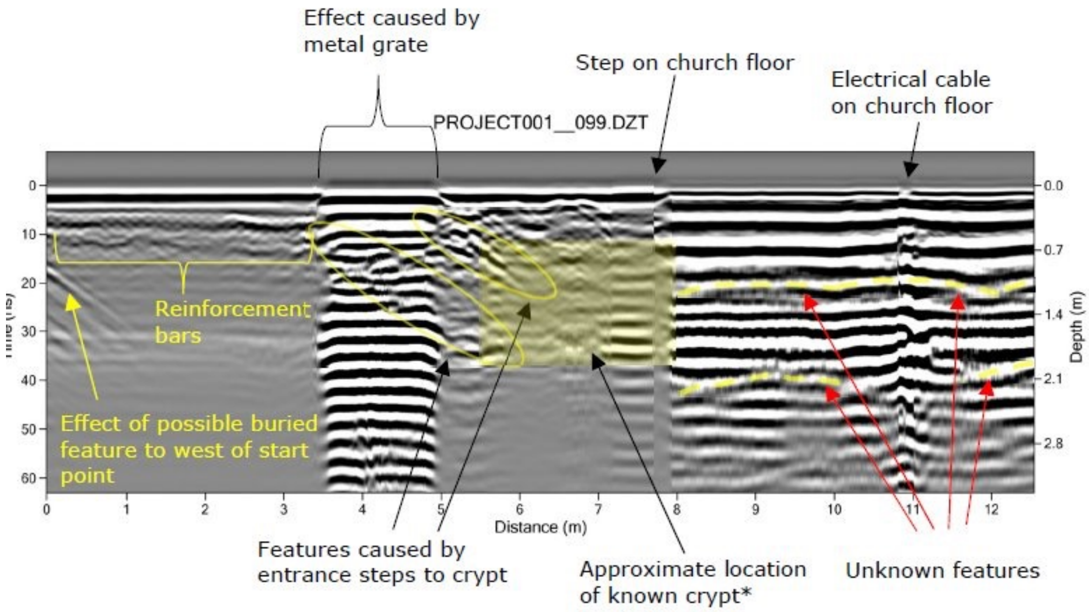


FIGURE 12: GPR Data: St Mary Abchurch Southern Aisle Walkway

Indoor temperature and humidity monitoring

The purpose of monitoring these historic buildings is to ensure that temperature and humidity are correct for optimal health, comfort, as well as for artefact/building preservation, thermal model calibration and energy efficiency. It also allowed us to determine which thermal comfort solutions might be required and more importantly where and when they might be required through building performance simulations which are discussed in the next section of the toolkit.

We monitored the humidity and temperature of six Wren churches: St Edmund, King and Martyr, St James Garlickhythe, St Mary Abchurch, St Mary Aldermary, St Margaret Pattens and St Martin Ludgate. Data was collected every half-hour and put into the graphs below. Unfortunately, some of the equipment was lost during the year, so full data of all six churches is not available. Still, a pattern can be seen, and our initial observations were that:

- **seasonal temperature variations had a huge impact on internal church temperatures.**
- **in summer, some of the churches reached over 25°C on particular days, highlighting that overheating may become a problem soon.**
- **in winter, temperatures were generally lower, between 18–22°C.**

