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Energy Efficiency and Comfort of Historic Buildings

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Preface

Preventing dangerous climate change is a key priority for the European Union. Therefore, Europe is working hard to cut its greenhouse gas emissions substantially while encouraging other nations and regions to do likewise.

In the meantime major progresses have been accomplished internationally through conventions such as the 1979 Convention on transboundary long distance air pollution and its various protocols, the UN Framework Convention of 1992 on climate changes and its now famous Kyoto Protocol (December 1997) and the Agreement of Paris (December 2015).

In order to reach this goal the following targets were established:

- By 2020 (figures compared to 1990):
  - 20% reduction in greenhouse gas emissions
  - 20% of total energy consumption from renewable energy
  - 20% increase in energy efficiency
- By 2030 (figures compared to 1990):
  - At least 40% less greenhouse gas emissions
  - At least 27% of total energy consumption from renewable energy
  - At least 27% increase in energy efficiency.

By 2050 the EU even aims to reduce its greenhouse gas emissions by 80 to 95% compared to 1990[1].

In addition to various regulations, the Commission also adopted an EU strategy for climate change adaptation and wants all its Member States to adopt national plans by 2017 to cope with the inevitable consequences of climate change. This transition to an energy efficient and low carbon Europe, is not only necessary to safeguard our environment, but should also stimulate the economy, create jobs and boost competitiveness of/in the EU Member States.

Whereas abovementioned intentions initially targeted newly built constructions, it is clear that these only form a part of the European building stock. In order to meet the proposed targets, historic buildings can no longer be exempted. On the contrary, they become more and more the core of our present energy efficiency and comfort interventions.

All of this built heritage, listed or not, is a witness of our past, our history and our constructive traditions. It adds significantly to the quality and charm of our built environment and therefore ensures

[1] http://ec.europa.eu/clima/citizens/eu/index_nl.htm (31 08 2016)

the added value of European cities and countryside. The social, commercial and cultural attractiveness of a place is clearly influenced by the quality and the rich heritage of its built environment.

It is clear that a sustainable society cannot be built without respect for its history, but it must also be anchored in the present and ensure its future use. It is therefore the duty of the present generation of experts to critically assess, evaluate and preserve / maintain / restore / adapt our built heritage for future generations to witness and enjoy this rich past.

Today, the focus of current conservation approaches in most cases still emphasizes on the preservation and restoration of our heritage to a condition as closely as possible to the state in which the building is handed over, using construction methods and techniques that approach the historic ones. The energetic and comfort optimization of these buildings, however, is not yet generally accepted and therefore a more delicate discussion. (Too) often these buildings are (too easily) exempted from adaptations because:

- the reconciliation of energy savings / comfort optimization and heritage values seems too difficult or even impossible,
- the (unqualified) application of new techniques could (possibly) do more harm more than good,
- the behavior and ageing of new techniques are often not yet fully understood, investigated or well-known,
- it is generally accepted that the original state should be restored as much as possible by traditional materials and construction methods.

However, one needs to be aware that adapting buildings and heritage to meet the actual needs of its users with evolving materials and techniques has always happened. Conservation of heritage in one certain original (?) historic state, makes that, in some cases, these buildings no longer meet present-day needs and comfort aspects. Whereas it should be acceptable for historic buildings only to meet the present-day standards partially, the users' comfort must be taken into account in order to assure the future use of these buildings. After all, it is common knowledge that unused buildings decay rapidly, and uncomfortable and energy consuming buildings are not likely to be used. Such an approach only would condemn them to be lost…

Our generation should make the decision to preserve our built heritage in a way it reflects and is adapted to the economic, societal, environmental, comfort and energy context of today, while ensuring the absolute preservation of the heritage's intrinsic values. After all, an optimized preservation and use of heritage buildings offers several opportunities such as:

- a more attractive use and better occupation of these buildings by assuring a reduced energy bill,
- the improvement of the indoor climate (and reduction of fluctuations in temperature and air humidity) would enhance the conservation of the building, its structure, finishing materials, interior decoration and collections,

- a more constant maintenance of the occupied buildings minimizing the risks of decay due to condensation, corrosion, biological attack, deformations, frost and salt damage ..., this way reducing the need for large restoration campaigns,
- and last but not least, a contribution to the reduction of greenhouse gas emissions by this collection of buildings.

All of these aspects would lead to an improved use and preservation of our heritage buildings, as used buildings remain preserved considerably better than unused.

Yet, it is essential that this thermal and comfort optimization of heritage buildings must be approached in a holistic way. Certainly for heritage buildings the main focus may not be the maximisation of the energy consumption / greenhouse gas emission reduction, but should always be the search for an *optimal intervention respecting the constraints of the heritage values*, as these values make the historic buildings that form the core of our European cities and countryside so special.

Luckily, in the last years the abovementioned approach and considerations are more and more accepted throughout an increasing group of (heritage, comfort and energy) experts and governments. One can notice for example the roadmap of EeB PPP (Energy Efficient Buildings Public Private Partnership) and several "Horizon 2020" calls in which energy intervention strategies and solutions for energy renovation of historic buildings are identified as a priority, several finished and ongoing nationals and European projects that focus on the interplay of energy efficiency and heritage preservation, or even the workgroup 8 "Energy efficiency of historic buildings" of the CEN/TC 346 on the "Conservation of cultural heritage" that is drafting a European standard (EN 16883:2015) entitled "Guidelines for Improving the energy performance of historic buildings".

All of the abovementioned considerations, evolutions, needs, thoughts and the implication, expertise and concerns of the BBRI Laboratory of Retrofitting on this matter formed the basis for the Belgian Building Research Institute to organize and host the **second edition of the International Conference on Energy Efficiency and Comfort of Historic Buildings** in close collaboration with the concerned public institutes from Brussels (*DMS* – the Brussels Monument and Sites Directorate), Flanders (*Onroerend Erfgoed* – the Flanders Heritage Agency) and Wallonia (*DG04-Patrimoine* – the Walloon Monument and Sites Directorate) from October 19^{th} to 21^{st} 2016 at the Royal Library in Brussels.

After a first edition organized by *Casas Históricas y Singulares* and *Ars Civilis* in Madrid (2014), this second edition will gather research groups, governments, building practitioners, product developers … working on topics related to the generation, transfer and application of knowledge, methodologies, materials and techniques to optimize the interplay between improving energy efficiency and comfort on the one hand, and preserving the heritage values of our historic buildings and cities on the other.

The EECHB2016 conference therefore brings together international experts and stakeholders, sharing state-of-the-art developments and their latest experiences, results, experiments, etc. around the following six themes related to the optimization of historic buildings:

1. Boundaries and obstacles,
2. Using and improving energy models,
3. Training and education,
4. Interventions related to (a) systems and indoor climate, and (b) materials,
5. Monitoring and feedback,
6. Governance issues.

For all those not able to attend this international scientific conference, forum and networking event, we hope that the peer-reviewed papers included in the conference's proceedings, might provide a valuable and interesting lecture and source of inspiration for further reflections, discussions, optimizations, experiments, research and development!

Michael de Bouw, Liesbeth Dekeyser, Samuel Dubois, Yves Vanhellemont
Editors and Chair of EECHB 2016

Brussels, October 2016

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Contents

EUROPEAN FEEDBACK

Eight years of energy efficiency in historic buildings

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Abstract – *The Swedish Research Programme for Energy Efficiency in Historic Buildings was initiated in 2006 by the Swedish Energy Agency. The overall objective of the program is to create a sustainable national research infrastructure and a national competence in the field. The projects within the program are expected to develop new methods and technical solutions and to communicate the results to different end user groups. In this context, historic buildings are not only listed and monumental buildings; the program addresses the stock of buildings built before 1945.The program is currently in its third four-year-stage. Previous four-year-stages were completed in 2010 and 2014. Each stage had a budget of 40 MSEK. During this time period the focus of program has evolved from monumental buildings towards houses and offices built before 1945. Following open calls, 40 projects have received financial from the program. This resulted in 19 journal papers, 54 conference papers five books and a number of technical reports. In addition to this, the projects have contributed to two CEN standards and resulted in a number of Bachelors and Master's thesis.*

Keywords – Research program; energy efficiency; historic buildings

1. INTRODUCTION

The built environment is a cornerstone in the pursuit of sustainable development. In order to realise the potential for improving energy efficiency in historic buildings we need to deliberately and carefully balance the techno-economic objectives with those of preservation of cultural heritage. Research in this field must be interdisciplinary and integrative, involving not only different academic disciplines but also end users.

This article will give an overview of the Swedish research programme for energy efficiency in historic buildings: objectives, projects and the general results of the program. Specific scientific results have been or will be presented in scientific journals and conferences, including EECHB 2016.

2. NATIONAL RESEARCH PROGRAM FOR ENERGY EFFICIENCY IN HISTORIC BUILDINGS

2.1 Background

In the wake of the energy crisis of 1973, the price of oil in Sweden rose by almost 400%. An ambitious and well financed national program was launched in order to reduce energy demand in the building sector by 25-30% in a decade. This included generous subsides and loans for energy refurbishment such as added insulation, replacement or improvement by windows and replacing oil with other energy sources. For the Swedish building stock in general and historic buildings in particular this lead to two types of problems:

- Unacceptable visual impact, typically from external insulation and window replacements
- Poor indoor climate due to moisture related problems.

The extent of these problems has not been investigated in a systematic manner, but one effect was that the perceived gap between building conservation and energy conservation was widened. Thus for a 20-year period energy efficiency in historic buildings did not get much attention in terms of policies, practice or research [1].

2.2 Description of the program

The Swedish Research Programme for Energy Efficiency in Historic Buildings was initiated in 2006, one point of departure being a growing concern for energy economy in monumental buildings such as churches and castles [2]. The program was initiated and financed by the Swedish Energy Agency with additional support from the National Heritage Board and the Church of Sweden.

The program has four main objectives:

- To create a sustainable research infrastructure for energy efficiency in historic buildings by involving more researchers and creating new research environments
- To facilitate a national competence of international prominence in the field.
- To develop methods and technical solutions for energy efficiency in historic buildings which combines old and new technologies
- To communicate the results in an efficient and appropriate manner to different end user groups.

In the context of this program, historic buildings are not only listed and monumental buildings; the program addresses a large part of the Swedish building stock. Approximately one third of Swedish buildings were built before 1945 and they constitute an important part of our built heritage even though most of them are not formally protected.

The program focuses on the use of energy in historic buildings throughout its whole lifecycle and focuses on issues and problems relevant to stakeholders. Interdisciplinary and applied research with a problem-oriented approach is encouraged within the programme.

The program is currently in its third four-year-stage. Previous four-year-stages were completed in 2010 and 2014.

2.3 Organisation

The program is financed and managed by the Swedish Energy Agency, a government agency for national energy policy issues. The Agency's mission is to promote the development of Sweden's energy system towards ecological and economical sustainability. The Agency supports research, innovation and development with a total budget of approximately 120 M€ per year.

In order to ensure the relevance and quality of the research program, there is a program committee with members from both stakeholders and academia involved in developing, focusing and dissemination of results from the projects. To position the program in relation to international research and practice there is also an international reference group linked to the program. Both of the advisory groups makes recommendations on project proposals and take part of the periodic monitoring of the program.

As part of the program, a national centre of competence, the Centre for Energy Efficiency in historic buildings (CEK), has been established at Uppsala University Campus Gotland and has the role of scientific coordination and research communication.

2.4 Projects in stage one: 2007-2010

Stage one of the programme supported sixteen different projects, see table 1, and had a budget of approximately 4 M€. Most of the projects in stage one dealt with indoor climate control in monumental buildings such as churches and castles. The common objectives of these projects were to facilitate both energy efficiency and preventive conservation in historic buildings. This includes development of appropriate climate criteria, control strategies and technical solutions.

2.5 Projects of stage two: 2011-2014

The evaluation of stage one called for a broadened focus in the projects, the projects of stage one related to monumental buildings, churches and castles whereas stage two also addressed a much wider range of historic buildings. Stage two of the programme supported fifteen different projects, see table 2, with a budget of approximately 4 M€. Some of the projects in this stage were clustered to facilitate interdisciplinary research and co-publicizing.

2.6 Stage three: 2014 – 2018

In 2014 a third stage of the programme was approved by the Swedish Energy Agency. The third stage will run from 2015 to 2018 with a budget of another 4 M€.

The focus of the programme has continued the shift, away from monumental buildings, churches and castles, towards the broader spectrum of buildings with historic value that were built before the year 1945.

The first six projects started in October of 2015, see table 3. A second call for project proposals ends in March 2016.

Table 1. Projects in stage one 2007-2010

Project title	Principal
Monitoring and evaluation of church heating based on liquid biofuel	University of Kalmar
Reducing energy use in old churches with respect to the cultural heritage	Husby-Rekarne and Näshulta township
Information and knowledge database for the research programme	Gotland University
Control of indoor climate in historical and cultural buildings using wireless systems	Linköpings University
Energy efficiency in cultural historical environments in Luleå diocese	Gotland University
Energy Efficiency and Preventive Conservation through Climate Control 30923	Gotland University Gothenburg University KTH
Careful energy conservation in churches: ventilation, climate control- and aspects of soiling	University of Gävle
Energy-efficiency to conserve buildings from the Modern Movement in urban areas	Lunds University
Energy system analysis of cultural historical valuable buildings	Linköpings University
Sustainable and careful renovation and energy efficiency in cultural historical buildings - a pre-study	SP Technical Research Institute of Sweden
Centre for energy efficiency in cultural heritage buildings (CEK)	Gotland University
Energy Efficiency and Preservation in Our Cultural Heritage: EEPOCH	Chalmers University of Technology
Curatorial competency for the Project; Preservation and Energy Efficiency in Historic Buildings	The Swedish National Heritage Board
Mould in church buildings a - pre-study	University of Gothenburg
Solar energy for heating and electricity in cultural heritage buildings	Dalarna University
The pressure pulse method - a new method for measuring the airtightness of historical buildings	University of Gävle

Table 2. Projects in stage two 2011-2014

Title	Principal
Energy efficiency and preventive conservation through climate control	Uppsala University Campus Gotland
	KTH Royal Institute of Technology
	University of Gothenburg
CultureBee for National Pilot Project in cooperation with the Swedish Church	Linköping University
Centre for energy efficiency in cultural heritage buildings (CEK)	Uppsala University Campus Gotland
Energy Efficiency and Preservation in Our Cultural Heritage: EEPOCH	Chalmers University of Technology
Refurbishment of windows in buildings of great cultural value	Sustainable Innovation Centre of Energy Efficiency in Sweden
Energy savings in churches: Air leakage, soiling and climate measurements.	University of Gävle
Potential and Policies for Energy Efficiency in Buildings built before 1945	Uppsala University Campus Gotland
	Linköping University
	SP Technical Research Institute of Sweden
A Historical Perspective on Energy Efficiency in Buildings	Uppsala University Campus Gotland
Mould in church buildings	University of Gothenburg
Smart Energy Efficiency of Historic Buildings in Cold Climates	Luleå University
Risk assessment methods of measures in historic buildings	Lund University

Table 3. Projects in stage three 2015-2018

Title	Principal
Energy efficiency and preventive conservation through climate control	Uppsala University
Potential and policies for energy efficiency in Swedish buildings built before 1945 - Conservation aspects	Uppsala University Linköpings universitet
Methods for Risk Assessment of Measures in Historical Buildings II	Lund University
An evaluation of previous policies on energy efficiency in buildings and their effects on energy use and historical values, Sweden 1974 - 2014	Uppsala University
Ventilation Measures for Cultural Historic Buildings	Sustainable Innovation i Sverige AB
Re-renovation: Possibilities for increased energy efficiency and the re-creation of cultural historical values in balance with modern demand .when once renovated multi-family housing are to be renovated a second time	Chalmers Tekniska Högskola

2.7 Outcome of research programme

The results from stage one and two are presented together as many of the results from the first stage were not published until after the end of the program period. New methods and technical solutions for both monumental buildings and more common historic buildings are the main results from the projects. Some of the results from stage one were presented at an international conference [3]. All in all, the results have been presented in 19 journal papers, 54 conference papers and five books (two handbooks). In addition to this, the projects have contributed to two CEN standards and resulted in a number of Bachelors and Master's thesis.

The results from stage one, dealing mostly with energy efficient climate control in monumental buildings have already had an impact in Sweden in that the knowledge base has been improved and research results have been transformed to new policies and improved practices.

A long-term effect of the program is that the number of Swedish researchers in the field have increased from practically none in 2007 to 18 senior researchers and 12 PhD students from ten universities in 2011. The Centre for Energy Efficiency in Historic Buildings, CEK, is established as a leading national and international research group on Energy Efficiency in historic buildings. This in turn has facilitated the participation in a number of European research projects, such as Climate for Culture and EFFESUS.

Researchers from the program have contributed to national policy development for the National Heritage Board, the Swedish Energy Agency and the National Board of Housing, Building and Planning.

The program website [4], with a bibliographic database, has continuously attracted considerable attention even outside of Sweden drawing close to 1000 unique visits per month.

2.8 Evaluation of stage one and two of the research programme

Both stages of the Swedish Energy Agency's research program for Energy Efficiency in Historic Buildings were evaluated by external experts [5, 6]. The purpose of the evaluation was to assess whether the activities are planned and conducted in line with the program objectives. The evaluation includes both a scientific assessment and an end user oriented assessment of results and effects of the projects.

The main conclusions of the first assessment was that the research area was considered relevant as it addressed important societal issues which had not received much attention form the scientific community. The outcome was considered satisfactory and it was recommended that the programme should be continued for another four year period. The evaluation group also stressed the importance of the interdisciplinary approach and coordination of projects through CEK. Finally, the Energy agency was recommended to shift the scope towards a broader range of building and issues, such as renovation processes and life cycle analysis, while not losing track of the unique character of the programme.

The evaluation of stage two concludes that the programme is "of national priority and international prominence". The external experts found the scope of the program to be relevant in terms of both the scientific content and to the needs of society. The evaluation group considered most of the projects to be of high scientific quality and strongly recommended that the program should continue. The output of the program in the form of methods, tools and highly skilled people was deemed to be good, but the evaluation also points at the need to improve information about the program in general and research communication to end users in particular. In order to have a real impact on the building sector, key target groups and stakeholders must be identified and the information tailored to their specific needs.

2.9 Discussion

In eight years, energy efficiency in historic buildings has been established as a research field in Sweden. Many researchers and a number of universities, with a broad range of competencies are involved in the field. The results from the research program have had an impact both on a practical and on a policy level. Even so, knowledge transfer from researchers to end users is still a limiting factor. In the current third stage of the program, resources have been earmarked to better address the needs of the end users.

Balancing the requirements of academic research, such as scientific stringency and peer review publishing, with the expectations of the end users for quick solutions to their problems is an eternal challenge for an applied research program. However, it is important not to polarize this discussion but to find a pragmatic synthesis of the dual objectives.

A research program is by definition time limited. For the future, one can foresee a development in two directions. The first is mainstreaming, where this research field becomes an aspect in the bigger context of renovation policies and processes. The second direction is specialisation towards the conservation field with a focus on sustainable management of historic buildings and preventive conservation.

In any given country, research on energy efficiency in historic buildings will be on a relatively small scale. In order to create a critical mass of researchers which can facilitate a sustainable research effort and knowledge management in this field, international cooperation is needed. This calls for cooperation not only between individual researchers and groups but also on a strategic transnational level.

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Comfort and energy efficiency in historic buildings – the 3ENCULT experience

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Abstract – *The FP7-project 3ENCULT demonstrated that reducing the energy demand up to Factor 4 to 10 is feasible also in historic buildings respecting their heritage value, if a multidisciplinary approach guarantees high-quality energy-efficiency-solutions, targeted and adapted to the specific case. Together with the energy benefit go numerous co-benefits: besides the economic saving and the more attractive living space, it is very often the increase in comfort to drive building owners and users to retrofit their buildings. Based on three 3ENCULT case studies, examples for the increase of air quality (in a school), visual comfort (in a museum) and thermal comfort (in a residential building) are illustrated.*

Keywords – Energy retrofit; historic buildings; comfort; 3ENCULT

1. INTRODUCTION

Historic buildings are the trademark of numerous European cities, towns and villages. They are a living symbol of Europe's rich cultural heritage and diversity and we need and want to preserve them.

As the Focus Area Cultural Heritage of the European Construction Technology Platform highlights [1], the real protection of Cultural Heritage – irrespective the formal one by conventions, laws and regulations – can be achieved by its integration in everyday life and economy to become a part of contemporary life as an asset having extremely important role in satisfying societal needs and fostering the development of society as whole. This is also the philosophy lying behind 3ENCULT, which fosters built heritage to become a vital and prospective part of European urban life.

Actually, in the EU-27 the building stock built before 1919 amounts to 14% - corresponding, in absolute numbers to more than 30 million dwellings [2]. Certainly the big part of this building stock makes part of the cultural heritage of European countries und gives identity to European cities, villages and public spaces. Including also buildings built between 1919 and 1945, the percentage rises to 26% and more than 55 million dwellings. Even if much less buildings from this latter epoch, than from the building stock before 1919, are listed buildings, they form a part of the city-center and the cityscape and retrofit interventions should take account of the specific demands in terms of aspect preservation. Translating these figures in people, it's about 120 million Europeans living in historic buildings.

Together with the energy benefit go a numerous co-benefits: besides the economic saving and the more attractive living space, it is very often the increase in comfort to drive building owners and users to retrofit their buildings. Based on three 3ENCULT case studies, examples for the increase of air quality (in a school), visual comfort (in a museum) and thermal comfort (in a residential building) are illustrated

2. METHODOLOGY

Methodologically, this paper presents the experiences from several 3ENCULT case studies, pointing out “lessons learnt”. It is not an analysis of a big data set of a large number of cases, has compared to such an approach however the advantage to present the single results with a high level of specific detail.

For each presented case study, the context and the main question are briefly described. Then the proposed solution is illustrated, both in terms of comfort increase and energy saving. Where available monitored data are used for this, complemented by calculations.

The monitoring concept proposed in the project included the necessary parameters for the assessment of energy consumption and user comfort as well as conditions of the building structure and historic surfaces. [3]

The energy balance was calculated for all 3ENCULT case studies with PHPP (Passive House Planning Package), an Excel based calculation tool which apart the U-value calculation and energy balance contains also calculation sheets for comfort ventilation and on summer comfort. For several case studies in addition dynamic simulations were performed.

3. RESULTS

3.1 Indoor air quality in a historic school building in Austria

The Höttinger School in Innsbruck (Austria) is listed as one of the most important examples of early modern architecture in Tyrol (1929-1931). A refurbishment of the school was envisaged not only because of the high heating energy demand, but also (i) to solve the severe overheating problems caused by large unshaded glazing areas and a highly inertial heating system and (ii) to increase both the air quality and thermal comfort.

Figure 1. Höttinger School, Innsbruck/Austria

Actually, the old photography implies that windows were often kept open – which meant cold air in winter, but was acceptable from noise and pollution point of view, as long as the school was "in the green". Today, the area around the school is heavily trafficated; opening windows for fresh air brings in also noise and pollution.

Measurements have brought up, that even with leakages the indoor air quality during lessons is insufficient and mechanical ventilation necessary to fulfil the obliged value with a maximum of 1500 ppm CO2. While the conservation authority pointed out that the "window is designed with the intention to be opened", they also stated "an additional ventilation system with the least possible impact on the genuine structure (using f. ex. secondary rooms for distribution) is conceivable but has to respect the high quality of the genuine interior architecture." [4]

Within 3ENCULT the "active-overflow principle, which uses staircase and corridors as fresh air reservoir and thus minimises the impact of ducting on the building, has been extended to be applied in schools (which need higher air change rate than a residential building or office). Measurements after the intervention show the success of the measure (see figure Figure 2).

Besides the ventilation system with heat recovery, the proposed retrofit interventions include improvement of the windows and integration of a shading system as well as the insulation of walls. Overall, the heating demand can be reduced from 129 kWh/m² to about 40 kWh/m². This whith increased air quality, better thermal comfort due to higher surface temperature and avoided overheating [5].

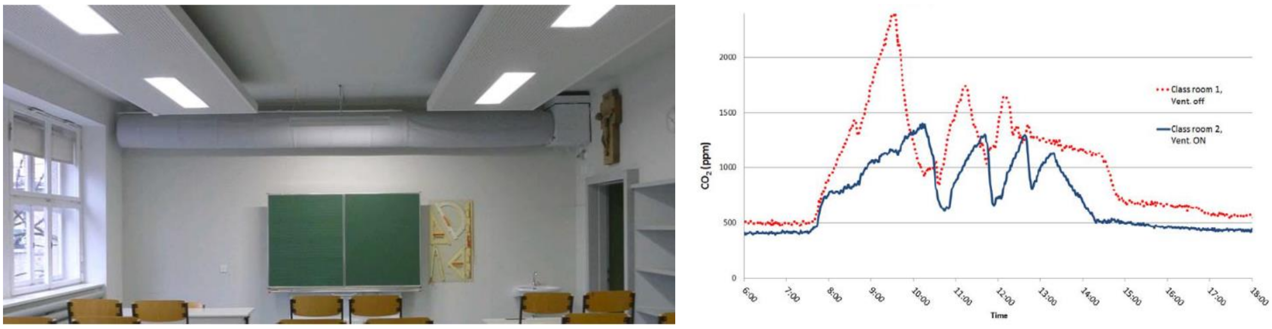

Figure 2. Left: a micro-perforated textile hose distributes the air in the room. Right: CO2 level during one day in two classes – blue WITH ventilation, red dots WITHOUT [4]

3.2 Visual comfort in a museum environment

"Sala degli stemmi" in Palazzo d'Accursio (Bologna/Italy) is a great example for the prestigious buildings of 1400 in Bologna, intended to show lordship and wealth. Today this and the adjacent rooms are used as a museum, being the room itself with its impressive frescoed walls and ceiling an important part of the exhibition [6].

Figure 3. Left: View from below of Sala Urbana's frescoed ceiling and walls. [7]
Right: Pre-3ENCULT - the lighting system produces high inhomogeneity and glare. [6]

However, the existing lighting design was of very poor quality: the incandescent halogen lamps did not only cause high energy demand, but also a lot of glare to visitors viewing the frescoes – especially the luminaires oriented to illuminate the floor – while at the same time they did not succeed in producing homogeneous illumination but rather single patches of high intensity.

The main goal of the energy efficient lighting installation in Palazzo d'Accursio was therefore to provide visual comfort to visitors viewing the frescoes while preserving the materials.