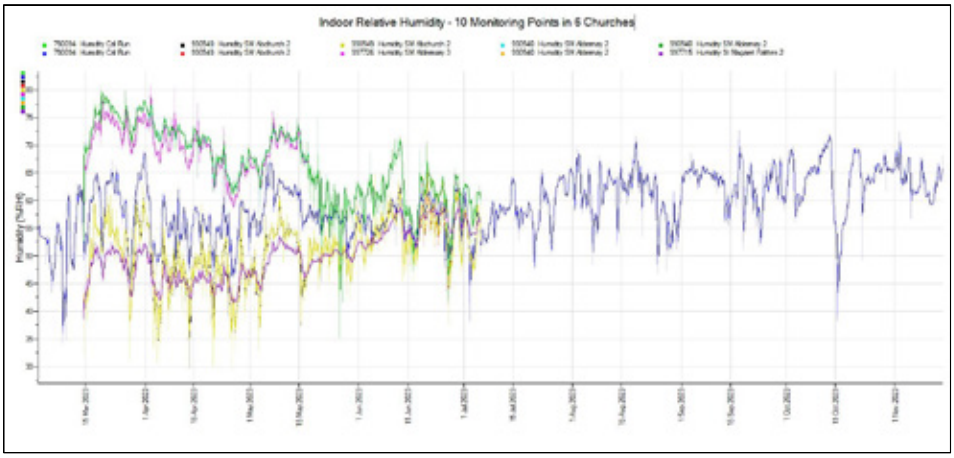


FIGURE 13: Indoor Relative Humidity Graph

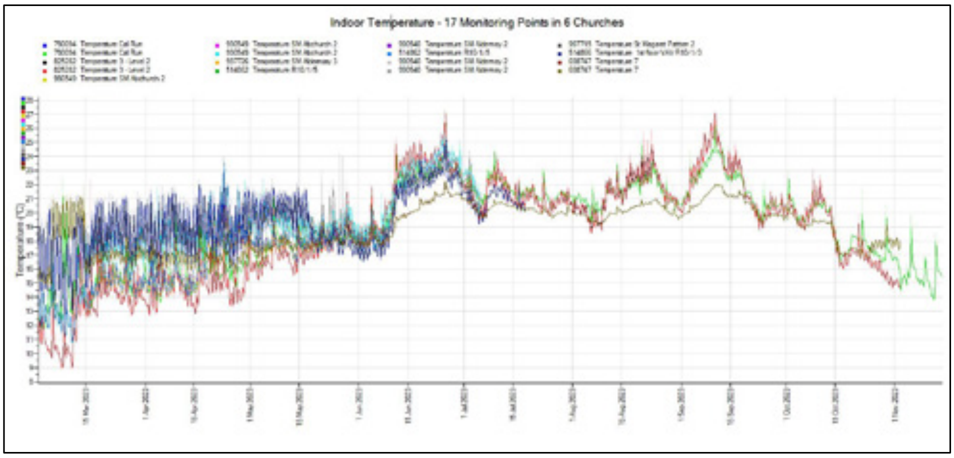


FIGURE 14: Indoor Temperature Graph

The monitoring and control of microclimatic parameters such as Temperature (T) and Relative Humidity (RH) are pivotal to establishing proper conservation policies in sensitive environments. It has also been argued that fixed ranges for T and RH are not always best for historical buildings. Conservation features typically adapt to seasonal fluctuations in T and RH. Imposing fixed values may cause unforeseen damage. Thus, the hygrothermal inertia for each building should always be considered.

www.electricheatingsolutions.co.uk

Heating Solutions, Under Pew Heating
Under pew heating systems are a common solution to heat churches in intermittent use.

jigsawinfrared.com

Jigsaw Infrared, Infrared Heaters In Situ
Infrared heating systems such as this one are being considered for application in some Wren churches, such as St Mary Aldermary.

Building performance simulation (passive retrofitting analysis)

Building Performance Simulation (BPS) for heritage buildings involves the application of computer models to predict and analyse the performance of historic structures in terms of energy usage, thermal comfort, lighting, and more, while carefully considering their preservation needs.

This application of BPS presents unique challenges and opportunities. Understanding the energy, lighting, and thermal performance needs of the buildings is crucial for informed decision-making in the construction and retrofitting of heritage buildings. However, simulating the thermal and hygrometric behaviour of historical buildings is a challenging task. The accuracy of the modelling results hinges on the quality of input data which are usually difficult to obtain due to the complexity and irregular structure of heritage buildings.

An inaccurate simulation may lead to inappropriate and dangerous actions for the building's heritage conservation. As such, the complexity of building simulation models demands specialised expertise and interdisciplinary collaborations.

To determine the effective course of action for improving the temperature and humidity regulation in our case studies, we simulated a variety of interventions designed to improve their efficiency, comfort and structural integrity. This process is known as a passive retrofitting analysis. It involves gathering detailed data, creating digital models, simulating various retrofitting scenarios, and analysing outcomes to determine the most effective strategies for improving energy efficiency, preserving historical value, ensuring cost-effectiveness, and enhancing indoor comfort and safety.

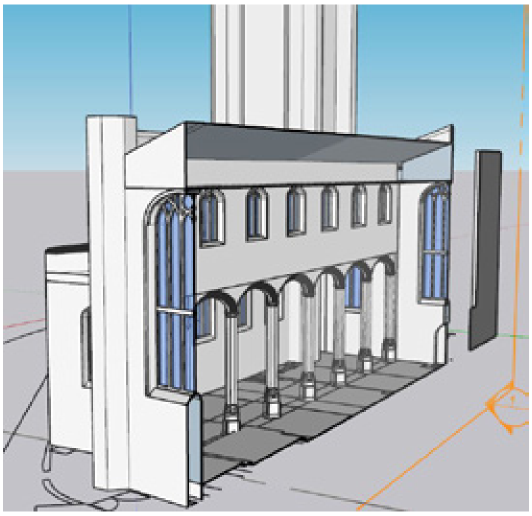


FIGURE 15A: St Mary Aldermary CAD Model Interior Side Passageway.

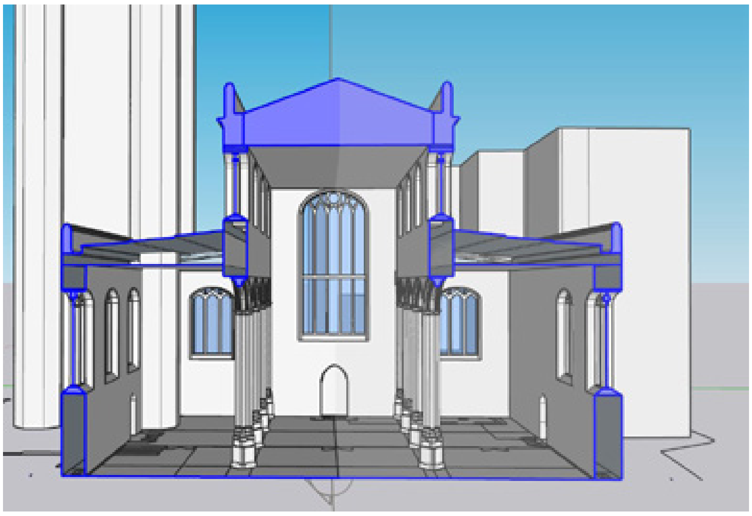


FIGURE 15B: St Mary Aldermary CAD Model Interior Central Aisle.

FIGURE 15: Figure 15: St Mary Aldermanry Building Performance Simulation Model.

This is a highly technical process and solutions are selected based on their ability to retain the historical essence of the building whilst offering the most efficient energy performance. It is a difficult scale to balance; however, these models allow those in charge of modifying said buildings to make informed and responsible decisions regarding energy solutions.

A database of essential input data (e.g. air change rate, thermal insulation properties) is established. The results of our analysis are currently undergoing the peer-review process and will be published as part of the open-access papers. In combination with indoor temperature monitoring, GPR and infrared thermal imaging inspections, our initial results indicate that:

- **St Mary Aldermary Church has high-quality building fabric (airtightness, and thermal insulation performance)**
- **Additional passive methods (e.g. reducing set point temperature and internal insulation) can reduce energy demand significantly.**

Thoughts for your church:

- Non- destructive investigative tools can identify defects, and areas of leaks and draughts which will impact thermal comfort of users
- If a net zero project is planned, monitoring the temperature and humidity could give insight into how the current system is behaving
- Thermal models can help calculate the efficacy of potential measures, however using accurate data is key for generating useful results

Many of the Wren's churches have a dome or vault with a plater-and-lath shell. The thickness of roof are varied, possibly between 10 cm and 20 cm. The heat loss through this roof structure is large. Thermal insulation has not been permitted until now in respect for the antiquarian values, doubts about the effect on water vapour transport through the vault, and the risk of condensation inside the insulation. Some lime-based materials are used for dome or vaults insulation, e.g., Lime–perlite mortar (k-value 0.14 W/mK) (reported k-value 0.08 W/mK) (Hansen et al., 2016) or hemp lime (k-value 0.14 W/mK) (Strandberg-de Bruijn & Balksten, 2019).