Within the project a wallwasher was developed, which (i) provides a very homogeneous illuminance, (ii) is limited in lateral direction to avoid that also neighbouring areas are illuminated (a typical problem of standard wallwashers) and (iii) has a very sharp cut off angle, which means that if positioned the right way, there is no glare for visitor waling by. Thanks to the sharp cut off angle, visitors can view even the frescoed ceiling without glare – and without noticing the luminaire which becomes kind of invisible since no "light at the source" can be seen.

The lighting system is based on LEDs, which together with the special optical design have a high overall efficiency of 90 lm/W. While in the past LED sources had some typical deficits in rendering colour, nowadays they are available in any category, also colour rendering index CRI>90 or CRI>95 (while for office >80 is needed, for surgery rooms >90). Moreover, the specific reflector coatings provide illumination down to 2200 K, which resembles historic incandescent light. Further advantage of using LEDs is that the deterioration of the works of art is slowed down because they do not emit invisible yet damaging ranges of the electromagnetic spectrum. [6]

The building owners finally pointed out, that the installation is a good balance between perfect illumination and conservation considerations and offers visual comfort as it is glare-free and has well balanced lighting levels on the walls and ceiling. The transition from the existing lights, which used halogen lamps, to a system of wall wash LED lighting, has reduced the electricity consumption by about 53%. [8]

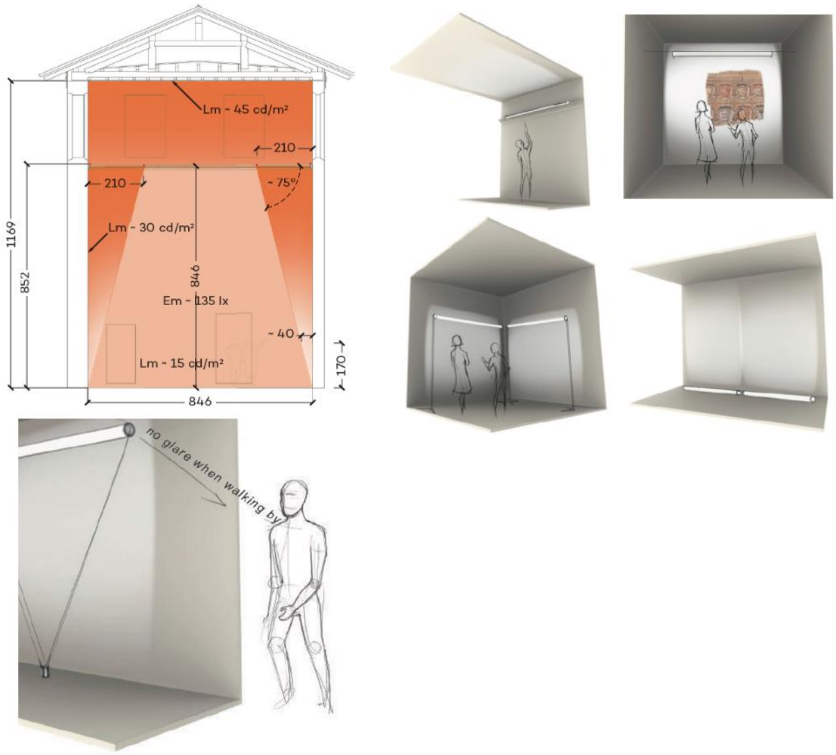

Figure 4. Left: Design of optimal illuminance. Right: Sketches of the new wallwasher, pointing out avoided glare and different mounting options. [6]

3.3 Thermal comfort in Strickbau in Appenzell, Switzerland

"Strickbau" buildings are prevalent in most alpine regions and consist of layered wooden beams, connected at the corners for stability and typically extending somewhat from the core block.

In the Swiss Kanton Appenzell, about half of the building stock are still "Strickbau" buildings – but the number is decreasing, since more and more people decide for new houses, which they believe would be more comfortable to live in. Demonstration, that a "Strickbau" can be refurbished to provide good comfort while keeping its historic charm – and its heritage value – is therefore urgently needed.

With the intervention as tested in the 3ENCULT case study, i.e. insulation of the walls (to decrease the U-value from 0.77 to 0.27 W/m²K), insulation of the basement and ceiling (from 1.19 to 0.29 and from 1.43 to 0.32 W/m²K), enhancement of the window with an additional layer and increase of the airtightness, monitoring showed that the demand could be reduced from about 200 kWh/m² to less than 100 kWh/m². [9]

 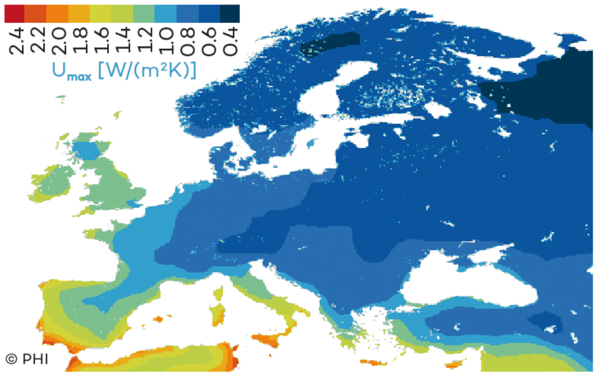

Figure 5. Left: Strickbau analysed in 3ENCULT [9].
Right: map of Europe with U-value necessary for meeting comfort requirements [10]

At the same time the thermal comfort increased considerably thanks to higher surface temperature. As shown in [10], the inner surface temperature depends on the outside temperature and on the thermal resistance of the wall. In order to reach the comfort criterion on not having a larger difference than 4.2K between the perceived indoor air temperature and the coldest surface, depending on the outdoor temperature a minimum thermal resistance is needed, i.e. a maximum U-value is allowed. The map in Figure 5 shows the U-value for typical outdoor temperatures all over Europe [10].

4. CONCLUSIONS

Decision for retrofit is in most cases not merely an energetic one! Economic, but particularly comfort reasons play an important role.

While saving energy by simply heating less and living in twilight would considerably worsen living conditions, energy saving achieved with retrofit measures does on the contrary improve the indoor comfort for the occupants: Higher surrounding wall temperatures increase the perceived temperature, airtight and isolating windows avoid air draught and irradiative losses, repaired thermal bridges decrease the risk of mould grow, small energy demands allow for more comfortable low-temperature heating systems, extensive daylight use improves health and well-being.

Considering rising oil-prises, the energetic retrofit is even an insurance for living comfort, especially for a socially vulnerable group leading a precarious existence, who might not be able any more to pay the energy bill. And it is not uncommon, that the latter is living in historic, but degraded areas.

Furthermore it can be sustained, that with the increased comfort demand of our society, the revitalisation of historic towns and its socioeconomic impact can be positively affected by the energy efficiency in these buildings.

5. ACKNOWLEDGEMENT

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BOUNDARIES AND OBSTACLES

Mismatch, exclusion and inclusion: threats / opportunities for historic buildings in the current energy efficiency paradigm

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Abstract *– The mismatch between the European "Energy Efficiency" paradigm rules & tools and the Historic Buildings characteristics & behaviour is so clear that "those officially protected as part of a designated environment" (EPBD, 2002) can be excluded. Although such exclusion may seem logical and easier, it casts a shadow of inefficiency and discomfort, urging owners to perform changes that those buildings were never designed to provide or endure. Simultaneously, interventions in similar buildings outside of these "excluded territories" are forced to undergo "deep renovation" works that compromise their original behaviour, structural integrity and cultural value. A 14-16th century residential building located within Coimbra's UNESCO Heritage area is used to demonstrate that by addressing the original problem —the mismatch— Historic Buildings can reassume their role as signs of versatility and resilience, offering measurable and replicable results where the EPBD is failing to deliver: the residential sector.*

Keywords – Historic Buildings; EPBD; energy efficiency; energy efficacy; quality of life

1. INTRODUCTION

This paper proposes that Energy Efficiency and Quality of Life can be achieved in Historic Buildings (and Areas) by intertwining traditional and new stakeholders into win-win neighbourhood scale decisions that best fit their individual and collective needs.

Energy Efficiency can be an instrument to demand for more, and better, information, but current regulatory simplifications and exclusions are casting prejudice on Historic Buildings, the most relevant examples of sustainability and resilience known so far. This paper demonstrates that a deep assessment –going beyond energy consumptions to include the "history" and use patterns– is essential to acknowledge individual specificities and to find the best alternatives and intervention scales. To achieve this goal it is necessary to empower potential middle-actors with basic Energy Efficiency (EE) underlying concepts; and to alert to the risk that "scaling up" the current EE paradigm, designed for new buildings, may represent to contemporary exclusion boundaries, and to Historic Buildings.

1.1 The Energy Efficiency goals in the buildings sector

"Buildings are responsible for more than 40 percent of global energy use and one third of global greenhouse gas emissions, both in developed and developing countries" [1] and are thus an important target for energy savings. The Energy Performance for Buildings Directive (EPBD, 2002/91/EC) [2] acknowledged this issue within the belief in a growing society and ever-growing need for more, and newer construction, and its formulation reflects this spirit. The Energy Performance Certificates (EPCs) and their European variants[2] where designed as a knowledge-through-evaluation tool with simplifications ranging from the decision support knowledge –mainly from new construction– all the way to facilitated inspections in some countries. The EPBD-"recast" (31/2010/EC) [3] focused on "nearly Zero Energy Buildings" (nZEB), and defined rehabilitation goals based on member/region defined cost-effectiveness parameters. The 2012 EPBD [4] version intertwined most of the energy related legislation in one package, defining it as a multilayered issue, although its impact on real actions is still scarce. As for the recent Energy Union approach [5], mixed feelings emerge, as scaling up current EE measures for existing buildings is suggested without verifying if they match.

Figure 1 depicts the mismatch of nZEB as a priority (for new buildings after 2020), as existing buildings prevail in constructed area / consumptions: as they exist and can be assessed, and energy consumptions benchmarked, effective results and optimization is possible with low investments.

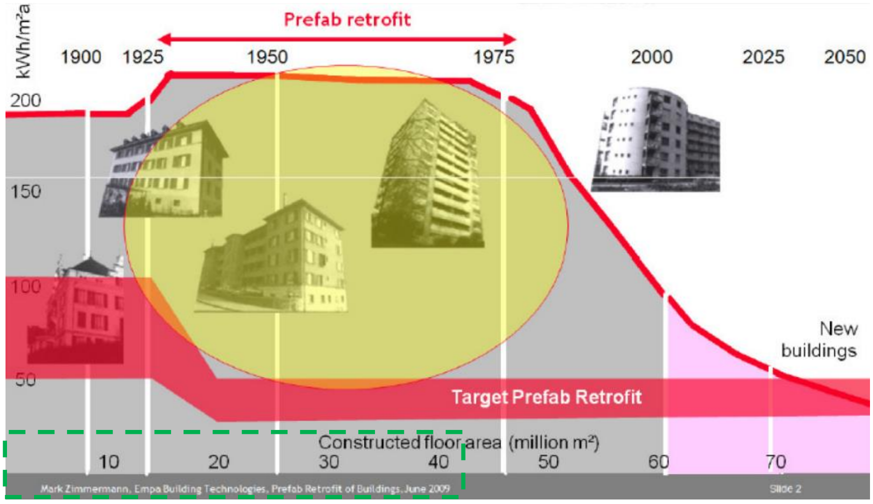

Figure 1. Estimated consumption in kWh/m²a (vertical axis, red line) of European buildings according to their construction decade and accumulated constructed floor area (horizontal axis, top and bottom). The "Target Prefab Retrofit" magenta bar illustrates the identified potential for savings in IEA Annex 50[3], and the superposed green dashed box on the bottom left demonstrates what optimized Historic Buildings, as described in this paper, can achieve.

[2] The author participated in the early Portuguese implementation process as a "Qualified expert", experts' trainer and evaluator, and implementation council member for some years: an insider.

[3] Illustration shared by Mark Zimmermann to the author and other participants of the IEA Annex 50 "Prefabricated Systems for Low Energy Renovation of Residential Buildings": a version at http://www.ecbcs.org/annexes/annex50.htm

The reason for this twist in priorities is simple: existing residential buildings have severe restrictions related to ownership, investment capacity, diversity and integration of new systems and technologies, while most of the new buildings legislative requirements are set over a *tabula rasa*.

1.2 The underlying issues

Climate Change mitigation is a goal in Europe's international long-range commitments, but European citizens must acknowledge that Energy Security is a major concern, as Europe imports over 53% [6] of its energy. Although many products and services seem reliable –heating, piped water and food in the supermarket– the majority relies in fossil energy: energy supply rupture can affect our daily life, and become a deadly risk in harsher climates. In short, Europeans need Climate Change mitigation to ensure future generations will have a liveable planet, but also need to invest quickly on Energy Security measures to guarantee a soft transition. And it was probably this urgency that transformed the Energy Performance Certificates (EPCs), a knowledge-through-evaluation over-simplified tool (for new buildings) into a decision-support tool for all buildings.

This case study approach demonstrates that alternatives with a lower cost and impact on environment exist, and that a deep assessment of Historic Buildings towards Energy Efficacy can contribute to harmonize Climate Change mitigation with Energy Security, "in" Quality of Life.

2. METHODOLOGY

An ancient building located inside the UNESCO Heritage protection boundaries in Coimbra, Portugal –thus automatically excluded– is used to reveal the potential Historic Areas have: beyond being the "worst case scenarios" for Energy Efficiency regulations, many other regulatory exclusions make them perfect crossroads for innovation [7]. Moreover, all lessons learnt and solutions produced in these difficult contexts are easily implemented in less demanding areas.

"Mismatch" will address the inadequacy of the current Energy Efficiency regulations to address Historic Buildings and Areas, the advantages of a deep assessment to acknowledge outcome-based alternatives and the contradiction of solving collective problems individually. Exclusion will refer how top-down and bottom-up individual actions leave many stakeholders behind, while Inclusion will propose some building users as middle-actors for feasible and inclusive alternatives deployment. In the Conclusion voluntary actions, and measurable results for these "excluded territories" will be proposed.

3. MISMATCH

Definition [8]:
"noun: 1 A failure to correspond or match; a discrepancy (...)
verb: Match (people or things) unsuitably or incorrectly"

Data from the Montarroio case study will illustrate the mismatch of the initial EPC certificate with reality [9]. Although "excluded", it represents 800 similar buildings nearby, and millions across Europe, many of them outside the protection/exclusion boundaries. "Learning from Traditional Knowledge towards engaged inhabiting" [10], the Montarroio deep assessment targeted on traditional uses and performance-based goals towards "nearly Zero Energy Building" (nZEB) and/or Net Zero.

3.1 A "deep assessment" to illustrate the mismatch

Definition [8]:

Assessment is the action to "Evaluate or estimate the nature, ability, or quality of"

Dimensions were assessed using technologies like terrestrial laser scanning / photogrammetry and drone flights, digital reconstructions from the point clouds processed into 3D faces and 3D models printed (Figure 2). Online monitoring of indoor and outdoor temperature, relative humidity and CO_2 parameters fine-tuned the reference case dynamic simulation models, and confirmed the massive influence of the thermal inertia for energy savings if adequately used [10].

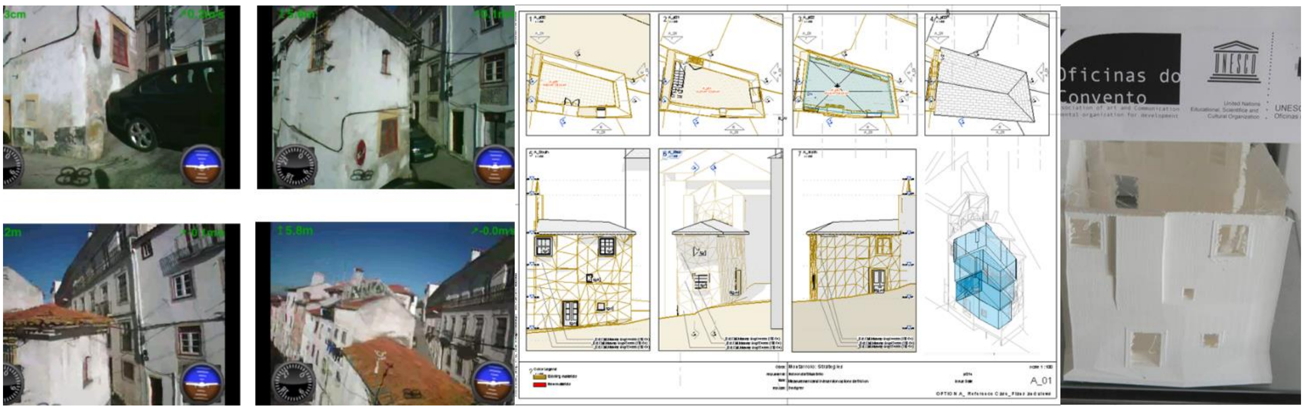

Figure 2. Drone flight images (left), Autodesk Revit 2012 model exported to dynamic simulation software as Ecotect and OpenStudio/EnergyPlus using gbXML (middle) and 3D printed model (right) (source: author).

Building Information Models (BIM) were processed to develop design alternatives, and to export simplified models for dynamic simulation. From onsite debate with other owners, the IEA Annex 56 on "Cost Effective Energy and Carbon Emission Optimization in Building Renovation" jointly developed methodology was extended to include demolition and reconstruction, the locally expressed "best solution" for ancient buildings like Montarroio. Five options were compared:

- Opt.0_Reference Case: The building "as it is", with the works to render it inhabitable, tagged as "Anyway Measures" [11] including materials/equipments maintenance and replacement;
- Opt.1_COMMON "REHABILITATION": "Business as usual" (BAU) / regulatory practices with interior insulation under plasterboard is placed to hide pathologies, with serious IAQ risks;

▪ Opt.2_DEMOLITION & RECONSTRUCTION: Primary choice for many, as it reduces surprise factors, uses common new construction techniques and increases useful space;
▪ Opt.3_UPGRADE WITHOUT EXTENSION: Detailed assessment to optimize building characteristics to achieve efficacy with users. Solar thermal heating/DHW with electric backup;
▪ Opt.4_UPGRADE WITH EXTENSION: Opt.3 with structural seismic reinforcement made financially viable with an area extension: safer users / investment, and space for a small family.

Figure 3 graphs the Initial Investment Costs (IIC) per square meter of renovation area, the Life Cycle Costs (LCC) –comprising the IIC, energy costs during 30 years and equipments maintenance / replacement costs (each 15 years), divided by 30 as if paid annually [12]– and Global Warming Potential (GWP) environmental impacts for those five options:

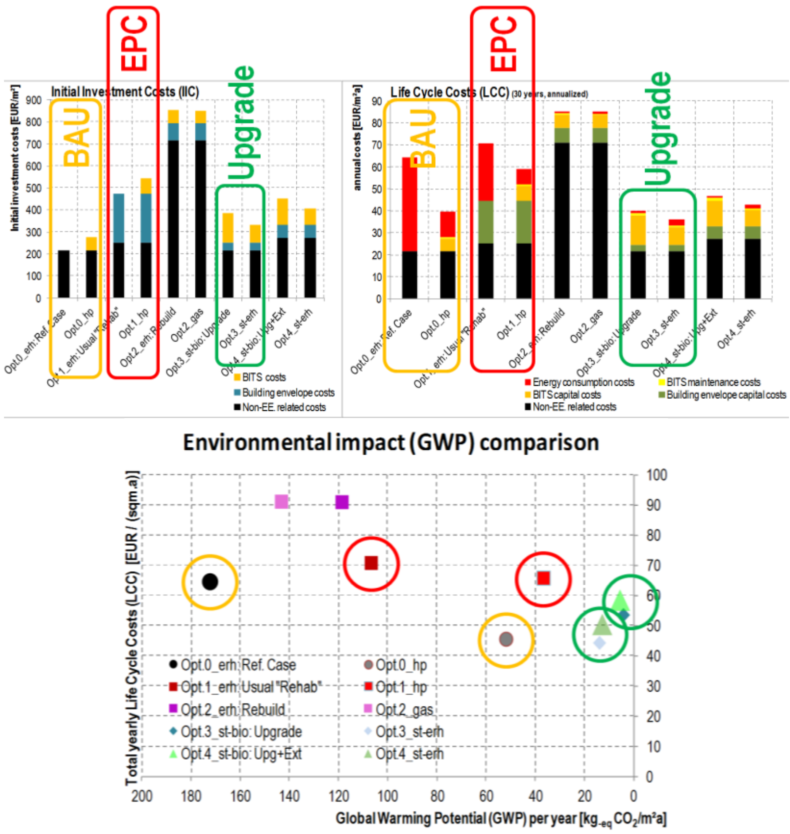

Figure 3. Initial Investment (IIC) (left), annualized Life Cycle Costs (LCC) in 30 years (middle), and Global Warming Potential (GWP) comparison in the same period using (EcoBat, 2014) (right). More detail and information in [12].

Data from a real case study is important to understand building owners, and realize why apparently straightforward solutions, recommended and/or imposed by regulations fail to happen. The results for this climate and building type are briefed only to illustrate the potential of deep assessments:

1) The blue dashed ellipse in the GWP comparison, Figure 3-right, demonstrates that Opt.0_hp, a heat pump (hp) based version of the reference case (second bar inside the yellow BAU box, grey circle inside the ellipse), has lower impact on environment, and owners' pocket, than Opt.1_erh, an energy conservation approach proposed by EPC that includes insulation on the walls and new double glazing windows (first bar inside the red EPC box, dark red square inside the ellipse);
2) More than 75% emission reductions and increased energy security are achievable in Opt.3, with easy to install insulation in the horizontal faces, ceiling and floor over the basement, and solar based DHW / heating with simple electric resistance heater (erh) backup (second bar inside the green Upgrade box), light green diamond inside the 20-0 range of GWP.
3) Increased area, comfort and security that result from a small extension with seismic and fire risk mitigation can favour owners' involvement, render the investment safer, add value to the building and create space for a small family city flat (Opt.4, green triangles) [13]

More detail is available in [12,13], but the value of a deep assessment lives within the process: the drone flights generated contact with neighbours, conversations on the value of their buildings and on the need of a better understanding of old practices, later facilitating information collection for [12]. Deep assessments of Historic Buildings (and Areas) lead to unexpected, yet measurable[4], results.

3.2 A Building Physics simplification mismatch

Table 1 displays the Montarroio 2009 EPC useful energy disaggregation to illustrate the mismatch of EPC with reality, as full occupation and temperature levels are assumed across the seasons, and then corrected through a national factor: "the actual energy use for space heating and for domestic hot water are only 5% and 22% of those obtained from the [EPC]" [9].

Table 1. Extract from the energy performance certificate issued 30-07-2009 considering a 32 sqm useful heated area, reaching a D class (issued according to the current legislation by the author)

	Estimated Consumption (EC) per sqm per year	Regulatory limit	Estimated Consumption per month (EV / 12 month * 32 sqm)
Heating	196,67 kWh/m^2.year	101,65 kWh/m^2.year	524,45 kWh/month
Cooling	2,34 kWh/m^2.year	18 kWh/m^2.year	6,24 kWh/month
Domestic Hot Water	119,39 kWh/m^2.year	73,91 kWh/m^2.year	318,37 kWh/month
Total	**318,4** kWh/m^2.year	193,56 kWh/m^2.year	**849,06** kWh/month

[4] Building Energy Models (dynamic simulation) are accepted in the Portuguese Regulation for service buildings, but their use in the residential sector is not accepted. Excluded areas suffer no restriction, and energy benchmarking is possible.

For those least versatile in energy accounting, the last column translates Estimated Consumption per month per building (annual estimate per square meter (sqm) * 32 sqm / 12 months) as if equipments were always on every day. Considering 0.15€ per kWh, costs would reach 127€/month without taxes every month, a significant mismatch with calculated and reported values in [12].

The problem only arises as these values, in significant mismatch with heating tests and dynamic simulation performed [14], are used to define energy efficiency measures, irrespectively of the number of users, their specific needs and expectations. And the results are not the same, as over dimensioned systems are rarely more efficient in daily use, and are definitely more expensive to buy and maintain.

3.3 A conceptual mismatch: an individual approach to a collective problem

The mismatch between the EPBD versions and the residential sector starts at the fractioned approach: by requiring each individual owner to certify buildings, or fractions of them, to promote individual improvement measures, the EPC forgets about their limited capacity to make informed choices, to invest or to reflect such investment in rents. Moreover, individual systems have lower efficiency and extra costs in acquisition, operation, maintenance, refurbishment and disposal. In the end, the Energy Performance Certificate becomes only one more cost to most of the owners.

By favouring individualism, the EPCs lost track of essential aspects for a sustainable future: collective approaches to scale results, reduce costs, increase efficiency and make the most of the existing assets. By simply reflecting the urban sprawl, the EPBD forgets its untamed impact in increased infrastructure construction, operation costs and transportation needs, and negative effect on the city centres' infrastructures, transportations, amenities; and collective Energy Efficiency. Surprisingly, the current EPCs strategy defenders only cite the collective –regions, municipalities, associations, owners and tenants, to name a few– to blame them for not getting together to better finance the individual actions proposed, or not implementing what was decided as "best for them".

4. EXCLUSION

Definition [8]:
"1 The process of excluding or the state of being excluded"

Exclusion is a two-sided event. By excluding Historic Buildings from the scope of EPBD, from investigation and from participation in contemporary societal goals, century's old traditions of continuous adaptation to the emerging needs are broken, and "Traditional Knowledge" [10] lost. Exclusion sentences these areas to negative judgments: Historic Buildings are deemed as "energy hogs", and people living in them as unwilling to participate in the collective Energy Efficiency (EE) goals. On the other hand, some Historic Buildings stakeholders deny embarking on EE "fashions", excluding themselves and thus losing the opportunity to cut energy costs, to harness their full potential, to affirm the continued validity of Traditional Knowledge, and to set examples.

Most of the Historic Buildings were built and maintained to provide safe and comfortable conditions for the generations that preceded us without fossil fuels. Although exceptions existed, like today, their sustainability is proven by their versatility and resilience, and supported by studies that state that “The Greenest Buildings” [15] are the ones already built. And there is much to learn from Historic Buildings to help existing residential buildings/neighbourhoods to reach “Net Zero” [16].

Exclusion, as a distant view of the other, is also a reason for lack of stakeholders’ cooperation, as each (owner, designer, contractor, university and research centre, public institution, energy service company, local community ...) often fails to understand the global intrinsic complementarities. Exclusion also happens when excessive diligence on the Historic Buildings materiality occurs without contextualization and/or alternatives, condemning residents to energy poverty and to loss of pride.

Exclusion is not always negative: by being excluded, most of these Historic Buildings remain in original conditions within areas that do not have to obey to contemporary regulations, and thus are magnificent sites for applied experimentation [7], as demonstrated in the next topic.