Future heating solutions

Church heating systems are costly and can make up for up to 80% of a given church's energy use. Their importance cannot be understated, influencing the people who visit, the historic features of the church (such as pipe organs), and the structural integrity of the building.

Fossil fuels are finite resources, we must move away from gas boilers which are commonly used in churches.

The Church of England champions a hierarchy of heating systems designed to limit the impact of the systems on the church's original design and construction. Initial solutions to heating problems come in the form of switching to renewable energy sources such as green tariffs and improving the efficiency of a church's heating or lighting. When these changes are not enough to reduce energy expenditure, the Church of England advises improvements to heat zoning which involves controlling the temperature of specific areas or rooms in a building, alongside data logging, and the consideration of infra-red heaters or pew heating.

The most drastic alterations come in the form of highly efficient LED lighting systems, solar panels, and heat pumps. Unfortunately, there is no one-size-fits-all solution for creating comfortable church environments. Achieving a balance between comfort, cost, and environmental impact necessitates dedicating time and effort to understand the specific needs of a church, to develop an effective heating strategy.

Renewable energy, decarbonisation and electrification of heating systems

There are several kinds of renewable energy a church might consider, of which the main ones are[2]:

- Solar PV (using daylight to make electricity, which is used to heat and light the church),
- Heat pumps (using the heat from the ground, air or water near the church to heat the church), and
- Biomass (burning wood pellets or chips in a boiler, instead of oil or gas).
- Very occasionally, other renewables are a possibility, such as solar thermal, wind turbines or hydropower.

Decarbonisation of heat is vital. Four approaches were discussed for the decarbonisation heating systems in the churches and reaching zero-carbon commitment by 2030[3], namely:

- Electrification of heating including different types of electric heaters, heat pumps and hybrid boilers;
- A switch from natural gas to hydrogen;
- A switch from natural gas to biogas,
- District heating.

Nevertheless, thermal comfort demand reduction will be a key component in the decarbonisation and electrification process. Passive zero-carbon approaches provided in this report will be the essential first step.

[2] Church of England, 2024, Renewable Energy, https://www.churchofengland.org/resources/churchcare/advice-and-guidance-church-buildings/renewable-energy

[3] Church of England, 2022, Church Heating – Decarbonising and the Future of Heat, https://www.churchofengland.org/sites/default/files/ 2023-5/Heating_Decarbonisation_and_the_future_of_heat.pdf

Global heating vs. local heating

Global heating (or central heating) aims to evenly distribute heat throughout a building and maintain its outer structure. It is typically used in large structures, employing radiators, warm-air systems, convectors, and underfloor heating. However, global heating consumes substantial energy, with much lost through thermal bridges, leaks, and storage within the building's envelope. Local heating targets only the occupied areas of a building, and leaves the larger volume of the space, such as in historic churches, largely unaltered, preserving its original climate. Ideal for smaller congregations or specific sections of buildings, common local heating methods include heated cushions (as in Figure 6), infrared emitters, pew heating with various elements, and heated carpets.

Local heating systems will reduce heat dispersion, protecting the building's envelope and preserving historical items from temperature fluctuations (Dario Camuffo, 2011). In the psychological research section, we discussed the impacts personal heating systems such as thermal comfort mats placed on pews could have on the mood of church attendants.

Some concerns have been raised regarding their usage, namely the inconsistency of thermal coverage throughout the buildings causing discomfort. Therefore, some behavioural change measures need to be promoted to adopt local heating solutions. Nevertheless, with the interdisciplinary research, a tailored practical thermal comfort approach can be developed to make Christopher Wren's Churches more sustainable and a delight to visit.

A study is required for each church to find the most suitable heating solution for it. Once all passive measures are in place, the intensity of use determines if local heating is the most cost-effective path to net zero, or a heat pump solution perhaps topped up with local heating solution will be best. Once the right electrified solution is in place, on-site energy generation should be considered, followed by a move to a green tariff to complete the net zero journey.

Conclusion

Decision-making constitutes a multifaceted process wherein the decision-maker identifies, evaluates, and selects from among various alternatives, guided by their values, preferences, and beliefs. Within the sphere of retrofitting historic buildings, this complexity is notably intensified.