5. INCLUSION

Definition [8]:
“1 The action or state of including or of being included within a group or structure (...);
1.1 A person or thing that is included within a whole”

Inclusion is essential for achieving the Climate Change mitigation and Energy Security goals, and Historic Areas are the perfect setting for demonstration: “Common Efficacy”[5], a recently awarded proposal [17], builds on “win-win” strategies to intertwine local communities, governance, universities and energy service companies towards the “democratization” of Energy Efficiency, renewable energy and comfort. Moreover, it demonstrates that “nZEB” [4] levels can be achieved in Historic Areas [12].

It proposes that the exclusion of Historic areas from the majority of the regulations creates the perfect setting to make nZEB neighbourhoods happen. The process addresses usual suspects –the lack of state funding, the limited knowledge of the state of the art by local actors, the lack of specific training, the little interest of the owners and tenants to invest and a fragmented sense of community, among many others– to propose collective interventions with mutual local and global gains. The “Common Efficacy” process is based on the strengths, needs and expectations of the various actors:

- Energy Service Companies (ESCOs) have the economic strength, technique and experience in the industry to finance, build, maintain and optimize neighbourhood scale energy efficiency solutions for Historic Buildings where the investment is paid by the savings achieved;
- Local Agents / Political Actors know/control the infrastructures and have privileged access to funding that can be used to fight energy poverty and promote attractive Historic Areas;

[5] A 4mn video of the “Common Efficacy” process is available at http://www.uc.pt/en/efs/destaques/2016/vinci

- Science and Technology, represented by universities, research centres or companies, know the state of the art of Energy Efficiency, the cost-optimal solutions for each site and possess the equipment and technical staff / students to translate theory into practice;
- Local Communities are agents with direct deployment on the ground, with knowledge of the local dynamics, with a direct interest in group support to develop their agenda and influence, and direct gains as aggregators of solutions towards better “Quality of Life” for their members.

Building users –the only stakeholder position that we all share, but continuously forget– can embrace a new role as actors of change in these territories of exclusion: “due to their position between top and bottom actors and between technology and implementation, middle actors play crucial functions in the transition process. Their abilities are based to their own agency and capacity which they can exercise to influence the agency and/or capacity of other actors.” [18].

6. CONCLUSION

In a present and future where Climate Change, Energy Security and scarcity motivate collective efforts to reduce energy, materials and water consumption, the needed Energy Efficiency (EE) is an opportunity to integrate long evolving Traditional Knowledge (TK) into practical use. In opposition to the wishful EPBD estimates that are pressing ancient buildings to adopt EE measures designed for new constructions, and to achieve goals that they were never meant to provide or endure, Historic Buildings and Areas can produce inclusive, and measurable, Energy Efficiency and Sustainability results.

Current threats can become opportunities for these territories of exclusion, as neighborhood scale deep assessments can harness the construction and use practices embodied knowledge to intertwine them with wider EE, sustainability and Quality of Life goals: **voluntary attractive neighborhood scale** guidelines to integrate EE measures with fire, seismic, water, energy poverty and other risks mitigation, aligned with users’ needs and expectations: current and future, individual and collective.

Europe needs results, not nice EPC certification letters. And Historic Buildings can help deliver.

7. ACKNOWLEDGEMENTS

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Valuation of medieval churches; towards an integration of experts' and laypersons' views

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Abstract - *In this paper we explore the dynamics and strategies that spring from the tension between energy retrofit and conservation by investigating the differences and similarities between experts' and laypersons' valuation of historic buildings, as well as their views on their energy efficiency. This paper presents four case studies of medieval churches in Groningen, Netherlands. Valuation studies is used to investigate the values that are attached to historic buildings by various stakeholders. We introduce the 'heritage as a spatial vector' approach, to position heritage in relation to developments in society. Our theoretical contribution lies in the combination of heritage approaches and valuation studies. We conclude that for a more balanced assessment of historic buildings, laypersons' valuations should be further integrated in heritage studies.*

Keywords – Medieval churches; retrofit; laypersons' valuation; heritage as spatial vector; Netherlands

1. INTRODUCTION

Preserving historic buildings does not always align with the ambition to promote sustainability in the built environment. In this paper we investigate the differences and similarities between experts' and laypersons' valuations of historic buildings, as well as their views on their energy efficiency. Our cases are set in the Dutch province of Groningen, a rural area renowned for its medieval churches. The Organisation of Historic Churches in Groningen (SOGK) is the owner of 86 historic churches, and takes care of building maintenance and repair. Local voluntary committees are responsible for day-to-day management.

Valuation studies investigate the different values that are ascribed to historic buildings by various actors. Architecture is a cultural product and as such all buildings are influenced by the culture and time when they were created. According to Walter [1], conservation focuses on the identification, description and prioritisation of values. Furthermore, the role of conservation is to "preserve and enhance values". De la Torre [2] recognizes the mutability of values and the complex process to identify them: "The values of heritage are not simply 'found' and fixed and unchanging, as was traditionally theorized in the conservation field (i.e., the notion of heritage values being intrinsic)."

Valuation and assessment is usually performed by experts. More recently other stakeholders are being included in the value definition process. Fouseki and Cassar [3] argue that it is important to understand how people feel and behave towards their built environment and how they value their buildings and the impact of energy efficiency improvements. Vatin [4] argues that valorising, or improving value, is an integral part of the practice of valuation. Heuts and Mol [5] suggest that stakeholders use specific sets of valuation criteria, which they call ‘registers’, related to professional background or interest. In this paper, we investigate valuation of historic buildings by laypersons, i.e. those without a background in architectural history.

To broaden our perspective, we draw on the ‘heritage as a spatial vector’ approach, which positions heritage in relation to its physical and social context [6, 7]. It is recognized that actors may attach different meanings, values and interests to heritage, therefore the ways in which heritage is preserved and enhanced can vary [8, 9, 10, 11]. However, these different views can also lead to tensions in conservation. We argue that sustaining historic churches should be positioned in a wider geographical and social context, thereby allowing developments such as demographic change, secularisation and earthquakes (caused by gas extraction) to be taken into account. Furthermore, utility values such as user experience, usability, thermal comfort and energy efficiency play a role in people’s valuations.

To demonstrate this, we carried out four case studies on medieval churches owned by SOGK. In the following, we briefly outline our methods first, then describe the case studies and discuss identified valuation processes and strategies. Finally, we draw conclusions finding that for a more balanced approach, laypersons’ valuations of historic buildings should be further integrated in heritage studies.

2. METHODS AND MATERIALS

Empirical data considered for the four case studies consists of site visits, archival material [14], technical information and interviews. We held a group interview with each local church committee; in total 10 interviewees took part in the study. The age range of interviewees is between 47 and 74, professions include teachers (4), painter, (physio)therapist (2), psychologist, supermarket employee and nurse. Five interviewees are pensioners.

Interviews were transcribed and analysed according to usual procedures in qualitative research [13, 14]. Before the interview, each attendee filled out a questionnaire about the building regarding its thermal comfort, interventions to improve its energy performance and how he or she valued it personally. Photo-elicitation was used for the evaluation of the energy performance improvement. The starting point for our assessment was a list of sociocultural values, based on the literature [2, 11]. However, we kept an open mind as to user values that came up during the interviews and site visits.

3. RESULTS

The churches in our sample are located in Nieuw Scheemda (figure 1), Leegkerk (figure 2), Lettelbert (figure 3) and Obergum (figure 4). Frequency of use ranges from five times a year to several times a week. Regarding their thermal comfort, the churches in Nieuw Scheemda, Lettelbert and

Leegkerk were considered acceptable, although in Lettelbert the interviewees differed in their assessment. Nevertheless, in Nieuw Scheemda and Lettelbert it was deemed necessary to wear heavy clothing in winter; while in Leegkerk warm clothing was needed all year round. In Obergum, the thermal comfort level was considered insufficient. Judgment was adapted in some cases by taking the age of the building into account. Pre-heating time before an event ranged from 1 up to 12 hours in advance. In this last case, the church was used only five times a year so this was not felt as a problem.

3.1 Stakeholders' valuation

In this section, we give an overview of the values that our interviewees ascribed to their buildings, and contrast these values with the values from the literature [2, 11]. We scaled the responses on a five-point scale: absolutely unimportant (--), unimportant (-), somewhat important (+/-), important (+), very important (++). Architectural and artistic/aesthetical value is split in two separate values. If the value did not come up in the interview this is indicated with 'x'.

Table 1. Values

Values	Nieuw Scheemda	Leegkerk	Lettelbert	Obergum
Age value	+/-	+	++	+/-
Architectural value	+	+/-	--	++
Artistic/ Aesthetical value	-	+	+	+
Emotional value	--	--	++	--
Historic value	--	+	+	+/-
Religious value	++	--	++	--
Political value	--	x	x	x
Educational value	--	x	x	x
Community value	+/-	+/-	++	++
Economic value	--	--	++	--

The historical values of the church were important to all respondents, which could both relate to the building itself as to certain elements that were deemed especially important. The majority of the respondents are interested in history and consider themselves to be knowledgeable about the history of the church. In some cases, the building was mentioned as a site of important historical events, such as Leegkerk, which had a role in the Eighty Year's War (1568-1648), fought by the Netherlands against the Spanish Empire. The architectural value of the church was considered not important by the respondents in Lettelbert, whereas the age value was considered very important. In Leegkerk the simplicity of design was mentioned as a special quality. On the other hand, in Nieuw Scheemda the respondents were unaware of the history of the church and considered the aesthetical value of the church as not very important. The value of authenticity was added as an important value in Obergum.

The interior of the church is often experienced as peaceful; in one case the atmosphere was considered one of the main qualities. In Nieuw Scheemda respondents stated that the (Christian) religious value of the church was ‘very important’, (general) spiritual value was put forward quite strongly in the case of Lettelbert. In the other two cases this original value of churches was considered ‘not important’. Furthermore, personal memories of the respondents themselves or others in the community were considered important.

Apart from the values in themselves, it is interesting to analyse who these values are for. Some respondents argue that the church fulfils an important role for the community by providing a place for local events. This includes cultural events, such as concerts, but also more commercial activities, such as weddings or funerals. Moreover, the organisation of events is the mainstay of the survival of these churches. Other values are considered important for the general public, including tourists, visitors of events, or ‘heritage visitors’.

Regarding the economic benefits of the church reactions were mixed. In three cases the general feeling was that the profits should only provide for the (daily) upkeep of the church. In Lettelbert the respondents envisaged a greater economic contribution of the church, by attracting tourists to the village.

An important characteristic of Nieuw Scheemda is its excellent acoustics, which makes the church attractive for concerts. The organ, by the famous organ builder Hinsz, is probably as valuable as the church itself. The interviewees even state that the church should be demolished, were it not for the good acoustics. On the other hand, in Obergum the church lacks good acoustics, which makes it less attractive for musical events.

The churches house several elements which are deemed important. Integral to the building are *niches* in the apse in Leegkerk. The *piscina* in Leegkerk and the *altar stone* in Lettelbert are remembrances of the period before the reformation. In Obergum the *cave* under the church was especially valued, maybe because of its authenticity. *Gravestones* in the floor provide memories of people who have lived and died in the community. The *pulpit* in Lettelbert is valued as a decorated wooden interior item. Other elements include an old *bible* in Nieuw Scheemda. Some of these elements contribute to other values, such as the peaceful atmosphere, memories of earlier periods or people.

3.2 Energy retrofit proposals

In the interviews photos were presented of energy retrofit interventions, interviewees were asked to give their opinion on the implementation of these interventions for their own church. Many reactions of the respondents were highly negative regarding most interventions. In Nieuw Scheemda there was powerful opposition against almost all the possibilities presented, although internal double glazing and floor heating had some agreement. In Leegkerk none of the interventions could count on unanimous agreement. In Lettelbert respondents agreed to double glazing and floor heating. Insulation attracted mixed reactions. In Obergum the respondent agreed with floor heating, internal double glazing, screening and shutters. He was interested in the glass double lobby. He was the only respondent to agree with PV panels on the roof.

Both internal and external insulation was strongly opposed by almost all respondents. Double glazing was strongly opposed by the majority of respondents. The reactions to the internal double door and lobby varied considerably, from strong opposition to strong agreement. This could be related to the authenticity of the interior and the impact this intervention would have. Partition heating was primarily opposed, while floor heating was the least controversial intervention. The reaction to solar panels varied from strong opposition to agreement, with respondents in Lettelbert suggesting the removal of gravestones to allow for the placing of PV panels in the graveyard.

3.3 Case comparison

The interviewees in Nieuw Scheemda defend the building under two principles: acoustics and religious nostalgia. The informants coincided that investments were not merited, because the building is not used for religious purposes anymore. They expressed no interest in energy efficiency, considering that the actual systems work well.

Figure 1. Church Nieuw Scheemda

The informants at Leegkerk are pensioners with a higher educational level; they showed much more environmental consciousness in their reaction to the energy-efficiency proposals. They would accept minor improvements in the thermal bridges and the heating system.

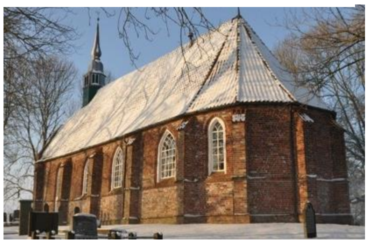

Figure 2. Church Leegkerk

Lettelbert church presents a grave problem of outdated technology, it has been renovated in 1995 without any improvements in energy-efficiency. The church is valued as a spiritual place, well suited to the icon-painting classes. During winter interviewees have to struggle with the two heating devices inside the classroom, while trying to avoid the cold coming in from the church.

For Obergum, the intervention for energy-efficiency is already programmed and it is also highly needed. Present conditions are uncomfortable and the heating system can hardly cope with the heat demand.

4. DISCUSSION

Traditional architectural-historical values did play a role in the valuations of the church, especially specific elements and historic value were mentioned. The valuation of the architecture ranged from valuing simplicity to considering the building as unimportant safe for its acoustics. In Obergum, the informant defended the authenticity of the church and rejected interventions which might compromise the walls. Considering registers of valuing we acknowledge several clusters of valuation, which can be related to actors' interests. For the 'history buff' the historical qualities of the church are its main attraction, including valuable elements. The 'community organizer' is primarily interested in what the church can do, as a meeting point, a place for cultural events, concerts. The 'spiritualist' is looking for religious or spiritual inspiration and values the atmosphere of peace and quiet. On a personal level this is related to personal memories or religious nostalgia. Economic benefit was not a very prominent motivator, only as far as the benefits are necessary for the upkeep of the building.

Figure 3. Church Lettelbert

In keeping with the 'heritage as a spatial vector' approach, the position of the interviewees seemed of importance. In Nieuw Scheemda and Obergum we have the impression that they were following a group agenda, instead of expressing personal values. Environmental consciousness was related to the level of education, with higher education leading to a greater interest in saving energy. Specific values can be related to a community perspective and the role the church plays in this community. The church in Lettelbert as painting school has become an important element in community identity and emotions. Also in the other cases the church is integrated in local activities and is a highly valued part of the local network.

Figure 4. Church Obergum

The present state of the building and the frequency of use obviously influence the need for energy retrofit. Therefore, Lettelbert and Obergum require the most attention for thermal upgrading. In the case of Nieuw Scheemda interviewees were very perceptive of the economic costs of the proposed interventions, even though the committee itself does not have to pay for restoration work. This probably also relates to the very low use frequency of five times a year.

We conclude that for a more balanced approach, laypersons' valuations of historical buildings should be further integrated in heritage studies. In particular, community values need to be more fully addressed in value assessments.

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Standardizing the indoor climate in Swedish churches: opportunities, challenges and ways forward

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Abstract – *Standardization for indoor climate control in historic buildings have recently taken a new direction with standards and guidelines that focus more on decision processes than outcomes. The objective of the paper is to explore and discuss how standards can evolve to both fit and guide decision processes to facilitate a sustainable management of Swedish churches. Interviews with engineers and heritage professionals in the Church of Sweden in combination with indoor climate monitoring were used to understand the technical and organizational context. The results show that the development of process standards solves some of the problems related to the conventional outcome-oriented approach by opening up for a wider set of solutions. However, available guidelines are difficult to apply and integrate in the existing management of churches. A stronger focus on strategic feedback and an increased use of local guidelines are suggested.*

Keywords – Indoor climate control; process standards; knowledge sharing; sustainable management

1. INTRODUCTION

To determine an indoor climate control strategy is oftentimes a complex task, involving social as well as technical dimensions: conflicting objectives have to be negotiated, facets of management that commonly are separated have to be involved and different types of expertise is needed[1]. Simple, generic advice is often not sufficient to guide decisions. Hence, the sharing of scientific knowledge and best practices, and their uptake in decision processes are paramount for the implementation of more energy efficient solutions. However, the way scientific knowledge is utilized in these processes is poorly understood.

Universal advice regarding set points for indoor climate has substantial shortcomings [2–4]. It therefore seems to be wise to produce standards that support decision making, rather than forego it. The diversity of historic buildings, collections and the ways they are managed imply that the decision processes regarding indoor climate control unfold in myriad ways dependent on the specific contexts. Hence, it is unlikely to find a simple, generic roadmap for the decision process to establish an indoor climate control strategy. In practice, such processes are often intertwined with other planning and management activities [1].

The objective of the paper is to explore and discuss how standards can evolve to both fit and guide decision processes to facilitate a more energy efficient management of Swedish churches. To achieve this objective, we discuss the recent progress in the standardization of indoor climate control for historic buildings in general and the European standardization of the indoor climate in churches in particular. The church of Sweden is then used as a case study in which we outline both the organizational and technical contexts in which standards are to be implemented.

2. RECENT DEVELOPMENT OF STANDARDS FOR INDOOR CLIMATE CONTROL IN HISTORIC BUILDINGS

The aspiration of standard makers has generally been to identify safe ranges based on scientific evidence, or, when science has been unable to deliver enough facts, on precaution in combination with practical experience and the potential of existing technologies [5]. Efforts to specify single, universal, “ideal” targets have been persistent despite “a steady undercurrent of thoughtful critique” [3]. In the last years there has been an intensified discussion about the optimal set points for T and RH in museums and archives, fuelled by the wish of cultural institutions to become more environmentally sustainable [4]. The scientific community is now increasingly focused on a better understanding of damage functions with the intention to inform evidence-based risk assessment e.g. [6].

Even though the discussion of set points historically has been, and to some extent still is, focused on “proper” museums, it is relevant for historic buildings housing collections, such as churches or historic house museums. Historic buildings have been treated as exceptions to the rule, which require special treatment. Suggested targets in standards and guidelines for museums and archives have sometimes been perceived as unachievable ideals to strive for. The pragmatic way to address historic buildings in standards has been to widen the allowable climatic range used for museums, accepting a slightly higher level of risk. In the following, four recent standards with bearing on churches are briefly presented.

The 2003 revision of the *ASHRAE handbook* was based on a risk management approach to preventive conservation [3]. The handbook provides heuristics to support decision-makers as well as generic advice in the form of target specifications for different levels of risk. It emphasizes the negotiability of the end result as well as the limitations given by different types of building envelopes and climatic conditions.

The European standard *EN 15757:2010 Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials* describes a methodology to establish allowable fluctuations based on the historical climate. It is based on the assumption that objects in the collection have adapted to their environment and that by limiting deviations from the historical climate there will be less risk for further damage. The standard opens up for a wider range of outcomes by taking the specific conditions of the individual building as the point of departure.

The limitations of standards that attempts to give universally valid recommendations about outcomes have resulted in a development towards standards that focus on decision processes. The European standard *EN 15759-1:2011 Guidelines for heating of churches, chapels and other places of* *worship* describes in its first stage a process for how to establish a target indoor climate, but does not suggest any numbers. In essence, it describes a procedure that needs to be followed rather than suggesting the outcomes.

The *UK PAS 198:2012 Specifications for Managing Environmental Conditions for Cultural Collections* outlines a risk-based framework for indoor climate management. There is an emphasis on how to achieve low energy strategies. The standard does not suggest target specifications but it is, in the same way as the ASHRAE handbook, accompanied by a summary of existing knowledge regarding damage functions in an informative annex. The scope of this standard is somewhat broader than the ASHRAE handbook or EN 15759-1:2011: it includes both the overall management process and the decision process to determine target specifications.

These examples show how standards have evolved from simple prescriptions of universal specifications to become more sophisticated, informative and flexible. The scope of standards is shifting: there is a tendency to standardize processes on behalf of outcomes. There is a need to advance the understanding of the role of standards as decision support tools. To become useful, process standards have to be complemented with both expert knowledge and value judgements. There is ample evidence that a successful development of decision support presupposes a sound understanding of the decision context, both regarding organizational and technical aspects [7]. If the organization adopting the standard lack the resources needed for a successful use of a process standard, it might not lead to improvements.

3. CASE STUDY: INDOOR CLIMATE CONTROL IN SWEDISH CHURCHES

There are no national standards for the indoor climate formally endorsed by the Church of Sweden. Considering this situation there is a timely opportunity to discuss the recent development of indoor climate control standards from the viewpoint of the organization as a whole.

3.1 Traditional outcome-oriented standards

In this section we discuss the application of two outcome standards (ASHRAE handbook and EN 15757:2010) in Atlingbo church, situated on Gotland in the Baltic Sea. We derive target specifications from the standards, and then discuss the practical consequences from a hypothetical implementation of these targets. Atlingbo church is used as an example of problems related to intermittent heating in a humid stone church, however based on the author´s experiences from monitoring the indoor climates in Swedish churches we suggest that the discussion points at problems that are relevant for many other churches in Sweden.

The application of the specifications from ASHRAE handbook depends on the chosen climate control class. Class C requires that RH is lowered below 75 % for extended periods which would require dehumidification or conservation heating during summer. This piece of advice is plausible for this church given the high risk for biodeterioration with the present indoor climate, but it will not lower the mechanical risks due to fluctuations caused by heating during winter. Maybe class B which is more focused on mechanical stability is more relevant, but such judgments necessarily require competent users of the standard.

RH and the target range proposed by EN 15757:2010 is shown in Fig. 1. The intermittent heating causes a number of excursions well below the suggested range. Hence, a compliance with the standard would limit the possibility of intermittent heating, which is currently considered a feasible heating regime for this church given its use and the cost for heating. To reduce the short-term fluctuations would most likely reduce the mechanical damage to artefacts in the church, but this has to be weighed against the expectations of thermal comfort and the financial situation of the parish.

This example illustrates how the seemingly simple adoption of plausible science based recommendations become difficult undertakings in practice. We suggest that this is a universal problem, rooted in the fact that there are conflicting objectives governing indoor climate control, and that the benefits derived are valued quite differently from case to case. In conclusion, we suggest that the following is important when using outcome standards: a) The user has to determine when the standard is applicable and for what purpose; b) The user has to be able to decide how the standard should be used, modify it based on the requirements of the specific situation and judge if the benefits of an implementation outweigh the costs; c) The standards will be most useful if used as decision support rather than as prescriptive formulas. Especially EN 15757:2010 seems to be most useful as a tool useful for identifying risky fluctuations.

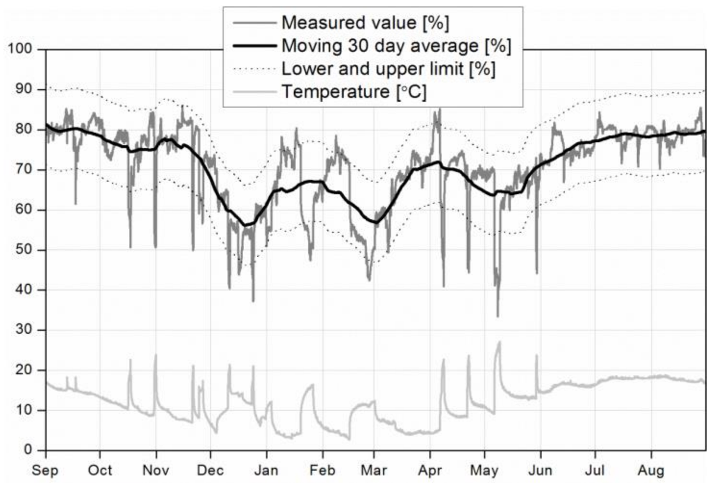

Figure 1. Allowable band of RH fluctuations according to EN 15757:2010 in Atlingbo church. RH data from the period 2009-09-01 – 2010-08-31. The logger was situated in the middle of the nave.

3.2 The organizational context of the management of Swedish churches: opportunities and challenges for future standardization

To further the understanding of existing decision processes regarding indoor climate control in the churches, as well as the role of standards in these processes, we conducted interviews with a group of professionals employed at the Diocese level. The individuals in this group consist of engineering and heritage professionals employed to support parishes with all aspects of the management of churches. In total, twenty interviews were made with engineers and building conservators employed at the Diocese level in the Swedish church. The interviews were made over telephone in 2014 and lasted about one hour each. A survey questionnaire was sent to the interviewees beforehand. The questionnaire consisted of questions related to indoor climate control and indoor climate related risks. All interviewees were probed to discuss the role and usefulness of standards, irrespective if they were used in the Diocese or not.

Only one of the interviewees reported that indoor climate standards were used in a deliberate or systematic way. The most common rationale for the unwillingness to use standards was that they were perceived as too general and not customized for churches. Handbook recommendations found in the conservation literature, even those intended for historic buildings and churches have been so far away from the actual conditions in the churches that they have not been perceived as realistic.

The management of Swedish churches is to a large extent organized as a decentralized layman-led activity, both regarding decision-making and practical work. Organizational deficits, inadequate decision processes and a lack of in-house expertise were described as the most important barriers to improved indoor climate control. Organizational deficits were often mentioned in tandem with a lack of professional competence within the organization. The status of parishes as one-time clients with limited competence is a cause of an oftentimes weak position in relation to contractors. This situation leads to problems with the acquisition of new technical systems, which turn out to be overly complicated or inappropriate for the specific conditions.

Generally there is an organizational division between continuous daily management and more infrequent projects related to major changes of control strategies and/or technical systems. The organizational and financial framework favour that major changes of indoor climate control systems are made as part of a package of other renovation or conservation work. In these projects there is a different set of actors involved than during daily management. The decentralized structure and the division between daily management and one-shot projects make it difficult to systematically use feedback for continuous improvement. There is generally a lack of communication between the permanent organization responsible for daily management and the temporary organization that emerges in connection with renovation projects. The feedback loop between these two is weak or non-existent. This results in a problem with knowledge sharing within the organization as a whole.

The present situation, with a lack of systematic decision making, can to some extent be explained by a complex decision context with conflicting views on the use of the churches and many stakeholders at local, regional and national level. It is not clear where the responsibility for strategic planning of the indoor climate is or should be.

Based on the results of the interviews we identify three major issues for the Church of Sweden regarding the future of standards: a) The management processes for daily operation and renovation of indoor climate control systems are decoupled. Standards for indoor climate control have to address both processes, link them together and integrate them better with the regular management of churches; b) A lack of evaluation and feedback regarding indoor climate control is evident at both the level of individual churches, as well as on aggregated levels; c) There is a need for simple and unambiguous advice to support parishes. The lack of competence and lack of resources make demanding decision processes unattainable in most cases.

4. CONCLUSIONS AND WAYS FORWARD

For long, the purpose of an indoor climate standard was undisputed: to recommend targets for the indoor climate. Some recent standards, acknowledging the complexity of the problem, are deviating from this approach by focusing on decision processes. Instead of debating if one approach is superior to the other, standard makers and users of standards should embrace the idea that standards with different scopes can be used in parallel to serve different purposes at different levels of abstraction [8]. At the top level there can be management standards that define processes, duties and roles for the long term management. The decision process to come up with target specifications and technical solutions could be the scope of another standard. Outcome standards focusing on various damage functions could be used as decision support tools, complementing other sources of risk information. Finally, there will probably always be a demand for standards that give simple and universally applicable advice. We suggest that there is a need for all these kinds of standards; the question is when and how to use them. The idea of such a landscape of standards opens up for the individual standard to be more specific about its scope, and thereby more focused.

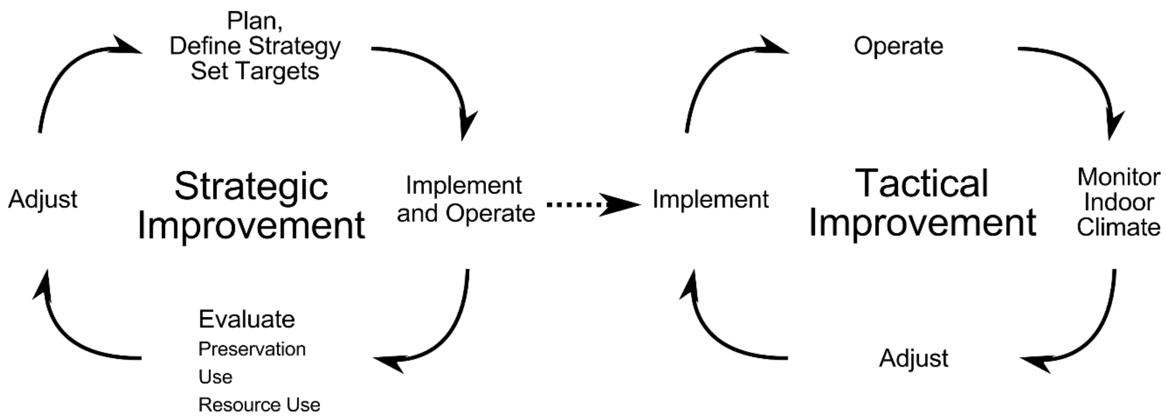

Figure 2. The two levels of continuous improvement for indoor climate control

If evaluation of indoor climate control systems are performed, it is almost exclusively to evaluate whether the indoor climate is in accordance with specified targets (tactical improvement), not whether the targets are the right ones (strategic improvement). This results in a situation where technical systems and control strategies are implemented, but it is not known if the consequences of the implementation are in line with strategic objectives such as energy use, preservation and use of the building. In order to achieve strategic improvement there is a need to use feedback of relevant parameters. We suggest that the addition of such feedback loops is both necessary and possible, and that the main feedback needed is about preservation, use and resource use (Fig. 2).

For churches which are similar in construction, use and geographic location there is a potential to use process standards to establish local guidelines for the set of churches in question (for example at the Diocese level). This simple solution could help to overcome the problem that process standards are time and resource demanding in their implementation. It would not be feasible to go through all suggested steps in a process standard such as EN 15759-1 for every Swedish church. However, there is an option to use a process standard to establish common advice regarding set points for a specific type of church, within the same climatic zone, with similar use and demands for thermal comfort. In reality such local praxis is already used in many Dioceses but it is not formalized and used in a systematic way. This approach would overcome some of the problems associated with the production of individual guidelines for each building which, given the decentralized management of Swedish churches and the lack of resources, almost certainly would fail.

Standards and guidelines are and will be an important tool for quality assurance in cultural heritage management. We have tried to point at some possible areas of improvement relating to indoor climate control of Swedish churches. However, the issues raised in this paper have bearing on other areas of cultural heritage management subjected to standardisation. While there is a discussion about the scope and role for standards in conservation, there is a lack of empirical knowledge on how standards actually are used in conservation, how they affect practices and the organizational processes that forms the infrastructure for decision-making.

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INVESTIGATION, DESIGN AND FEASIBILITY

Integrated diagnostic approach for the structural and energetic evaluation of historic buildings

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Abstract – *Concerns about the energetic sustainability of the existing building stock and about changes in both climatic conditions and comfort requirements, in recent years have put a lot of research focus on energy performance evaluation of our constructions, which also need periodic assessment of structural performances. Most often, historic masonry buildings present both structural and energetic deficiencies. Nonetheless, if carried out, commonly the diagnostic evaluation of these 2 aspects is undertaken separately. Instead, an integrated diagnostic approach considering several NDT techniques and advanced monitoring was developed in the frame of the 7th FP EU project 3encult to evaluate the health-state of historic buildings obtaining structural and energetic information before, during and after refurbishment. This novel multidisciplinary approach represents a first step towards a correct practice for historic buildings diagnosis and an example to be widespread, after careful translation according to the specific building under consideration.*

Keywords – Structural and energetic diagnose; non-destructive techniques; wireless monitoring system

1. INTRODUCTION AND AIMS OF THE WORK

Concerns about the energetic sustainability of the existing building stock and about changes in both climatic environmental conditions and indoor comfort requirements, in the last years have put a lot of research focus on energy performance evaluation of our constructions [1]. At the same time, when thinking about historic buildings, there is a need for periodic assessment of structural performance. Most often, historic masonry buildings present both structural and energetic deficiencies and their health-state's knowledge is important both for their preservation and maintenance and to design proper requalification or rehabilitation interventions. Nonetheless, if carried out, commonly the diagnostic evaluation of these 2 aspects is undertaken separately, independently, and at different time points, commissioned by figures with diverse expertise. Hence, usually there is neither dialogue nor comparison of outcome. Given the historic buildings preservation requirements, non-invasive methods and monitoring techniques are to be preferred [2]. Thus, in the frame of the 7th FP EU project 3encult, the authors proposed an integrated diagnostic approach for evaluating the health-state conditions of historic buildings both from a structural and energy-based perspective. The developed diagnostic procedure combined several NDT techniques used in innovative and non-conventional ways with innovative wireless monitoring systems, also used unconventionally. The comprehensive diagnosis was repeated in different phases of buildings' interventions. This paper is aimed at presenting the novel multidisciplinary approach throughout its application in a case study as it represents a first step towards a correct practice for proper and complete diagnosis of historic buildings being an example to be widespread. The recommendation is to carefully translate it in different, appropriate ways according to the specific building considered.

2. INTEGRATED DIAGNOSTIC APPROACH FOR HISTORIC BUILDINGS

The integrated diagnostic procedure presented in this work was developed in the frame of the recently concluded 7th FP EU project 3ENCULT, which was focused on energy efficiency improvements in historical buildings and on bridging the gaps between cultural heritage and climate protection. These purposes were pursued throughout a multidisciplinary approach, by encouraging and establishing a dialogue between parties and figures of different expertise and by considering 8 diverse case studies located all over Europe [1]. Within this research project, in order to reduce the energy consumption and greenhouse gas emission of historic constructions, to improve their energy efficiency and the users' comfort, on the one hand, existing approaches, tools and solutions were employed and adapted to the specific buildings; on the other hand, new methods, procedures and technical solutions were on-purpose developed and tested, always bearing in mind the needs for the preservation of the structures and artworks belonging to them [3]. In this context, diagnosis and monitoring played a key role, being of fundamental importance in all the building's intervention phases. Results of diagnosis and monitoring were intended to be used: i) for evaluating the starting conditions of the constructions both from a structural and energetic viewpoint and pointing out their deficiencies and strengths; ii) for planning the interventions and selecting the best retrofit solutions, also considering the current and future destination use of the buildings and iii) for assessing the performances of the implemented solutions at the end of the interventions [1]. These complex tasks needed multi-step approach and multi-disciplinary competences. For these purposes, the authors developed a diagnostic procedure by considering several non-destructive techniques and advanced monitoring methods, used in an innovative, combined and comprehensive way. An effort was made to further develop existing non-destructive diagnostic techniques, monitoring and testing procedures and to link different aspects -structural, energetic and comfort- in a holistic viewpoint. The proposed diagnostic methodology is herein described for a historical masonry building located in Bologna, Italy [4].

3. THE LIVING LAB OF PALAZZINA DELLA VIOLA

3.1 Brief description and history of the case study

The Palazzina della Viola, a 15^{th} C. light masonry building property of the University of Bologna, was revived after several years of abandon, thanks to 16-month refurbishment works. It now accommodates the headquarters of the Department of International Relations of the University (Fig. 1 centre). All the phases of the extensive rehabilitation and restoration works underwent by the building were closely monitored during the time frame of the 3encult project, although the research team was not involved in the interventions' design which was completely defined a few years earlier [4].

The Palazzina della Viola, a "jewel of the Renaissance art", was built in 1497 by Giovanni II Bentivoglio, on the edge of the city as a little hunting hut and leisure retreat. After several modifications and changes in the destination use occurred during the centuries, since 1803 it hosted the Agriculture Faculty of the University of Bologna with the adjacent Botanic Garden (Fig. 1 left). It is qualified as *building of historical and architectonic interest* in the Urban Building Regulation Code; therefore it admitted only respectful renovation and maintenance interventions which can preserve the original integrity of every architectonic, artistic and decorative elements of the building. This isolated, self-contained masonry building has a quadrangular plan, with 3 façades lightened by a double open gallery and it is enriched on the ground level and 1st floor level by frescoes and painted wooden ceilings dated back to the 15th – 16th C., attributed to Amigo Aspertini and Prospero Fontana among others (Fig. 1 right). The building is South- East oriented and shaded by trees on all sides with the exception of the South side where there is a meadow [4].

Figure 1. Palazzina della Viola in 1906 (left) and current state of the building after refurbishment works: main façade (centre) and front loggia (right)

3.2 Pre- and during intervention diagnosis and monitoring

Before the refurbishment works, the Palazzina della Viola showed several conservation problems concerning the structure (like cracks on walls and ceilings, moisture and salt rising in masonry walls), the frescos (due to indoor humidity, temperature variations and lighting) and related to energy efficiency (e.g. wide surface of windows, windows with single glazing, inadequate heating/cooling systems, etc.). To obtain a preventive knowledge of the building and simultaneously evaluate its energy performance and structural behaviour, it was followed an on-purpose developed diagnostic procedure [1]. The analyses were repeated prior to and during the interventions to monitor also the effects of the restoration works on both the building structure (i.e. by monitoring the vibrations and openings of cracks) and the delicate objects belonging to it, for example, by monitoring the environmental parameters and evaluating if the conditions for the right conservation of frescoes were respected during this time frame [4]. Energy demand and inefficiency of a building is strongly connected to its fabric and the comfort and needs of its users [3, 5]. Thus, the multi-phase diagnostic methodology employed was tailored on the specificities of the building materials, on the construction type, on the interaction between the building site and the surrounding environment, on the use destination (past, present and foreseeable future) and in view of expected users' comfort requirements (i.e. heating/cooling demands, daylight needs). Hence, the first part of the diagnostic phase was dedicated at evaluating the building's characteristics and peculiarities. It was based on visual inspections and searching for historic and archive information (photos, drawings, information about previous restoration works …), followed by geometric and materials surveys as well as decay and crack pattern surveys. For obtaining an overall picture on the building's starting conditions also from an energetic perspective, a search for previous energy consumption was carried out and the existing heating/cooling systems and lightening were examined, revealing their inadequacy and obsolescence. A detailed survey of the peculiar glazed façades which cause a sort of "greenhouse effect", pointed out the presence of very many types of windows' frames, diverse for materials – steel, wooden –, age and dimensions, and glasses (single, double, printed, …). Consistent air leakages areas were also clearly detected, i.e., in correspondence of the historic windows frames around the columns of the front loggia at the 1st floor of the building [4]. Moreover, instrumented monitoring systems and non-destructive techniques were combined to complete the diagnosis, after having extended the research aims of NDTs commonly used for structural investigations to energetic problems, instead of characterizing the energy behaviour of the building only throughout estimations from numerical simulations [5]. First of all, to analyse the micro-climatic conditions of this historic building as-it-is, daylight measurements and thermo-hygrometric surveys were carried out via portable instruments and repeated several times, in varying boundary conditions (i.e. closed/open doors; closed/open curtains,…). As an example, air temperature and relative humidity values were collected via a portable thermo-hygrometer at the discrete nodes of grids -previously marked on floors in each room of the building- in order to create psychrometric maps at diverse heights from the ground. The resulting maps clearly showed the non-uniform distribution of both parameters between the diverse rooms of the building even if located at the same floor, highlighting overheating areas and dry zones. For example, the maps recorded in winter, without heating system and with all doors closed showed air temperature differences of about 4°C and relative humidity differences of about 30% between the rooms at the ground and 1st floor, respectively (Fig. 2 left and centre). Among the available NDT techniques for the diagnosis of buildings, IR thermography [6-7] and GPR radar [8-9] were selected and used to collect reliable information about the building structure and health-state conditions (structural details of ceilings and walls, moisture problems, thermal bridges, …) without provoke any damage neither to the structure nor to the delicate elements belonging to it, like frescoes, paintings and painted ceilings. For example, by IR investigations on exterior walls, moisture-related problems, due to leakages from the roof and damp rise from the foundations were identified in the building rear side (Fig. 3 left and centre). More typical energy-related on-site tests like blower door tests or air flow dynamics were also considered, but following specifically developed testing procedures [4]. The blower door test is commonly carried out in new buildings [10] to measure their airtightness level but there is no standardised procedure for its application in historic buildings. Thus, herein, to obtain measurable pressure differences, it was necessary to follow a specific procedure and to repeat the test in sub-areas of the structure because of the large volumes involved (i.e. volume of main hall at 1st floor: 670 m^3) and the presence of consistent

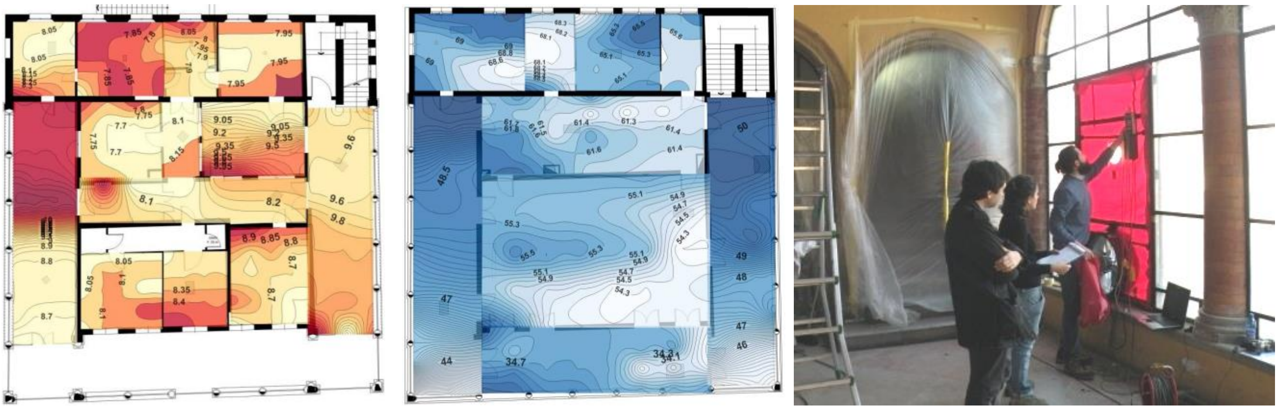

Figure 2. Psychrometric maps of air temperature at the ground floor (left) and air relative humidity at the first floor (centre), both collected with all doors closed; a phase of the blower door test at the ground floor (right)

Figure 3. IR thermography investigation pre-refurbishment condition: detection of moisture in the exterior wall, rear side (left and centre); post-refurbishment IR investigation of thermal bridges: concrete stairs landing (right)

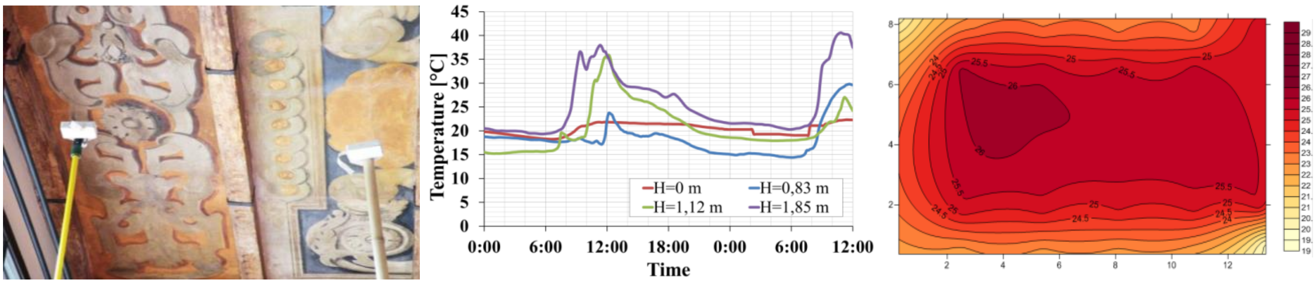

Figure 4. A phase of data acquisition with movable nodes (left), variation of air T with height (center), map of air temperature at 1.75m height (May 2012) (right)

air losses, not only through the historical window frames but also trough wooden ceilings and walls' cracks (Fig. 2 right). Innovative measurements of the air flows gave additional important information from an energy viewpoint, as by combining IR and white stripes, it was possible to experimentally obtain a visualization of warm and cool air fluxes between large volumes typical of historic buildings, up to now achievable only via complex dynamic modelling [11]. The overall picture of the building health-state conditions pre- and during-interventions resulted from the combination of the diverse diagnostic and monitoring techniques outcomes with several energy efficiency calculations (i.e. PHPP) [1] and with the data from continuous monitoring of environmental parameters performed via an innovative wireless sensor network (WSN). The latter, specifically targeted for historic buildings, was developed by the researchers of the DEI Department of the University of Bologna and in its final version consisted in 36 nodes, distributed in the four levels of the building, from the basement to the attic. Each node was equipped with sensors for the continuous monitoring of environmental parameters such as air temperature, air relative humidity, ambient light and accelerations along three axes [4].

3.3 Post- intervention analyses and monitoring

After the refurbishment works, which included structural consolidation, preservation of frescoes and energy efficiency improvements (such as improvements of light systems; new heating/cooling systems; installation of domotic controls, installation of curtains…), the health-state conditions of the Palazzina at this time period were evaluated similarly to what described above. The aims of the diagnosis were also to assess the performances of the adopted solutions, the quality of the interventions and the users' comfort. Moreover, some specific additional aspects i.e. related to air exchange and movements between large volume rooms were also studied by repeating some non-destructive tests or monitoring evaluations [4]. As an example, IR thermography investigations at the end of the works were mainly intended to evaluate the effectiveness of the renovations, the possible presence of thermal bridges i.e. in correspondence of steel beam-ends [1] and also at investigating structural configurations (Fig. 3 right). As already mentioned in the previous paragraph, the complete version of WSN was installed at the end of the interventions, and the 144 sensors were collecting data since March 2012 until 2015. An added value of the presented diagnostic procedure was represented by the use of these nodes as they were employed not only to collect data in "static" positions but some of them were used as mobile monitoring stations. The "mobile" configuration was employed for specific measurement campaigns or i.e. innovative dynamic environmental focused monitoring to create profiles or 2D maps of specific parameters (Fig. 4) [12]. The results of the long-term monitoring in terms of distribution maps of daylight, air temperature and relative humidity at various levels from ground, are useful for evaluating risk to Cultural Heritage and level of protection needed for delicate artefacts, as well as discomfort of working conditions [12]. The final phase of the post-refurbishment evaluation involved directly the users of the Palazzina della Viola which, through an on-purposes implemented on-line questionnaire were asked to anonymously give feedbacks about their workplace, thus acting as living sensors. The questions concerned a variety of aspects starting from the users' perception of their peculiar workplace which is inserted into a historical building, to their opinions about the implemented solutions for saving energy, i.e. regarding the domotics installed in the building to control lights, heating/cooling, etc., and to their current comfort conditions…The questionnaire was important not just to complete the diagnose of the building but also as a first step in establishing a necessary, continuous dialogue between the designers and the users.

4. CONCLUSIONS

An extensive and integrated approach for the structural and energetic diagnosis of historic buildings was developed in the frame of the 7th FP EU project 3encult and herein presented with reference to a case study of Cultural heritage. The multi-step approach proposed was used to evaluate the building health-state conditions at different time periods: before, during and after interventions. Several non-destructive diagnostic techniques were employed in innovative and non-conventional ways, following specific and on-purpose designed procedures to obtain information both from structural and energy perspectives. These were combined to an advanced wireless monitoring system installed in the building, which was also used unconventionally, i.e. to monitor air flow dynamics. The post-refurbishment diagnosis and monitoring phases together with the collection of the users' opinions (acting like human sensors) represented an added value of the proposed methodology. This integrated approach can lead to a new correct practice for a proper and complete diagnosis of both historic and existing buildings. It could represent an example of good practice to be widespread, with the recommendation to carefully translate it in different, appropriate ways according to the specific case considered, by employing the diverse possibilities and diagnostic methodologies as shown as a whole.

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Guidance for finding a sustainable balance between energy efficiency, comfort, moisture damage and cultural heritage value in historic buildings

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Abstract – *On the occasion of a study on the energy retrofitting of typical Alsatian historic buildings, a guidance has been developed to find a sustainable balance between energy efficiency, comfort, moisture damage and heritage value. Seven typical Alsatian historic buildings have been monitored and analysed before retrofitting in order to evaluate their weakness and strong points on five criteria. Then, a set of thermal and hygrothermal simulations and an architectural assessment have been performed to build and evaluate four global retrofitting scenarios: high energy efficiency with eco-materials, balance between energy efficiency and heritage conservation, and high heritage conservation. A web publication headed to Alsatian private individuals shows the results as spider charts and costs estimations.*

Keywords – Historic buildings retrofitting; public decision support tool; multi-criteria analysis

1. INTRODUCTION

As newly-constructed buildings consume less and less energy, improving energy efficiency of existing buildings has become a real concern to continue to reduce significantly the consumption of the building stock. But those built with vernacular materials such as stone masonry, bricks and mortar or wood and daub, have to be dealt with great care because of their sensitivity to moisture [1]. Also, they could often offer high cultural or architectural values that cannot be altered. This kind of buildings represents a third of the French existing stock of buildings [2]. Knowing that, any retrofitting measure can create a risk for the heritage value and the sustainability of the building.

The National Association of Cities and Countries of Art and History has developed a guidance for its members, on how to conduct a study on the energy retrofitting of their historical centre [3]. To help this time private individuals to retrofit their housing without damages, the local representatives of the French Ministry of Cultural Affairs and Ministry of Sustainable Development in the Alsace region have developed a more detailed guidance [4], based on [3], for finding a sustainable balance between five criteria: energy savings, thermal comfort in winter and in summer, moisture damage and heritage conservation. To assess these criteria, a multidisciplinary team has been formed, including building physics engineers, a local heritage architect and construction economists.

2. METHOD

This guidance has been applied to the “Habitat ancien en Alsace” study. It consists in two phases: a first phase of diagnosis of the thermal, hygrothermal and heritage situation and of the state of conservation of the building before retrofitting and a second phase of solution proposals that generally improves the thermal situation while not damaging the hygrothermal and heritage one.

Twenty different types of typical Alsatian historic buildings have been identified in the study. Seven of these types, which are the most representative of the Alsatian culture, have been studied. Real buildings, corresponding to these types, have been searching for, with some restrictions: they had to be occupied all year, with no retrofitting carried out and without wood-heating (because energy consumption prediction is not enough accurate in this case).

As every building is a particular case, diagnosis and solution proposals will differ from one building to another and suppose at every step a close collaboration between all members of the team, especially the building physics engineer and the heritage architect.

2.1 First phase: evaluating strenghts and weaknesses before retrofitting

2.1.1 First step: making the diagnosis of the heritage situation

First of all, a case-by-case inventory of what make the buildings representative of the Alsatian culture has been drawn up. All composing materials of the buildings envelope have been identified. Plans, cross-section views and constructions details have also been realised.

2.1.2 Second step: making the diagnosis of the state of conservation

If moisture damage occurred, causes are investigated. Components in poor condition are identified and the question of knowing if the buildings will fit to their intended future use is debated.

2.1.3 Third step: making the diagnosis of the thermal and hygrothermal situation

The real buildings have then been monitored during a winter period, in order to provide input data to dynamic thermal and hygrothermal simulations. Temperature has been measured in all rooms, an airtightness test of the housing has been conducted and occupancy has been measured by a survey. All systems have been identified and heating and hot water production bills have also been collected on a period of three years.

The dynamic thermal simulation has been conducted with the software Pléiades+COMFIE [5] and the dynamic hygrothermal simulation has been performed with the software WUFI 2D [6].

2.2 Second phase: proposing sustainable retrofitting scenarios

2.2.1 First step : drawing up the inventory of retrofitting actions

A large inventory of retrofitting actions has been drawn up, for each building envelope component (walls, ceilings, floors, windows) or the building services (ventilation system, heating and hot water production system). All these actions are supposed to be carried out professionally.

2.2.2 Second step : evaluating each action regarding five criteria

Five criteria have been defined : energy savings, thermal comfort in winter and in summer, moisture damage and heritage conservation. Each action is evaluated according to expert judgement. An action is excluded when it is considered incompatible with a sustainable retrofitting scenario.

2.2.3 Third step : creating retrofitting scenarios based on the remaining actions

Based on remaining actions, retrofitting scenarios with a sustainable balance between the five criteria are created and discussed between all members of the team:

- The first one is the most efficient in terms of energy savings : all components are insulated and all systems are replaced with more efficient ones in order to divide by 4 energy consumption when possible. Ecological or mineral and moisture-permeable insulation materials are selected.
- In the second one, components through which heat loss rate is higher than 20 % are insulated. Other components have their airtightness improved and all systems are replaced.
- The third one is the most efficient in terms of heritage conservation : only floors and ceilings are insulated when possible (if not, an other action is proposed), other components have their airtightness improved and all systems are replaced.