Researchers (Bordass, 2020)exposed the fallacy of single indicators for sustainable building retrofitting and argued that if oversimplified metrics are adopted, metrics become a means to an end, but are always at risk of turning into the ends themselves. Nevertheless, an excessive proliferation of metrics could engender confusion and disorder. For a distinct group of participants, the optimal approach might involve choosing a subset of metrics that elucidates their objectives while granting them autonomy over their unique challenges, thereby sustaining their forward progress within the process rather than focusing solely on the outcomes. Therefore, it is contended that enhanced diversity in reporting and benchmarking could significantly contribute to individual contributions towards the achievement of collective objectives.

The holistic passive zero carbon toolkit developed in this project can help stakeholders from different perspectives (e.g. historical, heritage, psychology) to explore potential zero carbon transition pathways, particularly learning passive thermal comfort features in city churches designed by Sir Christopher Wren to aid the current zero-carbon transition of Church of England sites.

APPENDIX A: Reading List

Below is a non-exhaustive list of academic works as well as relevant non-academic works which were consulted during the making of this project. We hope that curious readers will find some interesting and enlightening material in the list below, which will illuminate the research methods used during this project further. A full reference list for each section of the project will be available once each open-source paper is published.

History

Hawkes, Dean
Architecture and Climate: An Environmental History of British Architecture 1600–2000
(Routledge, Oxon: 2012)

Hoey, D. G.
The Science of Ventilation as Applied to the Interior of Buildings
Journal of the Society of Arts, vol. 37, no. 1906 (1889), p. 608, 617

Jardine, Lisa
On A Grander Scale: The Outstanding Career of Sir Christopher Wren
(Harper Collins, 2002)

Wookey, Rachel, Bone, Angie, Carmichael, Catriona, Crossley, Anna
Minimum Home Temperature Thresholds for Health in Winter
Public Health England (2014)

Jeffery, Paul
The City Churches of Sir Christopher Wren
(Hambledon Press, 1996)

Psychology

Parsian, N., & Dunning, P. (2009)
Developing and validating a questionnaire to measure spirituality: A psychometric process

Standard, ASHRAE. (1992)
Thermal environmental conditions for human occupancy
ANSI/ASHRAE, 55, 5

Watson, D., Clark, L. A., & Tellegen, A. (1988)
Development and validation of brief measures of positive and negative affect: the PANAS scales. Journal of personality and social psychology
54(6), 1063

Yaden, D. B., Kaufman, S. B., Hyde, E., Chirico, A., Gaggioli, A., Zhang, J. W., & Keltner, D. (2019)
The development of the Awe Experience Scale (AWE-S): A multifactorial measure for a complex emotion. The journal of positive psychology
14(4), 474-488

Building physics

W Bordass and C Bemrose, 1996
Heating your Church, Council for the Care of Churches
Church House Publishing, London

The Church of England
Advice and Guidance for Church Buildings
https://www.churchofengland.org/resources/churchcare/advice-and-guidance-church-buildings [accessed 08/03/2024]

D Camuffo et al, 2007
Church heating and preservation of the cultural heritage: a practical guide to the pros and cons of various heating systems
Electa Mondadori, Milano

D Camuffo et al, 2010
An advanced church heating system favourable to artworks: a contribution to European standardisation
Journal of Cultural Heritage, Vol 11, No 2

D Camuffo. 2011
Fabric-friendly Heating. Historic Churches
https://www.buildingconservation.com/articles/fabric-friendly-heating/fabric-friendly-heating.htm

Conservation of Cultural Property – Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials
(EN 15757:2010), European Committee for Standardization, Brussels

ED Mills
The Modern Church
Architectural Press, Princeton, 1959

L Samek et al
The impact of electric overhead radiant heating on the indoor environment of historic churches
Journal of Cultural Heritage, Vol 8, No 4, 2007

APPENDIX B: A Concise Glossary

ASHRAE 55 thermal comfort scale: A set of guidelines providing quantitative criteria to achieve acceptable thermal environmental conditions for human occupancy.

Awe experience scale (AWE-S): A measure designed to assess the complex emotion of awe, capturing various facets including physical sensations, connectedness, self-diminishment, alterations in time, need for accommodation, and perceptions of vastness.