2.2.4 Fourth step : evaluating each scenario regarding five criteria

For each criterion, all scenarios receive a rating. Ratings (Table 1) are based on:

- energy savings: the primary energy consumption for heat and hot water production and air conditioning (on which the French energy performance certificate is based), called *ec*;
- thermal comfort in summer: the annual number of hours with an interior air temperature above 27 °C, called *n*;
- thermal comfort in winter: the average interior wall surface temperature, called *Tsurf*;
- moisture damage: the average relative humidity in materials such as brick, stone, mortar and daub, called RH, and the average water content in mass percent in wooden materials (timber frame, end piece of a clamped beam) of an external wall, called *w*;
- heritage conservation: a weighted average between the heritage conservation ratings of each action (concerning walls, ceilings, floors, windows, ventilation system, heating and hot water production system) selected in each scenario, called *av*.

Table 1. Evaluation of the five criteria on scenarios

Criteria	**Ratings**			
	3	*2*	*1*	*0*
Energy savings	ec ≤ 90 kWh/m².yr	90 < ec ≤ 150 kWh/m².yr or 150 < ec ≤ 230 kWh/m².yr with a 38% decrease compared to the reference	150 < ec ≤ 230 kWh/m².yr	ec > 230 kWh/m².yr
Thermal comfort in summer	n ≤ 50	50 < n ≤ 100	100 < n ≤ 150	n > 150
Thermal comfort in winter	Tsurf > 18°C	16 °C < Tsurf ≤ 18°C	12 °C < Tsurf ≤ 16°C and improvement of airtightness of the walls	Tsurf ≤ 12°C or 12 °C < Tsurf ≤ 16°C and no improvement of airtightness of the walls
Moisture damage	HR ≤ 85% or w ≤ 20% in all materials	HR > 85% or w > 20% in one material	HR > 85% or w > 20% in two materials	HR > 85% or w > 20% in three materials
Heritage conservation	av > 2.5	1.5 < av ≤ 2.5	0.5 < av ≤ 1.5	av ≤ 0.5

Table 2. Evaluation of the heritage conservation criterion on actions concerning walls

Ratings			
3	*2*	*1*	*0*
No impact on living area and conservation of exterior and interior original finishes (exterior renders, interior plasters) and elements (ceiling moulding, woodwork) of the walls. Restitution of elements with the original material.	Minor impact on living area and conservation of exterior original finishes and elements and modification of interior original appearance while conserving original elements and allowing a traditional finish.	Negative impact on living area and conservation of exterior original finishes and elements and modification of interior original appearance while not conserving original elements. Modification of exterior original appearance and elements of the courtyard-facing façade of the building.	Modification of exterior original finishes and elements on house and on the street-facing facade of the building.

Table 2 is an example of the evaluation of the heritage conservation criterion on actions concerning walls, which meets the heritage conservation challenges in the Alsace region.

A spider chart summarises the evaluation of each scenario regarding the five criteria and compares it to the reference before retrofitting.

Finally, three economic indicators have been calculated: the total cost in €/m², the annual heating and hot water production bills in 2015 and 20 years later and with or without retrofitting (with an 8% rate increase of fuel prices) and the monthly payment of a credit took out to pay for the retrofitting works.

3. RESULTS

To illustrate the guidance, the case of a one-hundred square meters' apartment in Strasbourg, situated in the second floor of a Haussmannian brick terraced building of three, is studied.

The first phase showed that:

- the housing has wooden floor and baseboards, ceiling mouldings, woodpanels under windows and single-glass wooden windows with glazing bar;
- the primary energy consumption is 163 kWh/m².yr;
- heat losses by air infiltration takes first place (40%), followed by walls (25 %) and windows (24%);
- before retrofitting, there is few risk of moisture damage;
- thermal comfort in summer is very good, while in winter, it is rather poor.

Here is a description of the three scenarios that result from the second phase of the guidance:

- In the first scenario, walls are insulated on the inside with mineral and moisture-permeable insulation boards and plastered with a lime-based plaster. Baseboards, ceiling mouldings and woodpanels under windows are restored. Floors and ceilings are not insulated, because they are adjacent with other heated apartments, but their airtightness is improved. Simple-glass windows are replaced by double-glass ones and the front door by an insulated one, but always in accordance with their original style (in wood, with glazing bar, with identical profiles) and shutters are maintained. An air extraction system is installed in bathroom and kitchen and air inlets are integrated to the windows. A condensing fuel boiler is also installed.
- In the second scenario, walls are not insulated but plastered with a moisture-permeable insulated plaster. Windows and front door are not replaced but their airtightness is improved. The rest of the scenario is identical to the first one.
- In the third scenario, exterior wooden windows with single-glass and glazing bar are installed. Walls are not insulated but their airtightness is improved. The rest of the scenario is identical to the second one.

Ratings and economic indicators for the three scenarios can be found in Tables 3 and 4:

Table 3. Ratings for three scenarios for the Haussmannian apartment

Criteria	**Scenarios**			
	Reference	*Scenario 1*	*Scenario 2*	*Scenario 3*
Energy savings	1	3	2	2
Thermal comfort in summer	3	3	3	3
Thermal comfort in winter	0	3	2	1
Moisture damage	3	3	3	3
Heritage conservation	3	1.7	2.7	2.9

Table 4. Economic indicators for the three scenario for the Haussmannian apartment

Economic indicators	Scenarios		
	Scenario 1	*Scenario 2*	*Scenario 3*
Total cost	390 €/m²	270 €/m²	190 €/m²
Monthly credit payment took out to pay for the retrofitting works	230 €/month (with a 15-year credit and a 15-year sustainable development French tax credit)	220 €/month (with a 10-year sustainable development French tax credit)	160 €/month (ditto)
Economy on heating and hot water production bills	63%	45%	35%

4. DISCUSSION

In this case, the primary energy consumption before retrofitting is between 150 and 230 kWh/m².yr, which is what has been found for other apartments of the study, while the French average primary energy consumption of existing buildings is between 230 and 330 kWh/m².yr [7].

The scenarios 2 and 3 show that insulation is not the only way to improve energy consumption. In this case, using a moisture-permeable insulated plaster or installing double windows is enough to bring the energy savings rating from 1 to 2. Moreover, these two actions do not alter original elements as much as insulation, which gets consequently a bad heritage conservation rating.

Improving the airtightness of the housing envelope is another way to improve energy consumption without endangering its heritage value, but also at a lower cost. Indeed, in the study, air infiltration is often the first cause of heat losses for apartments and the second for houses, so repairing plasters, renders and windows and front door frames, filling cracks and closing unused chimney flues can be a first step to energy efficiency. A ventilation system has to be installed as a replacement.

It is surprising to see that thermal comfort in summer is always good, even with interior insulation, known to reduce thermal inertia of walls. Thermal comfort in summer is more altered in the other buildings of the study, when insulated on the inside.

All insulated materials that have been chosen in the three scenarios are moisture-permeable and guarantee no moisture damage in walls when carried out professionally, even with interior insulation, also known to induce internal condensation in some conditions [8]. In [9], Dugué et al. have shown that if moisture appears in the wall or in the insulation, these materials are able to redirect it to the interior or the exterior. Moisture barriers like vinyl wallpaper or cement render cannot be carried out at the same time, to avoid the accumulation of moisture.

Total costs of the three scenarios are close to what has been calculated for the other buildings of the study. But in this case, it is important to recall that walls have been insulated on the only two façades that look outside. This reveals that moisture-permeable insulated materials - which have been chosen - still are expensive and hardly can be applied on large houses at the present time.

More generally, the guidance that has been applied here would gain from being tested on real retrofitting projects. Additional studies may also help to improve the moisture damage and the heritage conservation criteria, since there is no standard on their scientific evaluation.

5. CONCLUSION

The study “Habitat ancien en Alsace” provided the opportunity for local representatives of both the French Ministry of Cultural Affairs and Ministry of Sustainable Development to work together. In particular, the architectural review board of Alsace has been associated. The study is a tool to convince private individuals that a balanced approach between energy efficiency, comfort, moisture damage and heritage value is possible and indispensable to carry out a sustainable retrofitting of Alsatian historic buildings. It has also been promoted in the Alsatian “Espaces Info-Energie” network, which provides independent and free advice to private individuals who have a retrofitting project.

The heritage conservation criterion developed in this study can easily be adapted to other regions and to other challenges. The guidance in itself can also be considered a starting point to elaborate more sustainable retrofitting scenarios that not only take into account energy efficiency, but also comfort, moisture damage and heritage value.

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Facilitating historic districts energy retrofitting through a comprehensive multiscale framework and its implementation in the EFFESUS DSS

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***Abstract** – The preservation of European historic cities relies in their capacity of surviving as living cities. The appropriate sustainable energy management can improve livability and quality of life of their citizens. Energy retrofitting of historic cities is basically a matter of sustainable management of its evolution. In order to support the decision making process, which will manage this evolution in a respectful and sustainable way, proper tools and technologies have to be structured, articulated and framed. Considering historic cities as complex energy and informational systems, a replicable methodological framework has been developed in order to facilitate urban energy retrofitting processes in their whole lifecycle from a multiscale perspective. Based on these principles and within this framework, the EFFESUS project (Energy Efficiency for EU Historic Districts Sustainability) has developed a Decision Support System that implements an ecosystem of methods and tools that allows the selection of the most suitable strategies.*

Keywords –Urban energy retrofitting; multiscale information management; CityGML; urban preservation; historic cities; multiscale framework

1. INTRODUCTION

The Amsterdam Declaration[6] established in 1975 that the protection of the social context of a historic area is as necessary as the material preservation of its buildings, turning the liveability into a requirement for the urban preservation. Sustainable energy management has been identified as a critical factor for the improvement of the liveability and quality of life of the citizens [1]. More recently UNESCO has highlighted also the importance of including sustainable principles in the management systems of its designated historic areas [2]. Preservation requires sustainability but, equally the preservation of our urban heritage is fundamental for the sustainability goals. As principle, since it maximizes the use of existing materials and infrastructure, reduces waste, and preserves the historic character [3], but also from a quantitative point of view since over 40% of the European housing stock was built before 1960 [4], 23% is pre-1945 [5] and a significant percentage of it has certain degree of heritage significance [6]. Sustainability and liveability are two modern concerns that are not unfamiliar to the historic cities. The traditional architecture was built bioclimatic by necessity, made by people in direct response to their needs and values in a time when energy was really a scarce resource [7]. The

[6] The Declaration of Amsterdam, adopted at the Congress on the European Architectural Heritage, Amsterdam (1975)

European experience shows that one of the key values of the historic cities is its capability to mutate and adapt to meet the needs of different times and this adaptability is what ensures the sustainability of any urban entity [8]. The preservation of our built heritage in this context cannot be a passive process, but rather a process of evolutionary improvement of historic urban systems to present time requirements (comfort standards, sustainability goals or energy efficiency objectives). A flexible framework can structure and support the decision making process which will manage this evolution in a respectful and sustainable way guiding and framing the adaptation and creation of proper tools and technologies. Taking into account the fact that the growing complexity and heterogeneity of the existing urban information makes proper information management crucial for the comprehensive sustainable rehabilitation processes [9] and considering that the improvement of the sustainability of urban building environments is basically a spatial decision process, there are two key factors that the framework has to contemplate: the information and the scale.

The first part of this paper proposes a comprehensive multiscale framework that will facilitate urban energy retrofitting processes in their whole lifecycle taking into account the energy and informational complexity of historic urban environments. The second part will give an overview of how the EFFESUS project has developed a Decision Support System (DSS) based on the previous framework and its implementation in the historic district of Santiago de Compostela.

2. A REPLICABLE METHODOLOGICAL FRAMEWORK FOR HISTORIC DISTRICTS´ ENERGY RETROFITTING

2.1 Methodology

Following research questions are in the base of the proposed framework: What are the requirements for a methodological framework that aims to articulate a comprehensive retrofitting process of a historic district or city? What is the logical structure of the process that ensures the coherence and long term sustainability? How is the information managed within this process in order to connect the different scales and phases? The literature review established the requirements that guided the design of the structure and consequently the development of the methodological framework. The validation of the framework has been carried out with its application in the EFFESUS project.

2.2 The information and the scale

Historic cities have not been strange to the trend of implementing sustainability and energy efficiency measures and strategies. The Edinburgh model [10], Retrofitting Soho [11] or the case of Santiago de Compostela [12] are noteworthy examples. But, lacking of a universal structure, they are too location specific to be easily replicable. More replicable methodological frameworks have been developed for urban heritage preservation in general [13] [14] but without the specificities of energy retrofitting. Another two limitations can be mentioned from these previous attempts. First, even though the importance of the information in urban regeneration strategies is highlighted, they do not envisage specific mechanisms or tools for an information management strategy integrated in the process, despite the fact that the informational complexity of historic cities as urban systems (due to their spatial, social and cultural richness, but also as result of their vulnerability) makes them special beneficiaries of information management strategies. Second, they did not contemplate a multiscale approach. The operative scale of energy retrofitting is the building, but it is proved that an approach from this scale is not the most optimal in reaching significant and cost-effective improvements [15]. In sustainable design the coordination and consistency between the different scales of intervention, from the macro (city) to the micro scale (buildings and components), in other words a multiscale approach, is a requirement [16], even more if we take into account that energy management is an interscalar topic [17]. For historic environments, a multiscale approach is even more necessary, as it enables a location specific heritage impact assessment that will support the identification of applicable strategies at element level in protected buildings and landscapes. Nevertheless, some lessons can be learnt from the previous initiatives and the literature review regarding a suitable framework: it has to be structured in phases and comprehend the whole cycle (from diagnosis to monitoring), has to be iterative and include feedback and monitoring mechanisms, and it has to be based on a careful analysis of the existing information for an integrated diagnosis.

2.3 Methodological flow and information flow

The proposed structure of the framework is based in the two main scales (the urban scale and the building/component scale), and the three main phases with six sub-phases. A diagnosis phase, where the modelling strategy that decides the way the complex urban reality is abstracted into a manageable, coherent, and predictive model is decided and consequently the current state identified. The decision making phase, where the strategic target and objectives are defined and the best strategies identified. And finally, the management phase, where the strategies are implemented and their performance monitored. In this phase, the structure is mirrored at building level in order to define an implementation methodology at building level, which can be seen in Fig. 1.

The interconnection between scales and the methodological continuity among phases can only be ensured managing the flow of information, since the methodological flow and the information flow are strongly interrelated. A single, logical, consistent source for all the specific information (geometric and semantic) regarding the historic city is required. This specific information is multiscalar (from urban scale to component level) and cross-thematic as includes information regarding four crucial domains: energy and cultural heritage characteristics of the building and district, indicators that measure the implications and impacts of the different measures, and dynamic data for monitoring important criteria. Within European historic cities a wide range of scenarios of information availability can be found [18], therefore the replication possibilities are highly linked to the flexibility of the system regarding initial information requirements. Different levels of decision making (LoDM) have been established depending on the information availability and the stage of the process [9]. These LoDMs range from low levels (LoDM 0 and I) where only general information regarding the city is necessary and just generic strategies are provided to medium-high levels (LoDM II and III) where an external data model is necessary to structure the information and tailored strategies are provided. The two highest levels can be considered as part of an incremental strategy of use of information: LoDM II addresses the agile generation of a basic functional model and LoDM III operates with a fully complete model. The strategy based on different LoDMs offers flexibility and continuity between the different levels of information, optimizes data acquisition when the available data are scarce and reuses existing information infrastructures when available data are rich. An interoperable multiscale information model that structures all the necessary information of the district in all the phases and that integrates information from different fields is the way to support this strategic information management [19]. Fig. 1 describes the structure and the methodological and informational flow of the framework.

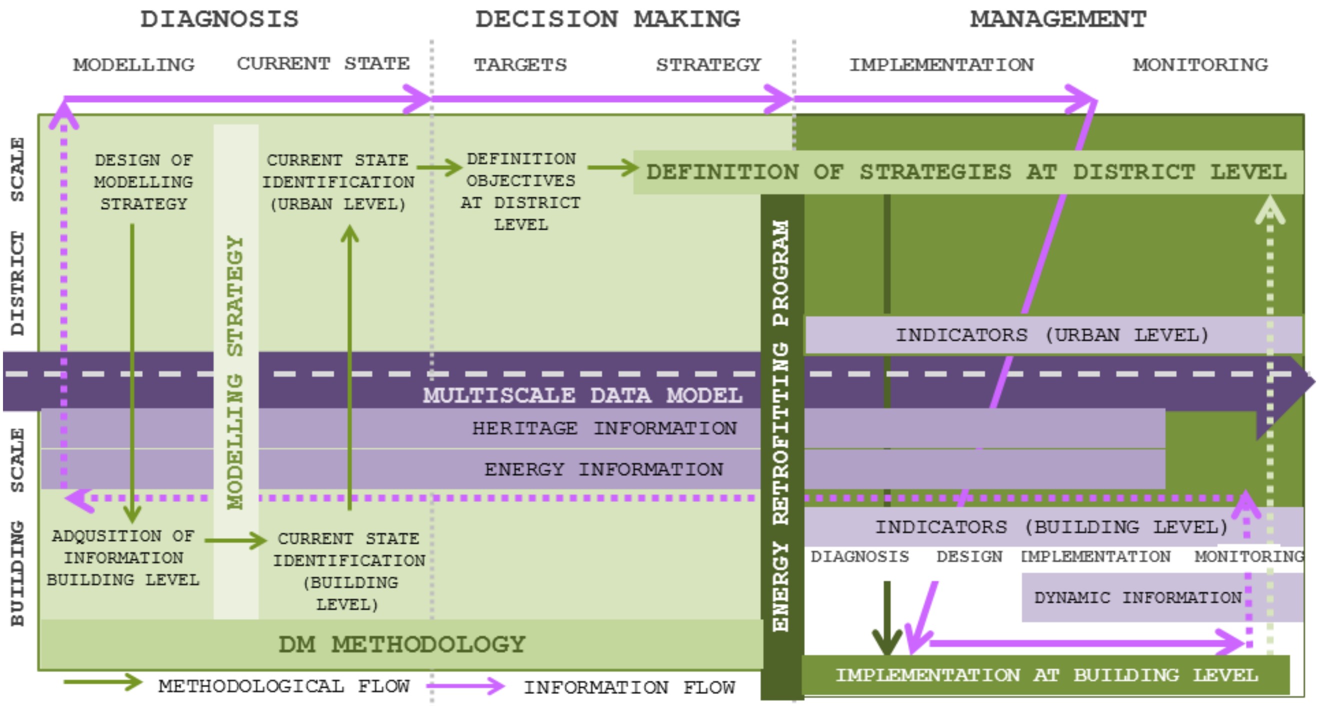

Figure 1. Methodological framework for historic districts energy retrofitting

The first phase for the required integral diagnosis is the design of the modelling strategy. At medium levels of information (LoDM II) the strategic scale can target the data acquisition at building level by selecting proper modelling strategies that operate with basic data easily acquired from public databases and from the geometry of the multiscale data base (e.g. year of construction, area, degree of heritage protection or exposed building surfaces). Two of these modelling strategies are to categorize the buildings in order to select representative sample buildings or to prioritize vulnerable building groups based on the basic data. At higher levels of information, when databases containing information regarding the buildings are available, the multiscale data model can be completed with much more detailed information allowing an automatic processing of those data to form the urban level vision. Since the global diagnosis have been constructed starting from the building level, in the posterior decision making phase, the strategic decisions at urban level (e.g. accorded global goals and decided packages of measures and actions) are easily translated to each building in form of specific building projects with their associated indicators and targets. It is in the implementation phase when the connection between the operational and strategic scales is fully considered and implemented. The implementation of the strategies at building level is an excellent opportunity to update and complete the model since the diagnosis, decision making, and implementation phases at building level can complete the building information in the model with information regarding the new strategies implemented or update with information that has been found inaccurate. This new information can improve the initial diagnosis. Likewise, the monitoring phase at building level will be the input for the indicators at urban level, measuring the real improvements and impacts of the implemented actions. This information provides the feedback that will refine all the system. To facilitate the implementation, the framework is divided in two stages: a first one where the diagnosis is carried out and the strategy is defined through a decision making methodology and a second one where the energy retrofitting program is implemented and monitored.

3. IMPLEMENTATION IN THE EFFESUS DECISION SUPPORT SYSTEM

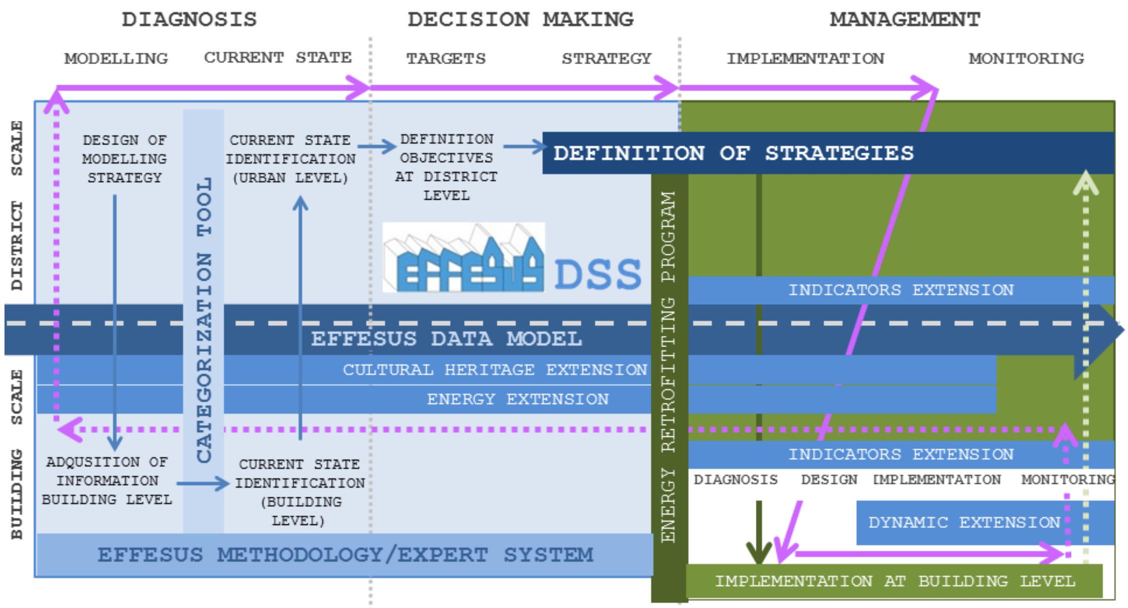

Figure 2. EFFESUS decision support system in overall framework

A framework, like the one that has been proposed in the previous section, that takes into account big amounts of interscalar and cross-thematic information can be difficult to implement without systematic methodologies and compatible software tools that are based on the same principles. EFFESUS is a four year research project funded by the European Commission under its Seventh Framework Programme investigating the energy efficiency of European historic urban districts and developing technologies and systems for its improvement. The project, with 23 partners and 7 case studies, has developed a DSS as an ecosystem of tools and methodologies to support evidence based diagnosis and decision making based on the previously described framework. As it can be seen in Figure 2, the project has developed a data model, two software tools and a methodology that supports the implementation of different processes within the framework. The main case study for the validation has been Santiago de Compostela (Spain), whose historic centre was declared World Heritage Site by UNESCO in 1985. The selected area is the one traditionally called the *Almendra* that coincides with the area that was historically inside the walls.

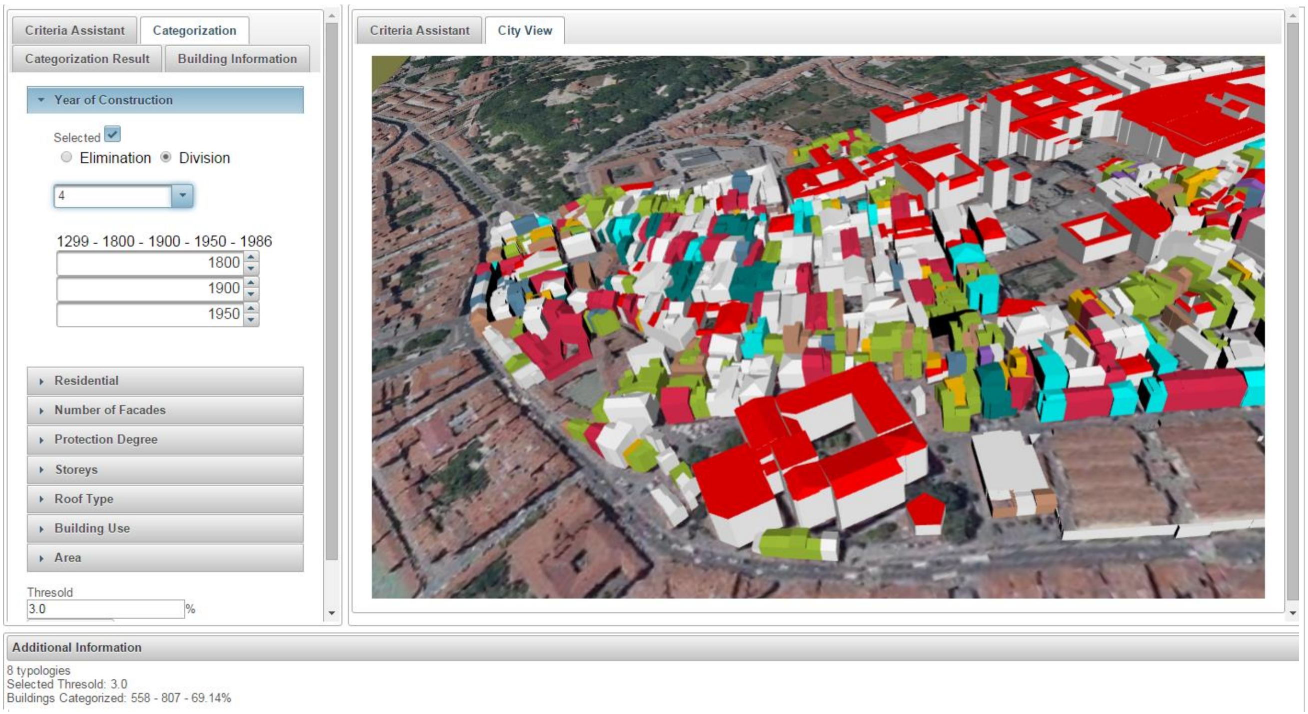

Figure 3. EFFESUS categorization tool and the 3D multiscale model for Santiago de Compostela

The required multiscale data model, the EFFESUS data model, has been generated based on the standard CityGML for the 819 buildings of the area. The extensibility of this schema allowed the development of four specific domain extensions that are designed to structure all the semantic information necessary for the whole process: *energy extension* with information required for energy assessment, *cultural heritage extension* with information required for heritage significance assessment, *indicators extension* and *dynamic extension* for monitoring purposes. Since initially the process only requires the information necessary to run the modelling strategy, the data model can be generated in a cost-effective way using public data bases as the cadastre. The selected modelling strategy was to categorize the historic district to select sample buildings. Therefore to facilitate the process, as well as to visualize and manage the model, a categorization tool has been created (see Figure 3). This web application functions with eight basic parameters which create typologies that cover the energy and cultural aspects: year of construction, protection degree, whether it is residential or not, number of façades and storeys, area, roof type and use. The tool provides an overview of the urban scale showing statistical and geographical distribution of the parameters in order to support the selection of the most suitable parameters and ranges for the categorization and after runs the process automatically. In Santiago four parameters were used (number of façades, use, year of construction and level of protection) as they provided the optimal balance regarding the number of typologies and the represented percentage of the building stock (the manageable amount of 10 typologies represent the 80,52% of the building stock).