Box pews: Enclosed seating found in churches, designed to contain warmth and offer privacy, characteristic of the period's church architecture.

Building physics: A field that applies the principles of physics to the built environment, focusing on the analysis and control of the physical phenomena affecting buildings.

Building performance simulation (BPS) refers to the use of computational models to predict and analyse the performance of buildings in various domains, including energy usage, thermal comfort, lighting, acoustics, ventilation, and sustainability.

Decarbonisation: The process of reducing carbon dioxide emissions through the adoption of cleaner energy sources and energy efficiency measures.

Round-headed windows/ semi-circular arched windows and opening casements: Architectural features in Wren's churches, designed for natural lighting and ventilation, where windows include a round-shaped top/ semicircular arch and panels that can open.

Emissivity: The efficiency with which a surface emits thermal radiation, influencing the accuracy of thermal imaging.

Ground penetrating radar (GPR): A non-invasive method used to examine the subsurface of a structure, identifying voids, fissures, and other anomalies without causing damage.

Glazing ratio: The ratio of window area to wall area in a building, affecting natural light entrance and thermal performance.

Infrared thermography: A technique that uses infrared cameras to detect temperature variations on surfaces, identifying thermal anomalies like heat loss or moisture presence.

Local heating: A heating strategy that focuses on warming specific occupied areas rather than the entire building, to improve energy efficiency and comfort.

Non-destructive inspection techniques: Methods used to examine the condition of a structure or material without causing damage, including infrared thermography and ground penetrating radar.

PANAS (positive and negative affect schedule): A psychometric scale used to measure positive and negative affect, reflecting the emotional state of individuals.

Passive measures: Building design strategies that do not rely on mechanical systems but use natural sources and architectural features to regulate indoor environment.

Psychological research framework: An approach in research that involves understanding human behaviour and experiences, particularly in relation to thermal comfort and building design.

Renewable energy: Energy sourced from natural processes that are replenished at a rate faster than they are consumed, like solar or wind energy.

Spirituality questionnaire: A tool used to assess the role of spiritual beliefs in an individual's life, often in the context of understanding human interactions with their environment.

Thermal comfort: A state of mind that expresses satisfaction with the surrounding environment, particularly in terms of temperature.

Thermoregulatory church towers: Architectural features in churches designed to facilitate natural ventilation and temperature regulation.

Wall panelling and draft lobbies: Design elements in churches that contribute to thermal insulation and control air movement to reduce drafts.

Zero-carbon buildings: Buildings that have a net zero carbon footprint, typically through a combination of passive methods, behavioural change, energy efficiency, renewable energy sources, and carbon offsetting measures.

References

Bordass, B. (2020)
Metrics for energy performance in operation: The fallacy of single indicators
Buildings & Cities, 1(1), 260-276

Dario Camuffo. (2011)
Fabric-friendly Heating. Historic Churches
https://www.buildingconservation.com/articles/fabric-friendly-heating/fabric-friendly-heating.htm

Hansen, T. K., Larsen, P. K., Hansen, K. K., Bjarløv, S. P., & Peuhkuri, R. H. (2016)
A lime based mortar for thermal insulation of medieval church vaults. Paper presented at the Proceedings of the 4th Historic Mortars Conference
HMC2016, 349-357.

Strandberg-de Bruijn, P. B., & Balksten, K. (2019)
Energy and moisture in historic masonry walls retrofitted with hemp-lime
Paper presented at the IOP Conference Series: Materials Science and Engineering, 660(1) 012070

Authors

Sarah Khan
Roger Mears Architects LLP

Dr. Yangang Xing
School of Architecture, Design and Built Environment,
Nottingham Trent University

ROGER MEARS ARCHITECTS

NOTTINGHAM TRENT UNIVERSITY

With dedicated work done by academic researchers:

Sam Williams
Prof. Belinda Winder
Prof. Alexander Sumich
Psychology Department,
Nottingham Trent University

Robert Evans
Bruno Bingley
Morgan-Ellis Leah
Eva Hroncekova
Dr. Andrew Knight
School of Architecture, Design and Built Environment,
Nottingham Trent University