For the decision making, a methodology has been developed that uses the selected sample buildings as representatives of the whole district. The methodology is implemented in an expert system (Figure 4). The system guides the user in the design of specific energy retrofitting strategies for a historic district following these steps: 1) identification of the current state regarding the energy demand, CO_2 emissions and heritage significance, 2) estimation of the applicability of the solutions through location specific heritage significance impact assessment, 3) ranking of the solutions according to the user preferences using multicriteria methods, 4) generation of retrofitting scenarios (manually or using optimization methods), and 5) estimation of impact indicators at district level calculating energy demand and carbon emissions reduction, thermal comfort and indoor air quality improvement, and the economic feasibility of the proposals. The implementation of the methodology has shown that low impact solutions have very good cost effectiveness and have to be preferred to other solutions as first step; but more invasive solutions that improve the envelope of the buildings (airtightness and thermal characteristics) have a great impact in thermal comfort and energy savings and are suitable for historic environments if an impact assessment is carried out before. For the case of Santiago high energy savings could be obtained per area (from 65% to 85% in thermal energy demand and more than 90% in CO_2 emissions) with solutions that are respectful with the historic significance. The categorization tool and the expert system will be accessible through the project website (www.effesus.eu).

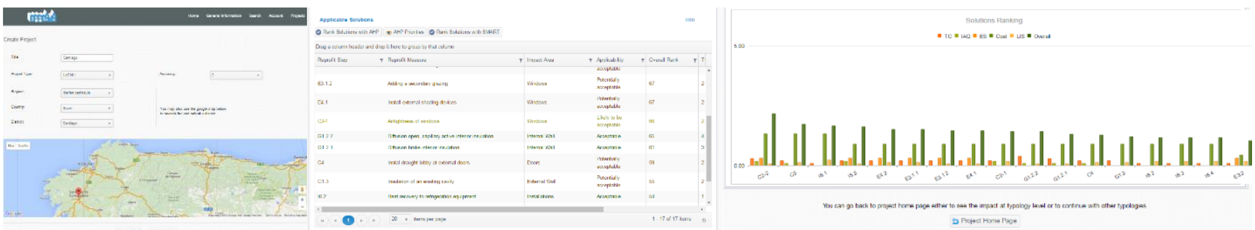

Figure 4. EFFESUS expert system (location of the district, applicability and ranking of the solutions)

4. CONCLUSIONS

Historic cities that are determined to improve the energy performance and liveability of their buildings and districts can highly benefit from a methodological framework that structures and articulates the whole cycle (diagnosis, decision making, implementation and subsequent monitoring and maintenance). But so far the frameworks and methodologies that were proposed have been tailored for specific cities, hindering their application to other scenarios. This paper proposed a replicable framework, flexible regarding the initial requirements, focused in two crucial issues that so far have not been fully addressed: the multiscalarity and the strategic information management. A multiscalar approach enables to overcome the limitation of historic environments regarding the possible visual, spatial or material alterations in their fabric maximizing the potential of tailored strategies. A strategic information management is the keystone for the feasibility of a comprehensive system in the long term as ensures the consistency among all the phases and scales and allows a self-learning system. In order to implement the system in efficient way multiscale tools, models and methodologies are required. Based on the proposed principles within the EFFESUS project a DSS has been generated, conceived as an ecosystem of tools and methods that implements key processes within the framework, and it has been tested in the case study of Santiago de Compostela

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Using the life cycle analysis approach for decision and policy support concerning built cultural heritage: Norwegian case studies

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Abstract – *Maintenance and refurbishment strategies for the built cultural heritage must be carefully promoted in the process of addressing climate change mitigation to avoid the reduction or loss of the very values which make this heritage culturally significant. A method to evaluate the environmental impacts of new building construction or building refurbishment is life cycle analysis (LCA). It can be used to compare the carbon emissions associated with the construction and operation of new and existing buildings, refurbished or not. This paper discusses the findings of two LCA reports, commissioned by the Norwegian Directorate for Cultural Heritage, which have assessed two traditionally constructed buildings –one historic and one recently built– to a comparable building constructed with materials in common use today in the mainstream construction industry. The results from the case studies show that the two traditional buildings, yielded smaller environmental impact than the new building with regards to their life cycle carbon footprint despite higher operational emissions. Worse operational energy performance can thus not necessarily be used as an argument against the conservation of historic buildings. Instead, the results indicate that the reuse of historic buildings and their sustainable refurbishment can contribute significantly to climate change mitigation and are serious alternatives to the replacement of existing buildings with new low-energy buildings.*

Keywords – Historic buildings; refurbishment strategies; energy efficiency; life cycle analysis; Norway

1. INTRODUCTION

To tackle global warming the EU is committed to reducing its greenhouse gas (GHG) emissions by at least 20 % by 2020 compared to 1990. The long-term aim is to reduce GHG emission by 60-80 % by 2050 [1]. It is well known that the refurbishment of the existing building stock, a significant contributor of GHG emissions, represents a large challenge. Improving the energy performance of historic buildings in particular is a balancing act between cultural resource management and environmental resource management. This aspect distinguishes working with historic buildings from working with the building stock in general. Policy instruments for the conservation of historic buildings should therefore be carefully designed to contribute to climate change mitigation strategies and vice versa.

However, the focus in present-day energy policy instruments on short-term energy performance improvement – instead of the reduction of long-term environmental impacts – raises important questions.

How can the life cycle approach and environmental resources invested in the construction of historic buildings be utilized when designing appropriate energy refurbishment policies?

This paper presents a critical summary of two life cycle analyses (LCA) conducted by the Norwegian Directorate for Cultural Heritage and discusses the potential of using LCA as tool in the sustainable management of historic buildings.

2. BACKGROUND

2.1 The life cycle approach

Due to the comprehensive nature of LCAs [2], relatively few LCAs have been conducted on historic buildings to date. One exception which has received much attention is the Green Lab study from 2011 [3]. It compared the potential environmental savings offered by reusing historic buildings to replacing them with new buildings. The study found it can take between 10 and 80 years for a new energy efficient building to recoup through its reduced operational carbon emissions those emitted during the construction process. The study also points out that the benefits of reuse can be reduced or negated based on the type and quantity of materials selected for a reuse project.

Munarim et al. [4] and Jackson [5] have promoted that the LCA approach can be used for conservation causes. However, LCA of a building by itself normally does not take into account sustainability in a broader sense [6]. Other aspects of sustainability, such as social or cultural, are in turn problematic to analyse on similar premises due to the lack of agreement on how to estimate their values. LCA of a building concentrates on its environmental impact and provides an opportunity to identify the building phase or modelled scenario with the largest impact. However, in combination with the use of a more practicable approach, such as the simplified LCA method proposed by Bribián et al. [8], a trade-off model can be used to link environmental aspects to economic and cultural heritage aspects. It can for instance help decision makers implement balanced sustainable measures where they are most relevant [7].

2.2 Norwegian building regulations

Norway has implemented the aforementioned EU directives and energy goals. Secondary legislation has been enacted to progressively raise the minimum requirements of energy performance in new buildings and major building refurbishments. The national building code document TEK10 [8] aims to ensure that all buildings are constructed, maintained and disposed of with as little impact on natural resources as possible. In practice, this means that the energy required for heating a building (the operational phase of its life cycle) should be as low as possible. To ensure this, TEK10 prescribes a maximum U-value allowed for different elements of the thermal envelope, see table 1. For historic buildings undergoing a major refurbishment, an alternative is provided: minimum energy requirements can be omitted if they are considered as having an adverse impact on the building's cultural heritage significance. This applies to buildings designated officially as cultural heritage through national, regional or municipal heritage legislation. Another perhaps somewhat unique exemption, introduced in the late 1990s, allows dwellings to be constructed with timber logs, a traditional Norwegian construction form. Instead of a minimum U-value requirement (generally ≤ 0.22 $W/(m^2 \cdot K)$), a minimum wall thickness of ≥ 8" (ca. 20 cm) is used.

Table 1. Minimum U-value requirements in TEK10.

Building category	**Exterior wall [W/(m²·K)]**	**Roof [W/(m²·K)]**	**Bottom floor/joist [W/(m²·K)]**	**Windows and doors [W/(m²·K)]**
General	≤ 0.22	≤ 0.18	≤ 0.18	≤ 1.2
One dwelling unit and heated floor area >150 m²	≥ 8″ timber	≤ 0.13	≤ 0.10	≤ 0.8
(holiday homes with) one dwelling unit and HFA <150 m²	≥ 8″ timber	≤ 0.18	≤ 0.18	≤ 1.6

2.3 Policys and subsidies

As energy requirements are becoming more demanding, governmental policies in Norway, such as the Enova grant [9][7], aim to stimulate large-scale energy refurbishment by providing support for retrofitting buildings with energy performance improvement measures - as long as the measures comply with the aforementioned minimum U-value requirements. The design of the Enova system, essentially a positive driver for mitigation, also represents some challenges since physical performance alone is not enough to assess properly the sustainability or effectiveness of existing structures. Curtis [10] has for instance has argued that in order to refurbish the historic building stock in a sustainable way, improvements need to not only consider operational energy consumption, but also the embodied energy and other long-term life cycle environmental impacts associated with the refurbishment. A second problem is that "over-doing" the refurbishment can risk being counterproductive as some measures aiming to improve the energy performance of existing buildings can in fact have a negative impact on the environment in the long run [4]. Last, and with respect to the individual merits of the historic building, the generalizing nature of the subsidized measures risk affecting the heritage values of a historic building - which should have an equal position with energy priorities at the beginning of any refurbishment project [11].

In an attempt to elucidate this topic, the Norwegian Directorate for Cultural Heritage commissioned two pieces of LCA research. In 2011, the environmental impacts of the refurbishment of an existing historic timber building were compared to the construction of a new low-energy building [5]. A few years later, when the removal of the TEK10-exceptions for timber constructions was suggested, a second piece of research investigated, in 2015, the LCA of a timber log building to a new built reference building [12] (the suggestion had been discarded at the time of writing this paper). Both LCA

[7] Enova is a public enterprise owned by the Norwegian Ministry of Petroleum and Energy.

studies considered only the carbon emissions associated with the construction (or refurbishment, regarding the historic building in the 2011 study) and operational phases. The latter was assumed to be 60 years. Energy associated with material extraction, transportation and building demolition were not included. The LCAs were done by experts using the free software Klimagassregnskap.no [13].

3. CASE STUDIES

3.1 LCA 2011: historic versus new low-energy reference building

In the 2011 study, a historic building was compared to a low-energy reference building. Built in 1812, the historic buildings had a floor area of ca. 180 m^2 and contained 3 dwellings units. It had been moderately refurbished in order to achieve somewhat comfortable environmental conditions indoors. Its heating system was a combination of wood stoves, and oil boiler and electrical radiators (each assumed to cover 1/3 respectively, though exact figures are not known). The annual energy performance was calculated as 510 kWh/m^2. The reference building was modelled to have corresponding geometry, size and use to the historic building and ascribed technical attributes in compliance with minimum requirements of TEK07, the predecessor to TEK10. It was built using construction forms typical in the mainstream building industry, mainly using wood; no extra effort was made to choose low-emission building materials. The annual energy consumption was calculated as 80 kWh/m^2 with approximately 27 % used for heating, 37 % for hot water and the remainder for electricity.

Three different packages of retrofit measures with increasing impacts on energy saving were modelled to establish a basis for comparison with the new reference building. As the historic building had restrictions for exterior alterations, all measures were designed with respect to the legislative restrictions. The major refurbishment package, covering all considered and relevant measures, included an ambitious upgrade of the thermal building envelope, including attic and ground floors and external doors, windows and walls, as well as the conversion of the heating and hot water systems to a bio pellet boiler with additional support from a solar hot water system. Post-refurbishment annual energy performance was calculated as 252 kWh/m^2. Information on building material used in the analysis of both buildings was acquired from datasets from Klimagassregnskap.no. The LCAs were produced using standard temperature in the entire heated volume of the buildings; specific users' behaviour was not factored in.

Prior to its refurbishment, the historic building in-use emitted annually 115 $kgCO_2e/m^2$. Post-major refurbishment figures showed a vast improvement: 23 kg CO_2e/m^2 per year. This includes, over the course of a 60 year period, the embodied energy associated with the retrofitted materials, which only contributed 10 % to the emissions. The construction and operation of the reference building would have consumed annually 26 $kgCO_2e/m^2$, including the energy associated with its construction ca. 17 $kgCO_2e/m^2$ per year (68 %) of the emissions. If the historic building were to reach equivalent emission levels as the low-energy a source conversion for the heating and hot water systems would have had to be installed also.

Though the LCA method was much simplified, the results show that a major refurbishment of the historic building would be preferable if the goal was to reduce GHG emissions quickly. In other words, the reuse of existing materials and the reduced use of new materials compensate partly for the higher operational energy consumption of the historic building. In the long-term perspective, emissions caused by operation and maintenance intervals are distributed relatively even over time for the historic building. Conversely, emissions for the new building are intense in its initial construction phase and lower during the operational phase, though new "unmaintainable" components are likely to have shorter lifespan. In summary, the results show that the environmental impact of the construction and operation of the new building requires 60 years before it evens out in terms of GHG emissions with the fully refurbished historic building.

3.2 LCA 2015: new log house versus new Tek17 reference building

The 2015 LCA compared the carbon footprint associated with materials and operation of a traditionally constructed log house to a new house designed in accordance with the proposed new energy requirements where the exemption for log buildings was removed. The former building is a single-family dwelling from 2006 with a timber log wall and otherwise modern roof construction. The reference building was a modelled modern dwelling of equivalent size and use that reached the proposed new requirement in TEK17. The building has an air source heat pump, supplemented with a wood burning stove. As the fuel consumption for the stove and the average indoor temperature were not known, carbon emissions were calculated on the basis of data acquired through in situ energy monitoring, correlated climatic conditions and predefined datasets for building components from Klimagassregnskap.no.

The LCA showed that the carbon emission associated with the production of the building materials for the timbered building (2.40 $kgCO_2e/m^2$ per year) was approximately half of those associated with the materials used for the TEK17 building (4.89 $kgCO_2e/m^2$ per year) over the course of 60 years, see table 2. The difference was caused by the larger use of reinforced concrete in the building foundation, and of mineral wool insulation and gypsum plasterboards in the building's thermal envelope. The envelope of the log house does not contain insulation and plasterboard, as the log walls and roof remain exposed externally and internally, therefore resulting in significantly lower carbon emissions. Obviously, the modelled new building has lower annual operational carbon emissions compared to the log house: 7.9 $kgCO_2e/m^2$ compared to 8.1 $kgCO_2e/m^2$ respectively.

Table 2. Annual carbon emissions [kgCO$_2$e/m^2] of a new timber log house and a new TEK17 reference building including the emissions associated with its construction and its operation prorate for a 60 year period. The use of more timber and less concrete in the log house affects the emissions significantly.

	Annual emissions	
	Reference building	*Log house*
Construction phase	4.89	2.40
Foundation and ground work	2.16	0.95
Load bearing walls, exterior walls, incl. windows and doors	1.10	0.22
Interior partition walls	0.53	0.19
Joists	0.54	1.01
Roofing	0.56	0.18
Operational phase	7.90	8.10
Sum	12.79	10.50

4. DISCUSSION

4.1 General outcome

A key outcome from the two LCAs was the quantification of time needed for a newly built structure to recoup the energy resources consumed in the construction process and compare it to the retrofit of a historic building. Similar to the Green Lab study, results showed that the reuse of a building with average energy performance offers immediate emission reductions compared to more energy efficient new construction. This "performance peak" is underlined by the critical impact caused by quantity and types of materials used in refurbishment and in the construction of the new building (cf. the timber building with its low emission materials). Yet neither the Norwegian energy building codes nor the Enova grant system requires or incentivises the use of low emission materials.

The results underline the need to integrate the LCA approach in the decision making process when planning energy efficiency retrofits of historic buildings. The results show also, on a higher level, how aims and methods associated with energy policy instruments, such as the Enova system, should consider the actual environmental impact of subsidized measures. Another conclusion to be drawn is how the accuracy of data, e.g. energy consumption (or user behaviour which was not considered in the case studies), is crucial for comparing two different cases where a reference building is modelled and data for an existing building is measured.

4.2 Further research and conclusion

The LCAs discussed in this paper were conducted on single case studies with methods that could have been more detailed. The results should thus be seen as indicative. Yet they have demonstrated that the reuse of historic buildings and their sustainable refurbishment can contribute significantly to climate change mitigation and can represent serious alternatives to the building replacement with new low-energy buildings. However, to make LCAs more useful in praxis and to acquire more accurate results, it would be benefit to:

- improve existing life cycle inventory data for traditional materials and building techniques,
- evaluate the durability and thermal characteristics of historic building materials,
- simplify the LCA method by focusing more on construction and operation stages,
- encourage more LCAs to be performed on historic buildings with different refurbishment scenarios while also showing the influence of user behaviour.

The here presented case studies have shown that building conservation can and should utilize LCA, as an environmental impact assessment method for the evaluation of historic buildings. At building level, LCA can be used as decision support for single refurbishment projects, provided that the appropriate data and practicable tools are available. And at policy level, LCA can help identify energy refurbishment strategies specifically tailored for the historic segment of the building stock.

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Integrating conservation aspects into energy performance assessments for 20th century buildings: Canongate Housing

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Abstract – *The integration of conservation aspects is rarely considered in energy-related retrofit assessments. Particularly vulnerable to inappropriate retrofit is the mid-20th century heritage, constructed during an era of experimentation with new materials and construction techniques and little regard to energy performance. This paper presents an assessment methodology and its application on a retrofit assessment of the 1960s Canongate Housing complex in Edinburgh, United Kingdom. The aim was to systematically integrate conservation with energy performance, economic feasibility and construction practices. The paper demonstrates that, through production of a Statement of Significance and the identification of character-defining elements, conservation can be integrated into retrofit assessment in the form of a long- and short-listing process. The assessments show that retrofit of technical building systems and renewable energy generation systems achieves larger reductions than fabric improvement measures and that payback periods can vary substantially for different flat types, leading potentially to diverging interests amongst flat owners.*

Keywords – 20th century heritage; assessment methodology; building conservation; energy performance; retrofit

1. INTRODUCTION

1.1 Context

The Energy Performance of Buildings directive [1] of the European Union required member states to adopt or develop tools for assessing, predicting and simulating building energy performance in order to inform improvement measures. The still limited suitability of these tools, from a technical perspective, when applied to older buildings, has been well researched and improvements are being made. [2, 3] The integration of conservation aspects, however, is rarely considered in energy-related retrofit assessments. Heritage designation is more often than not perceived as incompatible with retrofitting historic buildings. Particularly vulnerable to inappropriate retrofit is the built heritage of the mid-20th century, constructed during an era of experimentation with new materials and construction techniques and with little regard to energy performance at the time. This paper presents an assessment methodology and discusses its application on a retrofit assessment of the 1960s Canongate Housing complex in Edinburgh, United Kingdom (UK). The aim was to systematically integrate conservation with energy performance, economic feasibility and construction practices. The work was part of a joint initiative in 2012/2013 by City of Edinburgh Council, Edinburgh World Heritage Trust and Historic Scotland (now Historic Environment Scotland; HES), commissioning a fabric condition survey, conservation statement and energy performance assessment. Simpson & Brown Architects wrote the conservation statement [4]; Glasgow Caledonian University (GCU) produced the energy assessment.

1.2 Case study building

Built between 1961 and 1969 to designs by the renowned architectural firm Sir Basil Spence, Glover & Ferguson, the building complex consists of three five-storey blocks with thirty flats and four commercial units. Two larger blocks face the Canongate, a main street in the city centre; the third, smaller block is set back on a short cul-de-sac. (Fig. 1) "All three blocks are characterised by an informal arrangement of monopitch roofs, harled and rubble facings, a variety of horizontal and vertical windows, slightly projecting segmental-arched canopies to ground floors and cubic concrete balconies to the side and rear elevations." [5] The complex is officially designated as cultural heritage, by *listing* at category B and inclusion in the Old Town Conservation Area and Edinburgh's UNESCO World Heritage Site (WHS). [6] The complex is of *special interest* as "an important example of Scottish Post-War housing occupying a critical and historically sensitive location". [7]

Figure 1. Ground floor plan of the Canongate Housing complex and photograph along Canongate with blocks 2 and 3 in the foreground (Image © left: HES (Spence, Glover and Ferguson Collection) Licensor canmore.org.uk; right: HES)

2. METHODOLOGY

To identify and evaluate retrofit measures that would improve the energy performance of the building complex, a five-step methodology was developed, based on professional experience, a conservation statement and energy performance and costs calculations. The five assessment steps are:

1) building inspection and occupant engagement
2) assessment of cultural significance
3) long-listing technically possible retrofit measures
4) short-listing measures by comparing them to the recommendations in the conservation statement
5) energy and cost assessment of short-listed measures, optionally grouped into packages

This assessment methodology is similar to that proposed in the draft European Standard, *prEN 16883:2015 Guidelines for Improving the Energy Performance of Historic Buildings*, which also proposes the creation of long- and short-lists of retrofit measures to factor in conservation aspects. This paper only presents the assessment of some residential units. The energy use and carbon dioxide (CO_2) emissions were calculated using SAP 2009. SAP is "the methodology used by the Government [of the UK] to assess and compare the energy and environmental performance of dwellings". [8]

3. RESULTS AND DISCUSSION

3.1 Building inspection and occupant engagement

The assessment process started with a review of historical drawings and photographs, two site visits and a building occupant questionnaire to provide an understanding of the complex and its occupants' perception of comfort, energy costs and environmental impact of their homes.

3.2 Assessment of cultural significance

The conservation statement has assessed the cultural significance of "the site as whole and for its various parts", so that "informed policy decisions can be made which will enable that significance to be retained, revealed, enhanced or, at least, impaired as little as possible in any future decisions for the site." [4] The statement concludes: "The overall level of significance of the building is considerable. A number of individual features are of moderate or neutral significance, with the distinctive cast *in situ* concrete balconies, canopies, vaults and external stair all being of considerable significance." The character-defining elements and spaces were also presented in the form of drawings. (Fig. 2)

Figure 2. Example of colour-coded drawings in the conservation statement, illustrating the significance levels of different building elements and spaces of blocks 1 (left) and 2 (right) (Image © Simpson & Brown Architects)

Based on its significance assessment, the statement recommended as development policy: "Elements of considerable significance should be retained and respected as part of any future alteration of the building. Elements of moderate significance should be retained wherever possible, whilst areas of neutral or negative significance may provide opportunities for alteration, restoration or enhancement." The statement further notes: "With wider concerns relating to modern environment standards and the application of these standards to post-War listed buildings, there is an exceptional opportunity to explore ways in which these popular and well-liked homes can be upgraded whilst maintaining that which is culturally significant." [4]

3.3 Long-listing of retrofit measures

Concurring with the writing of the conservation statement, GCU, using professional experience, produced an initial selection of retrofit measures. This long-list contained nineteen measures, of which nine are improvements of the building fabric, five are improvements of the technical building services and five are installations of renewable energy generation systems. The measures are listed in Table 1, together with the pre- and postretrofit U-values used in the assessment, where applicable.

3.4 Short-listing by comparison with conservation statement

The long-listed measures were assessed for their impact on heritage significance. Three measures were considered *unacceptable*: external wall insulation due to its visual impact; ground-source heat pumps because of their impact on underground archaeology; and wind turbines due to planning restrictions due to it being a conservation area. All other measures were *acceptable*, but some might require careful design, for example with regard to the placing of flue outlets or roof panels. (Table 2, columns Heritage and Technical; also noted are other technical installation issues)

3.5 Energy and cost assessment

For each short-listed measures, the energy use and CO_2 emissions were calculated for two flats: a one-bedroom, end-terrace, top-floor flat and a two-bedroom, mid-terrace, first-floor flat. The former has, relative to floor area, the largest external building envelope area of all the flat types; the latter has the smallest. Thus, the calculations of these two flats represent the range of improvements the other flats will achieve. The energy and CO_2 emission reductions were calculated for all measures (except the not short-listed wind turbines), with internal wall and attic floor insulation assessed together in two groups (Table 2). The reductions were benchmarked against the flats' energy performance at the time of construction. (Other benchmarks are not presented in this paper.) Back then, a flueless gas fire provided heating to each living room; the other rooms had electric panel heaters. The percentile CO_2 reductions (Table 2, column Emissions) suggest that, of the *acceptable* measures, a communal biomass plant would perform best (81-83%), bettered only by the not short-listed ground-source heat pumps (92-94%). Except for roof-mounted renewable energy measures, the short-listed measures relating to technical building services achieved larger reductions (>48%) than the fabric improvements. Of these, the internal insulation measures performed better (14-45%) than the cavity fill insulation (9-10%) or the not short-listed external wall insulation (9-11%). The installation of decentralised mechanical fan ventilation (DMEV) resulted in an emission increase of 2%, as these fans run continuously.

Table 1. Long-listed retrofit measures identified by using professional experience

ID	Retrofit measures	**Details** with pre- and postretrofit U-values where applicable [W/(K·m^2)]		
		Improvements of building fabric		
1	*Cavity-fill wall insulation*	50 mm blown mineral wool insulation	1.31	0.55
2	*External wall insulation*	50 mm mineral wool insulation with 20 mm render	1.31	0.49
3	*Internal wall insulation with EPS backed plasterboard*	Plasterboard with 37.5 mm EPS backing on 22 mm timber battens to external walls	1.31	0.25
4	*Internal wall insulation with aerogel-backed plasterboard*	Plasterboard with 10 mm aerogel fibre backing fixed to existing plaster to external walls	1.31	0.64
5	*Internal wall insulation to stairwells with aerogel-backed plasterboard*	Plasterboard with 10 mm aerogel fibre backing fixed to existing plaster to walls to stairwells	2.09	0.81
6	*Internal insulation to underside of attic floor*	Plasterboard with 10 mm aerogel fibre backing fixed to existing plaster finish	3.24	1.03
7	*Internal floor insulation over pend*	Replacement of existing floor finish with 50 mm EPS insulation with 22 mm timber finish	0.88	0.33
8	*External insulation over attic floor*	150 mm EPS insulation to floor of roof space	3.24	0.25
9	*Window improvements*	Either internal single-glazed secondary windows, or double-glazed replacement windows	4.80	1.20
		Improvements of technical building services		
10	*High-efficiency combi-boiler*	Replacement boiler with modern controls and flue-gas heat recovery		

11	*Decentralised mechanical extraction ventilation*	Replacement of intermittent ventilation fans
12	*Communal gas-fired heating*	Replacement of flat boilers with communal gas-fired heating system with flat heat meters
13	*Communal biomass plant*	Replacement of flat boilers with communal gas-fired boiler (90 % efficiency); internal hot water cylinders (150 l) and heat meters in flats
14	*Communal combined heat and power (CHP) system*	Replacement of flat boilers with CHP system providing 70 % heat demand; for remaining demand, gas-fired boilers (90 % efficiency); internal hot water cylinders (150 l) in flats
Installation of renewable energy generation systems		
15	*Solar thermal roof panels*	on south-facing roofs, connected to insulated hot water cylinders (150 l) in flats
16	*Photovoltaic roof panels*	on south-facing roofs, with a size of 6 m^2 per flat
17	*Air-source heat pump*	to each flat complete with radiators and insulated hot water cylinder (150 l)
18	*Ground-source heat pump*	communal pump (300 % efficiency) with heat meters to each flat
19	*Wind turbines on roofs*	one turbine per flat (rotor: 1.5 m diameter, hubs: 3 m above ridge) delivering electricity to displace energy in use and exporting surplus

In this paper, detailed costings are presented only for fabric improvement measures and a combi-boiler retrofit, assessed for three measures packages: individual (internal measures and window upgrades excluding insulation below attic floor), communal (cavity-fill, insulation above attic floor, window upgrades) and combined (all measures excluding insulation below the attic floor).

Table 2. Impact assessment of long-listed retrofit measures against flats as originally built

ID	Retrofit measures	Heritage	Emissions	Technical	Cost	Scale
Improvements of building fabric						
1	*Cavity-fill wall insulation*	minimal	9-10%	expert advice required	low	communal
2	*External wall insulation*	unacceptable visually	9-11%	improves cold-bridging	moderate to high	communal
3+5+6	*Internal EPS insulation*	none	17-45%	redecoration required and loss of space	moderate	individual
4+5+6	*Internal aero-gel insulation*	none	14-42%	redecoration required	moderate	individual
7	*Internal floor insulation*	none	10%	significant occupant disruption	moderate	individual
8	*Internal attic floor insulation*	none	41%	might need craneage	moderate	communal
9	*Window improvements*	match original visually	5-13%	Localised redecoration required	moderate	communal or individual
Improvements of technical building services						

9	*Mechanical ventilation*	outlet placing	-2%	DMEV fans help control condensation	low	individual
10	*Combi-boiler*	flue placing	60-63%	Requires gas supply	moderate	individual
11	*Communal gas heating*	flue placing	56-58%	block-by-block distribution network and heat meters required	high	communal
12	*Communal biomass plant*	flue placing	81-83%		high	communal
13	*Communal CHP system*	flue placing	69-71%		high	communal
Installation of renewable energy generation systems						
14	*Solar thermal roof panels*	unacceptable if south-facing	7-11%	separate systems require connection to individual flats via communal areas of the buildings	moderate	communal consent, individual implementation
15	*Photovoltaic roof panels*	unacceptable if south-facing	5-8%		moderate	
16	*Air-source heat pumps*	unacceptable externally	48-52%		moderate	
17	*Ground-source heat pumps*	unacceptable due to archaeology	92-94%	as measure 11	very high	Communal
18	*Wind turbines on roofs*	unacceptable if above ridge	-	as measure 14	low	as measure 14

Table 3 lists capital costs, annual energy costs and payback periods. The combi-boiler installation has the shortest payback period, reflecting the fuel choice and inefficiency of the original heating systems. Comparing the two flats, payback periods for the mid-terrace flat are substantially higher, as the benchmark energy cost is lower compared to the end-terrace flat with its larger building envelope area.

Table 3. Capital and annual energy costs and payback periods for select retrofit measures for two flat types

Retrofit measures	**One-bedroom top-floor end-terrace flat**			**Two-bedroom first-floor mid-terrace flat**		
	Capital cost	*Energy cost*	*Payback*	*Capital cost*	*Energy cost*	*Payback*
Unimproved flat	-	1 987 £	-	-	1 305 £	-
New boiler	1 200 £	690 £	0.93 yr	1 200 £	511 £	1.51 yr
Communal fabric	5 533 £	909 £	5.12 yr	5 195 £	1 015 £	17.95 yr
Ditto + new boiler	6 733 £	386 £	4.20 yr	6 395 £	425 £	7.27 yr
Individual fabric	13 056 £	1 048 £	13.90 yr	11 869 £	950 £	33.47 yr
Ditto + new boiler	14 256 £	419 £	9.09 yr	13 069 £	360 £	13.83 yr
Combined fabric	10 157 £	810 £	8.63 yr	12 362 £	805 £	24.74 yr
Ditto + new boiler	11 357 £	351 £	6.94 yr	13 562 £	355 £	14.28 yr

4. CONCLUSIONS

This paper has demonstrated that, through the production of a statement of significance and the identification of character-defining elements, conservation aspects can be integrated into energy-related retrofit assessments in the form of a long- and short-listing process. A similar approach is under development for a forthcoming European standard. The conservation integration showed that, despite the listed status of Canongate Housing, many retrofit measures are acceptable, provided details are designed appropriately. The energy, CO_2 and cost calculations have shown that retrofit of technical building and renewable energy generation systems achieves larger reductions than fabric improvement measures, but can be more costly. The use for calculation of two very different flats has revealed that payback periods can vary substantially, leading potentially to diverging interests amongst flat owners.

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An investigation of the energy efficiency of traditional buildings in the Oporto World Heritage Site

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Abstract – *Oporto's traditional buildings are the major contributors for shaping the World Heritage Site Despite this, and as is the case in most European historic cities, they are not individually listed and any adaptations to make them comply with current energy efficiency requirements may cause negative impacts on their authenticity and integrity. This paper aims to identify which energy efficiency improvement measures can be applied without damaging the buildings' heritage value. For this purpose, fieldwork and simulation data of ten case studies were used. On-site results revealed that the energy consumption in Oporto's traditional buildings was below European average and the households expressed that their home comfort sensation was overall positive. Simulations showed that introducing insulation and solar thermal panels would be ineffective in terms of energy and cost efficiency as well as comfort improvement.*

This study reinforces the idea that traditional buildings perform better than expected in terms of energy consumption and can be retrofitted and updated at a low-cost and with passive solutions.

Keywords – Oporto traditional buildings; energy efficiency; assessment and simulation; fieldwork

1. INTRODUCTION

In Oporto, traditional buildings are the major contributors for shaping the World Heritage Site (WHS). Despite their heritage relevance, like in most European historic cities, these are not individually listed. For this reason, their adaptation to make them compliant with current energy efficiency requirements may provoke negative impacts on their authenticity and integrity. Furthermore, the cumulative impact of such changes to individual buildings may also endanger the overall significance of the WHS.

1.1 Traditional buildings and energy efficiency

Over the past 15 years, an increasing number of literature on the thermal behaviour and energy efficiency of traditional buildings has been published. The Building Research Establishment (BRE) in England successfully promoted the sustainable refurbishment of several Victorian and Edwardian era buildings, providing effective measures to promote energy efficiency in these types of dwellings [1, 2]. The use of renewable energy sources in traditional buildings was addressed by English Heritage, which evaluated the impacts that introducing such systems into a historic environment would cause to the heritage values [3, 4].

Figure 1. Oporto World Heritage Site

Moreover, the Society for the Protection of Ancient Buildings (SPAB) has undertaken on-site research focusing on several aspects of the thermal behaviour of traditional buildings that showed a clear gap between the calculi and the effective measurements taken, revealing that traditional buildings have a better thermal performance than predicted [5, 6]. Previous literature has established that the perception of traditional buildings as having poor thermal performance and being inadequate to meet the current targets of energy efficiency is erroneous. The passive characteristics of this type of building give them some potential to achieve higher levels of energy efficiency. The literature also points to a gap between the technical approach and heritage conservation in the process of improving the energy efficiency of traditional buildings.

Using traditional buildings in Oporto that are part of the WHS, this research aims to identify the means by which urban traditional residential buildings can be upgraded to improve their energy performance while preserving their heritage significance.

2. MATERIAL AND METHODS

2.1 Methods

The current research uses 'environmental impact assessment' methodologies [7] and their adaptation to the specific field of 'heritage impact assessment' [8, 9]. A baseline situation was established, a plan of adequate changes drawn and its impact determined at both building and historic urban townscape level. Measuring impact included several components: heritage (impact of change measurement), energy and CO_2 (measured improvements), cost-effectiveness (pay-back time measured), and comfort (acceptable Predicted Percentage of Dissatisfied - PPD). These components were ranked in hierarchical order, with heritage impact assessment at the top and comfort at the bottom of the list.

Through a bottom-up process, ten case studies from the Oporto WHS were selected to apply the previously described methodology. The selected cases were measured on-site (fieldwork), followed by computational model analyses using the IES-VE software for the baseline scenario and for the dynamic simulation of the improvement measures. The developed models were based on detailed data that had been obtained through fieldwork: geometry and construction systems were identified, as well as equipment and the household's behaviour pattern. On-site temperature and humidity data for model calibration purposes was also collected.

2.2 Oporto traditional buildings

Traditional buildings in Oporto have mainly been built or transformed between the 17th and 19th century. They can in short be described as terraced houses facing the street, inserted in narrow and long lots and mainly residential (with shops on the ground floor). They have hip roofs, three to five floors, two or three windows per floor, solid granite exterior walls, inner wood structure, and plaster or tiles on the main facade. In the centre of the building, a staircase connects the multiple floors and provides light and ventilation from the skylight above for the inner rooms.

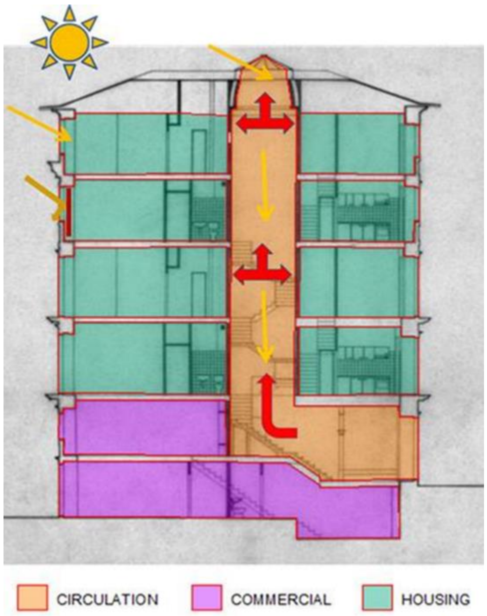

Figure 2 – Oporto traditional buildings schematic longitudinal section

2.3 Fieldwork

2.3.1 Identification of typological variants

A research area representative of Oporto's historical centre was delimitated and typologies of traditional buildings collected and described. The area selection was based on the following criteria: it had to be part of the WHS and contain a majority of traditional buildings with a high level of apparent integrity. This accounted for 89.4% of the total number of buildings. From a total of 316 buildings, 191 met the inclusion criteria (built before 1919 and mainly residential) and were examined.

The analysis of the selected buildings showed a typological homogeneity of the sample, which was composed almost exclusively of similar terraced houses. Hence, instead of different typologies, the survey showed the existence of several variants of one main typology. Taking into account the building's urban insertion and form factors, six variants were identified. These can be grouped into three main categories: corners (end-terraced), including V1 and V2 (with 3 and 2 street facades, respectively); row houses facing the street (mid-terraced), including V3a (2 street facades), V3b (1 street and 1 back facade) and V4 (solely 1 street facade); and detached, comprising V5, which was excluded due to its irrelevance (representing less than 1%). The mid-terraced group (V3a, V3b and V4) is largely predominant, accounting for 91% of the total number of buildings. This is consistent with the predominant compact urban block identified in the historic city. The five variants (V1, V2, V3a, V3b and V4) to be modelled as case studies were further subdivided into middle and top floor sub-variants.

Figure 3 – Research area building variants

2.3.2 Case Studies

Following the process of determining the variants, ten real cases representing each of the variants were identified. The selection was made with the support of local institutions and professional knowledge of the field. All households that participated did so with informed consent. The cases were scattered throughout the research area and comprised mainly 18th and 19th century buildings. The cases also covered several types of integrity, ranging from buildings with their original spatial and architectural structures intact, to buildings that had been subject to profound refurbishing measures. The data collected in the field included real energy consumption (monthly, over 2 years from the energy supplier), temperature and humidity (half-hour intervals, for 3 months with on-site sensors), noise and light (during the household interview), survey of the geometric and constructive characteristics of the houses (direct measurement and visual survey), and assessment of all household equipment and appliances.

Additionally, the households answered a semi-structured questionnaire, with both open- and closed-ended questions in order to provide information about their behaviour towards energy use and comfort perception.

2.3.3 Modelling

Based on literature, several improvement measures were identified and, taking into account the specificity of the case studies, a set of 19 design scenarios was selected to be simulated. Two types of simulation methods were used, a spread sheet software for equipment and appliances and dynamic simulation software for all other data.

The design scenarios were further classified as 'short-term' and 'long-term', based on their cost effectiveness and their feasibility of implementation, with ‘short-term’ being classified as a pay-back period of less than three years.

Table 1. Design scenarios

Scenario	*Measure*	*Simulation Method*
1	Nulling equipment standby	Spreadsheet
2	Replace existing lamps with more efficient Compact Fluorescent Lamps	Spreadsheet
3	Replace existing equipment with more efficient models	Spreadsheet
4	Draught-proofing windows and doors	Dynamic
5	Improve single glazing with insulating film	Dynamic
6	Use of internal shutters	Dynamic
7	Use internal shutters plus change the profile	Dynamic
8	Reduce Domestic Hot Water (DHW) temperature from 60° to 55° C	Dynamic
9	Upgrade DHW storage tank insulation (to 100mm)	Dynamic
10	Introduce double glazing	Dynamic
11	Introduce secondary glazing	Dynamic
12	Introduce insulation in floors and ceilings	Dynamic
13	Introduce insulation in roofs	Dynamic
14	Introduce exterior insulation in party walls	Dynamic
15	Scenario 14 plus introduce exterior insulation in facades	Dynamic
16	Composite scenario (4, 8 and 9)	Dynamic
17	Composite scenario (4, 6, 8 and 9)	Dynamic
18	Introduce solar thermal DHW	Dynamic
19	Introduce solar thermal DHW plus scenario 8	Dynamic

3. RESULTS

3.1 Baseline

The baseline results for energy, comfort and cost for each case study are listed in Table 2.

Table 2. Baseline results

Variant	Results		
	Energy consumption (yearly mean - kWh/m²)	*Comfort (mean PPD - %)*	*Yearly energy cost (€/m²)*
V1 mid	73.69	17.43	12.73
V1 top	37.28	30.17	5.48
V2 mid	138.75	26.29	17.31
V2 top	128.19	26.63	10.78
V3a mid	76.99	22.29	10.45
V3a top	57.59	26.49	11.29
V3b mid	93.72	16.63	12.42
V3b top	63.94	27.49	10.00
V4 mid	201.92	33.42	26.97
V4 top	60.34	26.75	9.25

3.2 Simulation

The average energy savings from introducing more efficient lighting and stand-by avoidance in the ten case studies were 3.76% and 1.78% respectively.

Small gains were obtained from the draught proofing of external windows and doors, reaching a maximum of 1.39%.

The introduction of double and secondary glazing in the traditional windows reduced the average simulated U-values from the initial 4.6 W/m^{2}K to 3 and 2.8 W/m^{2}K respectively.

The insulation of roofs and walls achieved relatively low reductions for energy consumption. While the top saving value reached 9.58%, the majority of the cases presented insignificant savings. However, the improvement obtained from insulating the case studies' external walls was relevant as it achieved average simulated U-values of circa 0.54 W/m^{2}K, down from the original 2.28 W/m^{2}K.

The introduction of solar thermal panels, also presented relatively low savings, with an average reduction in the energy consumption of 7.9%.

4. DISCUSSION

4.1 Baseline situation

In Portugal, residential buildings built before 1950 consume an average of 200 kWh/m^2, while the ones built between 1950 and 2005 consume on average 140 to 110 kWh/m^2 [10]. Further data states that the most recent and most efficient residential buildings (2006-2010) consume an average of 109 kWh/m^2 per year [11].

The current study shows that for the most numerous building variants (V3a and V3b) the average energy consumption was below these values (63.94 to 93.72 kWh/m^2), thus showing better results than the expected. These values were not only below the European and Portuguese averages for residential buildings, they were also close to the values that have been verified for the most recently built buildings. In terms of the cost spent on the energy per dwelling, the average for the ten cases (€ 710.30 per year) was again below the national average (€ 840.00 per year) [12]. It is necessary to stress that the householders reported a reasonable overall comfort sensation in all ten cases, with the mean PPD of the living areas remaining under the peak result of 35%. This suggests that fuel poverty is not the reason for the low consumption measured, rendering increased heating and/or cooling unnecessary. This is in accordance with the general tendency for Portugal and Oporto, where cooling was identified as irrelevant and heating represented around 20% of the overall domestic sector energy consumption [12, 13].

4.2 Simulations

Simulations addressing the residents' behaviour showed a high efficiency, in particular for low-cost measures like the upgrade of lighting and stand-by nulling. The results from this last measure confirm the outputs of similar studies that were performed either in Portugal [14, 15] or at a European level [16, 17]. The Portuguese studies identified a potential energy saving of 5.1% in the domestic sector, simply by not leaving devices in stand-by mode and a saving of 2.6% by adopting more efficient lighting. The averages identified in the ten case studies were slightly lower and revealed an inverse trend, with lighting presenting a higher potential than stand-by avoidance.

Glazed elements in the ten cases represent on average 40% of the total area of the main facade (ranging from 25% to 51%). This high share highlights the importance of potentially upgrading these glazed elements. The small gains obtained from the draught proofing of external windows and doors verify the laboratory tests carried out by Baker [18]. Nonetheless, the comfort improvement obtained in most of the case studies' simulation favours the use of these measures.

The introduction of double and secondary glazing in the traditional windows allowed reducing the U-values from the initial 4.6 W/m^{2}K to 3 and 2.8 W/m^{2}K respectively. This highlights the fact that the introduction of secondary glazing is slightly more effective than upgrading to double glazing. This also confirms Baker's results [18] and is in line with the ones obtained in the Oporto guidance [19]. It is worth noting that these results were consistent across all ten case studies.

The use of insulation in the envelope is widely promoted in the literature and in thermal regulations as one of the most effective measures [19, 20]. However, this could not be verified in the simulations of this study, where the insulation of roofs and walls achieved relatively low reductions in energy consumption. The top saving value was 9.58%, but the majority of cases presented insignificant savings. These results, combined with the high cost of such measures, the heritage limitations, and the relatively reduced area of walls in the facades leads to the conclusion that the insulation of the envelope of traditional buildings in Oporto is surprisingly ineffective. This is in contrast with the results obtained in the Oporto guidance, which presented an energy consumption reduction of up to 60% from the baseline situation [19]. These results may be explained by the use of the standard steady calculation method promoted by the thermal behaviour regulation, which is based on fixed heating and cooling loads, which is not in line with the real-life behaviour verified in the surveyed case studies. Nonetheless, it is worth to analyse the energy savings and the fabric's thermal behaviour improvement separately. While the first was found to be ineffective, an improvement of the fabric's thermal behaviour could be observed, thus confirming the expected improvements widely disseminated in the literature.

The introduction of solar thermal panels, another widely promoted measure, also showed lower savings than expected, with an average reduction in the energy consumption of 7.9%. This result is consistent with the simulation performed in the Oporto guidance, which achieved a reduction of 6% in the energy consumption through the use solar collectors by addressing 40% of the total DHW demand [19]. When comparing the cost savings with the required investment, solar thermal systems lose their efficiency and attractiveness as their average pay-back period amounts to 86 years. Additionally, the multifamily occupation identified in the case studies would result in a high demand and thus a high number of solar panels for each roof. The consequences to Oporto's historic townscape caused by the massive use of solar panels are highly disruptive for the World Heritage Site's authenticity. Considering all these factors, it can be concluded that solar thermal solutions are not adequate for historic buildings in the Oporto World Heritage Site.

5. CONCLUSION

The overall energy efficiency performance of Oporto's traditional buildings was better than expected and previously described.

The most effective solutions to improve energy efficiency of Oporto's traditional buildings are upgrading the DHW tank insulation and the efficient use of existing equipment. From the simulated short- and long-term scenarios, yearly cuts on energy use and carbon emissions of 464.76 MWh and 106 tonnes of CO_2, and 914.65 MWh and 209 tonnes of CO_2 respectively, were identified. On average, each dwelling could save € 121 and € 238 per year in the short- and long-term scenarios, respectively, corresponding to a decrease of 17% and 33.5% from actual average costs.

Upgrading the fabric was found to be less important than is commonly pointed out in literature, which relieves the pressure on the heritage values of these traditional buildings. Surprisingly, envelope insulation was ineffective overall, resulting in irrelevant energy savings and low comfort improvements on the top of its high-cost and negative impact on the building's heritage values. The same situation was verified for the introduction of solar thermal panels, which additionally cause a high negative impact on the historic townscape of the HWS.

This study supports an approach diverging from the established envelope-centred upgrade and reinforces the role of behavioural and passive enhancement solutions for the energy efficiency improvement of traditional buildings

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Eco-efficiency in a UNESCO World Heritage site: safeguard, innovation and compatibility

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Abstract – *This text deals with reflections on the delicate relationship between "energy" and "landscape", taking into account a particularly sensitive site, placed under the guardianship of the state and international interests; the National Park and UNESCO site at the Cinque Terre, Porto Venere and the archipelago comprising Palmaria, Tino and Tinetto constitute one of the most appealing areas in Italy. The research, of a methodological and operational nature, contains specific elements useful to understanding and solving problems inherent to the recovery of rural buildings and to improving the thermal performance and energy supply of the same - especially in contexts not comprised in existent network installations. Outlined herein is a comprehensive framework of technical solutions, whose efficiency, effectiveness and compatibility with active protection are assessed. An in-depth examination is reserved for the integration of solar technologies – to be placed at the disposal of local government and safeguarding bodies so as to gauge the acceptability of proposed intervention.*

Keywords – Protected landscapes; micro-generation; energy efficiency; solar panels; compatibility

1. INTRODUCTION

The main, accepted thought processes in Europe throughout the twentieth century point to an ecological perspective, driven by a progressive awareness of the profound changes taking place in the environment - with related short and long term consequences caused by production processes [1]. In the face of an ever increasing option to manipulate the environment - at times an irreversible process - and of the knowledge pertinent to the fragility of our very life, we are, thus, urged to search for a different balance involving nature, memory and culture, where new forms of responsibility towards the common good are taken as a guideline.

Indeed, “Sustainability” and “Historical heritage”, both material and immaterial, seem to belong to increasingly related and frequently interacting spheres, starting from the claim which holds heritage to be the expression of civilization, the first and foremost cultural reference for any determined site. It may, moreover, embed substantial connections with sustainable growth and development principles, at least in the perspective outlined by the international organisms charged with dedicated safeguarding [2]. Thus historical heritage assumes its rightful place alongside what has been for some time now recognized as the “four pillars of sustainability”; trade, tourism, education and training, all considered as the true driving force of related economic activities [3].

The herein presented research aims to identify technical strategies and planning criteria for the improvement of the thermal performance and energy supply to rural buildings scattered around the

UNESCO site of the Cinque Terre, Porto Venere and the archipelago of Isole Palmaria, Tino and Tinetto, eastern Liguria – among the most appealing areas in the whole of Italy (Fig. 1). It is all aimed at allowing new forms of land utilization (be it for agriculture, tourist accommodation or temporary stays), bearing in mind principles of active guardianship and compatibility with the landscape and architectural features of so important a site. The research, extending from the scale of the single building to the landscape system, was ordered by Direzione Regionale per i Beni Culturali e Paesaggistici della Liguria (Regional Offices for Cultural and Landscape Heritage, Liguria) to lay down guidelines useful for planners and dedicated protection organizations; it stands as the first initiative of its type in Italy in favour of a site of local state and international interest [4].

Figure 16. Examples of rural settlements to be reused in the Cinque Terre UNESCO site.

2. GUIDING PRINCIPLES AND METHODOLOGICAL STRUCTURE OF THE WORK

The work was carried out based on some general principles, which may be summed up as follows:

- consideration of effective management of natural resources (water for supply and possible recovery; wind; sun; land; biomasses) in reference to vocations and landscape compatibility;
- developing of reliable calculation methods to evaluate effective energy performance of the heritage under examination;
- recourse to simple technologies available on the market and financially sustainable to improve the thermal performance of buildings, recurring to integrated systems (building envelope and plants), making clear the most advantageous conditions, even when supplied by renewable sources;
- maintenance and repair of traditional buildings rather than the replacing of materials and parts, also and especially whenever the application of new technical apparatuses is made necessary – with a view to achieving true architectural and landscape compatibility [5];
- consequent adoption of preservation conditions for buildings, complementing their architectural and construction values as one of the basic criteria in recommending specific intervention or not;
- adequate communication of results and effectiveness in various possible improvement solutions, enabling the end users to know how to benefit from the research and to verify or resubmit necessary energy audits [6];

- aspiring to fruitful dialogue between technical innovation and architectural evaluation, banking on sensitivity and creativity typical of single item design, thus shifting the vision from the mere mimetic level to one more deeply linked to the values of architecture and landscape.

More specifically the study was articulated over the following phases, planned to suit the different scales required by the research, be it territorial, architectural or constructive – all three disciplines being inter-complementary:

1) The reading of the landscape as a system: reading of the morphological system as installed and accessibility to small settlements, identification of morphology-types already in place and recurrent building types and census of the most representative usable views from accessible public records, analysis of environmental resources, vocations and territorial sensitivity (exposition, presence of the sun, steepness, windiness...).
2) The study of rural buildings and their thermal performance: analysis of thermal features, and the energy requirements of the buildings chosen as typical of various case histories, with clarification of any criticalities arising from installed and constructive conditions (as established by Regolamento Regionale della Liguria n.1/2009 (Regional Regulations Liguria n.1/2009), with calculation of standard type (as indicated in norm UNI/TS 11300), according to European Directive EPBD 2010/31/EU.
3) The identification of technical operations suitable to improve the energy performance of the buildings (insulation techniques and plant intervention) and the definition of architectural criteria compatible with traditional building features.
4) Quantification of energy consumption saving achievable by way of the adoption of suggested technical solutions, evaluated individually (in such a way as to be able to compare the effectiveness of different intervention proposals) and in a combined way (i.e. integrating plant intervention and intervention of various types on the so-called building roof).
5) The identification of impacts on the application of energy saving technologies: visual intrusion and perception alteration: modification of ground structure and ecological systems; replacement of existing materials and loss of traditional building characteristics and the definition of recurring installation, landscape and architectural situations [7].
6) Critical analysis of guides and manuals, published mostly abroad, with particular reference to conditions of applicability and acceptability of micro-generation apparatuses in sensitive historical and landscape contexts, so as to pinpoint some criteria and determining factors for good quality intervention [8].
7) The identification of conditions for applicability of micro-generation implants fed by renewable energy sources (see the contents of Regional Energy Plan) and of factors impinging upon the architectural and landscape compatibility, with particular reference to solar technology.
8) The construction of photo-simulations and landscape insertions for recurring morphology-type situations (point 1), for different plant technologies previously referred to (point 3), for clarification of criteria and factors as at point 6 and for the laying down of guidelines.

3. TOWARDS ECO-EFFICIENCY OF RURAL BUILDINGS

The calculation of the energy performances of the three buildings chosen as representative of a larger part of rural buildings was carried out considering the climatic conditions of the localities in which these are located (Fig. 2). The first two examples are located in Cacinagora, near Riomaggiore, and feature 1437 Degree Days, in climatic zone D, corresponding to a heating season of 166 days, from 1st November to 15th April. The third case study is situated in La Costa, near Monterosso al Mare, which features a value of 1321 Degree Days, in climatic zone C, corresponding to a heating season of 137 days, from 15 November to 1st April. For the calculation of the average monthly external temperature, an interpolation has been necessary, as indicated by the norm *UNI 10349 – Heating and air conditioning of buildings. Climatic data*, of the data concerning the province of La Spezia, where the municipalities of selected examples are located.

Figure 2. The three case study (from the left): 1) bi-cellular building; 2) pluri-cellular building; 3) manor house

Assuming as hypothesis low-efficiency technical installations, in relation to the examined case studies (abandoned), the Theoretical global performance index of the buildings has been determined and associated to the energetic class of the building (Table 1 where $EPH_{,env}$ energy performance index during heating season for building envelope, represents the energy needs for the building envelope; EPH energy performance index in the heating season represents the primary energy needs of the building-heating system; EP_{gl} global energy performance index ($EPH + EP_W$) represents the primary energy needs during the heating season for the heating system and for the production of domestic hot water.

Table 1. Energy performance index [kWh/(m^2 year)]

Case study	*EPH_{env}*	*EPH*	*EP_w*	*EP_{gl}*	*Class*
1	160.9	320.5	36.1	356.6	G
2	136.2	251.3	21.8	273.1	G
3	140.2	271.8	22.06	293.82	G

The most suitable intervention to improve, in a compatible way, the thermal behaviour of a rural building are insulation of ground floor, walls and roof and substitution of the wooden frame of windows, often irreparably damaged. The analysis took in consideration also thermal lime plasters for interior or exterior uses (Fig. 3).

Figure 3. On the left a general view of insulations; technical phases of a thermal lime plaster

Table 2. Results of different improvements for case study n.1 [kWh/(m² year)]

Interventions	*EPH_{env}*	*EPH*	*EP_{gl}*	*Class*
Current state	160.9	320.5	356.6	G
Envelope isolation (10 cm), new windows	26.7	68.1	104.4	D
Envelope isolation (4 cm), new windows	44.2	100.5	136.7	E
Insulation (10 cm), condensing boiler, radiant floor heating	26.7	36.1	69.9	C
Insulation n (4 cm), condensing boiler, radiant floor heating	44.3	55.1	88.9	D
Insulation (10) condensing b., radiant floor h., solar panel	26.7	36.6	58.4	B
Insulation (10 cm), heat pump, PV cells	26.7	21.9	30.4	A
Insulation (4 cm), heat pump, PV cells	24.9	12.5	17.8	A

Table 3 Results of different improvements for case study n.2 [kWh/(m² year)]

Interventions	*EPH_{env}*	*EPH*	*EP_{gl}*	*Class*
Current state	160.9	320.5	356.6	G
Envelope isolation (10 cm), new windows	24.9	54.5	76.3	D
Envelope isolation (4 cm), new windows	33.8	74.1	96	E
Insulation (10 cm), condensing boiler, radiant floor heating	24.9	28.2	47.6	B
Insulation (4 cm), condensing boiler, radiant floor heating	35.9	39.8	59.3	C
Insulation (10) condensing b., radiant floor h., solar panel	24.9	28.5	45	B
Insulation (10 cm), heat pump, PV cells	24.9	12.5	17.8	A
Insulation (4 cm), heat pump, PV cells	35.9	18.2	23.9	A

4. LANDSCAPE AND SOLAR ENERGY: COMPATIBILITY CRITERIA

A substantial in-depth portion of the work is dedicated to the issue of micro-generation, especially in isolated contexts, not reached (or unreachable) by network systems, and to the opportunity to install plants fed by renewable energy sources, mainly but not exclusively from solar energy. The latter's undoubted potential is highlighted without neglecting the considerable limitations, especially in some sensitive landscape contexts such as of the territory under examination.

It is intended to favour respect of criteria of compatibility, clarifying a series of factors hailing from a careful reading of the state of the art for what concerns regimes and conditions of authority nationally and guidelines for the energy improvement of historical building internationally.

Such factors, of quantitative nature (depending on whether isolated systems or repeatable/grouped based on the grade of ground covering and orography), of qualitative nature (morphology of apparatus, whatever colour is chosen, possibility of impact reducing), have been clarified, visually, by way of recourse to photo-simulations to make their content clearer and their meaning more operative (Fig. 4).

The evaluation of possible impacts is not, however, limited to a strictly visual level. In it, indeed, an important role is played by the state of material preservation and construction systems. There criteria concern the possible necessity to remove traditional parts and materials, the degree of invasiveness of projected intervention on the structure and morphology of the ground, on the terracing systems and their delicate static and hydro-geological order [9].

List of determining factors for intervention quality:

- Factors of quantitative order
  - Surface extension and covering rapport (maximum size acceptable for photovoltaic plants on the ground and on roof)
  - Height (from ground, for e micro-wind photovoltaic plants)
  - Width (for ground photovoltaic installations of a large size to avoid cumulative effects and excessive ground occupation)
- Factors of qualitative order
  - Shape (relationship between geometric shape of one or more solar panels, placed alongside each other or like a roof pitch)
  - Colour (chromatic features of solar panelling)
  - Texture (installation methods of photovoltaic elements and of integration with traditional surfaces)
  - Slope (relationship with the disposition plane of the element the solar panel must be installed onto)
  - Methods of fastening/anchorage (visibility of ground and covering panel supports)
  - Methods of apparatus (possibility to fit linking panels or in a more discreet manner)
  - Methods of massing, proportion and aligning (identifying of any symmetries, generating lines of simple geometries and proportional relationships to respect both in the case of ground application and of roof installation - true for solar and micro-wind technologies).

A series of photo-simulations, in autonomous graph tables, visualizes some hypothesized intervention of integration of solar technologies. They are localized on traditional roofing, in cases of total replacement of roofing because of advanced structural disrepair (Fig.4), or in small buildings, attached to the manor house, used for farming purposes, or in overhanging shelters, not to alter the traditional roof. Technology used for the simulation is the current one, preferably coloured PV cell or copper solar tiles. The purpose is to complete as rich a picture as possible of potential projected intervention, to be considered acceptable or, conversely, non pertinent to the characteristics of the place and, therefore, unacceptable. Indeed, simulations carried out, based on a single context, often aim at clarifying conditions based on which the factors earlier identified contribute to obtaining the quality of intervention and to minimizing the impact.

Figure 4. Example of one of the photo-simulations showing the impacts of a new solar roof on the landscape. On the left, current state, on the right a virtual reconstruction of the ruined roof using solar copper tiles

5. DISCUSSION OF RESULTS AND CONCLUSIONS

The results of the research, concluded in January 2015, were partially published and gathered as a whole in a nationally edited volume [10]. Nevertheless, beyond circulation in “scientific” echelons, the most interesting spreading is at professional level, within specific training programmes organized outside the university environment by nationwide associations of engineers and architects.

The work, even without forgoing scientific rigour, aspires to offering its benefits and immediate use, as in the example of the wide range of manuals of an Anglo-Saxon nature. Spreading of knowledge and training, not only pertinent to technicians but also to owners, is key to what Anglo-Saxons identified some time ago as priority in reaching true levels of cultural betterment. It is to such publications, even online open access, the work has looked suggesting new communicative modes, in digital form, with the construction (yet to be finalized) of a specific platform on the site of the Ministry of Cultural Heritage.

In the meantime the peripheral representative of the Ministry of Cultural Heritage has permitted a site for working on a pilot recovery and energy re-qualification project of a small rural holding in the

UNESCO site, applying the principles and techniques expressed in this work. Once completed, it will then be possible to implement the study with real results in terms of resource saving.

Finally, it is hoped that the work will soon evolve into effective guidelines to be adopted by the Ministry to evaluate the acceptability of energy potentiating intervention in the site to be looked after. Even if the safeguarding organisms responsible for the site - a site classified as patrimony of mankind - have always expressed themselves most cautiously towards the installation of plants fed by renewable energy, no matter how small or even smaller still, the definition of correct permission procedure and the specification of clear criteria of compatibility remained, indeed, an open issue, the solution to which this work has offered a positive contribution. Basically the work has, in no uncertain terms, faced a particular question of method as the cautionary clarification of the criteria, in a non-limiting, binding or excessively technical way, which administrations, finance-releasing bodies and organizations in charge of patrimony protection may employ to evaluate and then certify the acceptability of specific intervention geared towards energy saving.

6. ACKNOWLEDGMENT

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The impact of architectural design interventions and occupant interactions on thermal comfort in built vernacular heritage

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Abstract – *The present paper discusses the relationship between built heritage conservation and comfort establishment. The research focuses on the contemporary architectural intervention of converting a semi-open space into an indoor space by adding extended glazed surfaces. A representative building that reflects the typical arrangement of rural vernacular dwellings in Cyprus was selected for detailed investigation. Simulation tools are used in order to investigate the impact of the specific architectural intervention in the semi-open space. Computational fluid dynamics are employed in order to present graphically the temperature distribution of various window-operation patterns that are evaluated according to the adaptive thermal comfort for both the cooling and heating period. The results indicate that occupant behaviour, concerning window operation, affects the overall thermal performance of the building and has a more prominent impact during the heating period. Conclusions highlight key directions regarding conservation practices, taking into consideration the energy efficiency and thermal comfort of the built vernacular heritage.*

Keywords – thermal comfort; semi-open spaces; architectural interventions; ventilation; occupant behaviour

1. INTRODUCTION

Cultural heritage encompasses a complex set of qualities of great significance for individuals, communities and society as a whole. The academic study of cultural heritage thus, poses great potential for defining sustainable design principles in architecture [1]. Considering the intrinsic environmental performance of heritage buildings, as well as their potential for energy upgrade, conservation and thermal comfort studies become highly relevant. However, vernacular heritage is a continuously self-regulating environment, in which occupants have a prominent role. The growing need for indoor spaces induces architectural interventions in heritage buildings, i.e. extensions, additions and other architectural adjustments, including the conversion of semi-open spaces into indoor spaces by the use of extended glazed surfaces. The introduction/insertion of contemporary architectural interventions with the use of contemporary materials and techniques, such as steel and glass, is a very common approach in the restoration/rehabilitation of vernacular dwellings. This practice is in line with international principles on conservation as the new additions differ from the original fabric, and, at the same time, establish an interesting impact in the aesthetic value of the existing structure. Conservation practices promote changes with reversibility and minimum impact on the authentic fabric [2], preserving the morphology and typology of heritage buildings and thus highlighting the principle of integrity in terms of material selection [3]. Environmental and social aspects in conservation are highlighted in the Declaration of Amsterdam [4], as well as in more recent documents, such as Faro Convention [5]. It should be underlined that the occupants' interaction with the building elements entails a valuable intangible essence as it affects the living conditions and, more specifically, the thermal performance of the dwellings.

The study of Thravalou et al. [6] gives an insight on the seasonal and daily operation of the openings of vernacular buildings and the use of semi-open spaces in Mediterranean climatic conditions. It is demonstrated, that the addition of an extended glazed surface on south facing semi-open spaces is beneficial (in energy terms) during the heating period, while it has negative results during the cooling period which indicates that the space should return to its original semi-open state. The present paper builds on the above findings and further investigates the argument in order to highlight the intangible value of original occupants' behaviour and establishes the optimum behaviour pattern concerning window-operation in heritage buildings in Mediterranean climatic conditions. Simulation tools and CFD methods are used for the evaluation of multiple ventilation strategies. The objective is to enrich the open dialogue towards conservation practices across the Mediterranean region, bringing energy efficiency and comfort into the discussion about cultural heritage.

2. METHODOLOGY APPROACH

2.1 The case study building

The study focuses on rural vernacular architecture as it has evolved in a typical traditional settlement in the central lowland area of the island; namely, Pera Orinis. The local climatic conditions are described by short mild winters and hot dry summers. Minimum temperatures reach 5.7°C whereas maximum temperatures reach 35.5°C. The semi-compact configuration of the settlement of Pera Orinis, and the prevailing southern orientation of dwellings, allow direct and indirect solar gains during the heating period, i.e. winter, and desirable shading from the immediate environment during the cooling period, i.e. summer. A semi–open space, locally referred to as *iliakos*, is adjacent to the building volumes, usually on the south façade of the main living space of the dwellings [7].

A representative traditional dwelling, located in this particular settlement, is selected as a case study for in depth investigation (Fig.1). The dwelling under study is a one-storey house attached to adjacent buildings. It consists of the typical traditional rooms of the vernacular architecture of the island - a main double space room (*dichoro*) with an arch dividing the space into two parts, an inner space (*sospito*) with a mezzanine for storage purposes (*sente*) and two small auxiliary spaces (*monochoro*). In contact with the *dichoro,* and in direct relation with the central courtyard, lays the south adjacent semi-open space (*iliakos*). *Iliakos* has a notable height/width ratio of 1.50, with a space height of 4.20m, and a rather narrow width of 2.80m. Its geometrical features allow sun rays to penetrate into the *iliakos* and *dichoro* during the heating period, while providing protection during the cooling period. This is due to the higher altitude of the noonday sun, during the summer solstice, i.e. 78° compared to the relative altitude during the winter solstice, i.e. 32° (Fig. 1). Respectively, the *dichoro* is a deep space with a high ceiling, at approximately 4.50m. The height and inclined roof reduce the negative effect of excessive solar heat gains through the roof. In terms of materials and construction techniques, the masonry walls, of approximately 0.50m width, are made of adobe bricks laid on a stone base and thus have high thermal mass. The floor is covered by traditional gypsum slabs and the roof is made of timber, reeds, earth and traditional ceramic tiles. In recent renovation works on the roof, the earth was removed and a thermal insulation material, i.e. extruded polysterne of 0.05m width, was added.

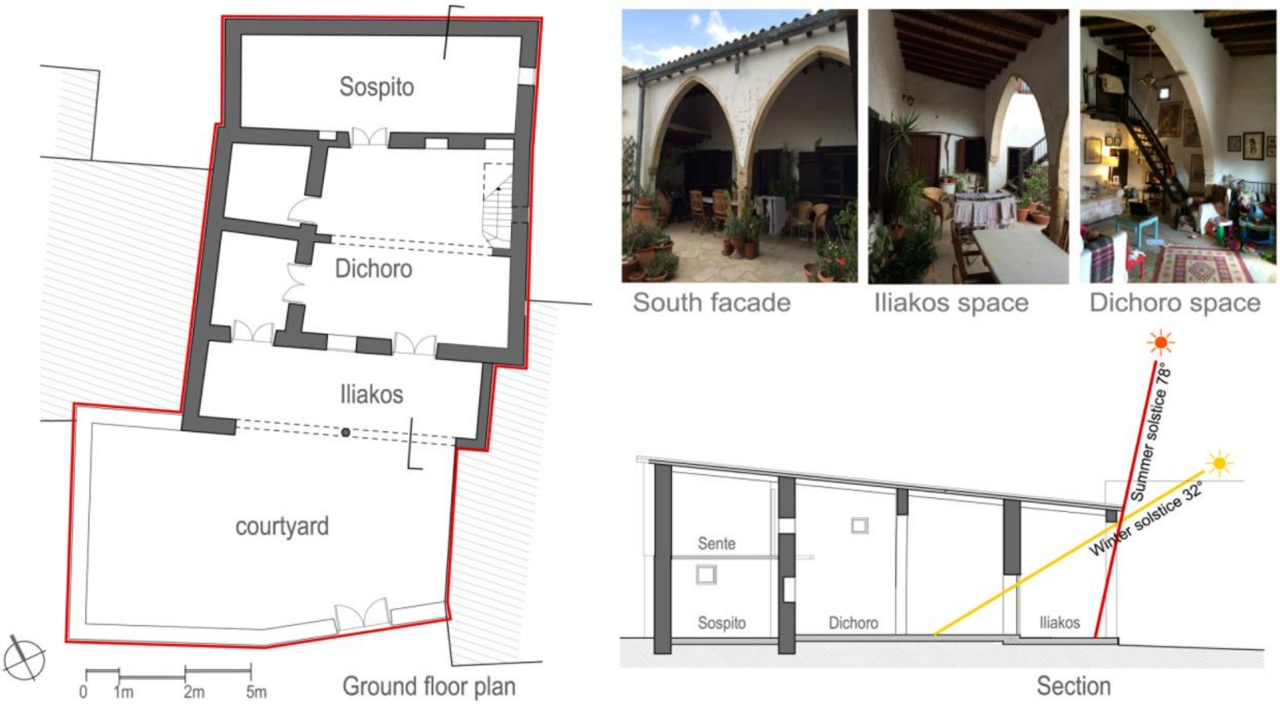

Figure 1. The case study building plan, section and views

2.2 Simulation tool

This study employs the dynamic thermal simulation tool EnergyPlus v8.3 through the graphic interface of Design Builder v4.6 software and the CFD flow solver of the same platform. Natural ventilation and infiltration were calculated based on window openings, cracks, buoyancy and wind-driven pressure differences. The ventilation control mode was set to constant and the airtightness of the building is deemed good. Simulations employ full interior and exterior solar distribution, taking into account direct solar and light transmission through internal windows. The thermal properties of the construction materials were identified by the use of non-destructive experimental methods [6]. For the CFD simulation, finite volume methods (FVM) were used to solve the partial differential equations with the turbulence model k-e. The initial surface temperatures were set using the boundary conditions from EnergyPlus results. The default grid spacing and merge tolerance were defined as 0.20m and 0.025m, respectively.

Field measurements were recorded and used comparatively in order to confirm the predictive accuracy of the model. For this purpose, indoor temperature and relative humidity levels (USB-2-LCD data loggers), as well as external weather data (Davis Vantage Pro-2) were recorded. Following, the inequality coefficient (IC) [8] was used, ranging in value between 0 and 1, with 0 indicating a strong correlation between measured and simulated data. The IC was found to be 0.15 for the *dichoro* and 0.19 for the *sente*. The results indicate a fair level of accuracy of the simulation tool and credibility in terms of prediction of the indoor and outdoor environment.

2.3 Thermal comfort background

The case study building is a free-running building; therefore, the adaptive approach integrated within ASHRAE Standard 55 [9] is adopted. The acceptable indoor operative temperature, T_{comf}, is calculated as by $T_{comf} = 0.31 \times T_{a\ (mean)} + 0.31$, where $T_{a\ (mean)}$ is the mean monthly outdoor air temperature. Results are reported for the temperature band of 7°C, i.e. T_{comf}±3.5°C, which applies for 80% acceptability. Although the above approach is used for predicting indoor comfort, it is noted that for the purposes of this paper it is also used for the assessment of the transitional space of the *iliakos*.

2.4 Case study scenarios

According to previous research [6], the installation of glazed surfaces on the arched openings of the *iliakos* is beneficial during the heating period, i.e. December to March, whereas during the cooling period, i.e. June to September, the intervention is not desirable and should be reversed. The different states of the *iliakos*, i.e indoor space during heating period and semi-open during cooling period, are further investigated in terms of preferable window-operation pattern. More specifically, various natural ventilation strategies, i.e. no ventilation (C1, H1), all-day (24-hours) ventilation (C2, H2), daytime (07.00-19.00) (C3, H3) and night-time (19.00-07.00) ventilation (C4, H4) are comparatively examined.

3. RESULTS AND DISCUSSION

An overview of the thermal performance of the spaces under study, shown in Table 1, reveals that the dwelling is more apt during the cooling period. Despite the south orientation of the building, the *dichoro, sente* and *sospito* have limited potential of direct solar gains exploitation. On the other hand, the introverted and compact character of the building, in addition to the thermal mass of the buildings' envelope, enhances thermal comfort during the cooling period. Specifically, the *sospito* is the most preferable space during the cooling period, with comfort conditions offered for the vast majority of time, varying from 98.4% to 99.9%. By contrast, it is the least preferable space during the heating period, with comfort conditions offered for the minimum percentage of time, varying from 5.8% to 9.4%. This is attributed to its limited potential for direct and indirect solar gains, as it is located on the north side of the building. However, the *sospito* demonstrates high thermal stability during both seasons, due to its limited exposure to the external environment (Fig. 2). On the contrary, the *sente* is the least preferable space during the cooling period, with the percentage of time offering thermal comfort conditions varying from 43.1% to 53.5%. The above performance is linked to the fact that the *sente* is directly affected by solar heat gains through the roof, as well as by the rise of warm interior air from the lower level of the *dichoro*. The main space of the house, i.e. the *dichoro,* has quite satisfactory performance during the cooling period with comfort conditions offered for the majority of time, varying from 80.6% to 88.6% compared to the rather poor performance of the space during the heating period when the respective percentage varies from 19.6% to 32.3%.

Table 1. Percentage of time within the comfort zone of 80% acceptability for heating and cooling period

	Iliakos	*Dichoro*	*Sente*	*Sospito*
***Iliakos* as semi-open space** *(Cooling period)*				
C1- No ventilation	55.1	84.9	43.1	99.9
C2- All day ventilation	57.1	81.5	48.5	99.8
C3-Daytime ventilation	56.2	80.5	47.9	98.4
C4- Night-time ventilation	56.9	88.6	53.5	98.7
***Iliakos* as indoor space** *(Heating period)*				
H1- No ventilation	59.1	19.6	12.7	5.8
H2- All day ventilation	49.0	32.3	15.0	8.8
H3-Daytime ventilation	51.6	31.6	15.5	9.4
H4- Night-time ventilation	51.6	27.8	14.5	8.2

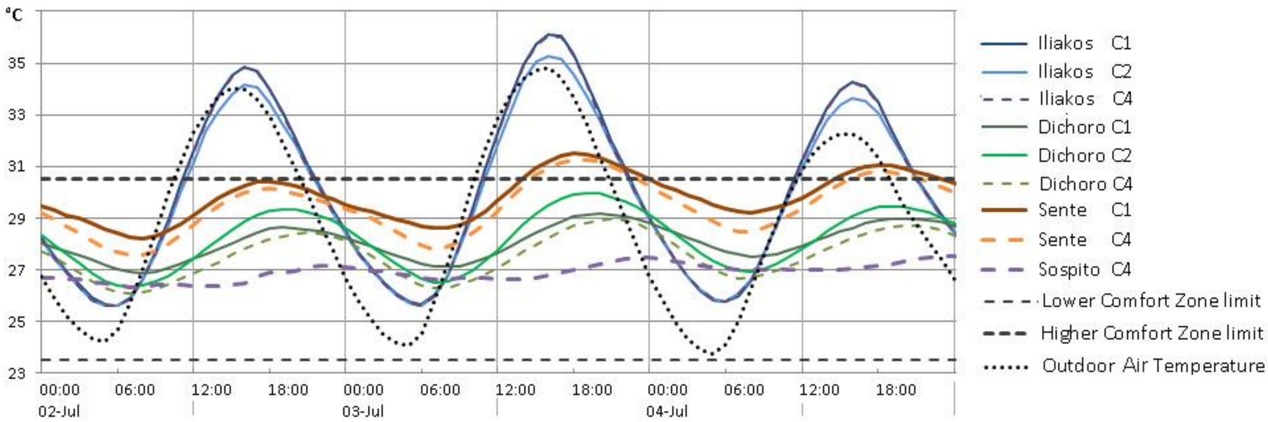

Figure 2. Hourly temperature distribution during cooling period

The CFD results shown in Fig. 3 present the air temperature distribution in cross sections for two selected case study scenarios for each period under study. As observed, there is a continuous airflow between the *sente* and *dichoro*, through an interior window that has no frame or glazing. In this way, the temperature difference between the two spaces causes a density difference whereby the interior opening between *sente* and *dichoro* drives outflow and the lower opening at the *dichoro* drives inflow (more intense during the cooling period) (Fig. 3, C3 and C4). The temperature distribution across the examined spaces is produced as a consequence of the two simultaneous effects of wind driven ventilation and stack effect ventilation. During the heating period, the installation of glazed surfaces on the arches of the *iliakos,* enhances the operation of the *iliakos* as a thermal buffer zone converting it into a solar space which acts as an effective passive heat gain system. As observed in Fig 2, the temperature in the *iliakos* reaches higher levels than in the external environment. This is mainly attributed to the thermal mass of the building envelope (adobe walls) that absorbs direct and indirect solar gains during daytime and releases thermal energy, with a time delay, during night-time. Consequently, maintaining the openings of the *dichoro* open allows heat flow towards the main living areas of the building. Indeed, according to the findings, case study H2 that reflects all day ventilation of the *dichoro,* corresponds to the greatest performance of the *dichoro*, presenting 32.3% of time within the comfort zone. Similar performance (31.6%) is recorded in case study H3, i.e. daytime ventilation, as direct solar heat gains of the *iliakos* are exploited and distributed (Fig.3, H2). When maintaining the *dichoro* openings closed, i.e. H1, heat distribution from the *iliakos* is prevented (Fig.3, H1) and thus the poorest performance in the *dichoro,* and in all the other spaces under study, is noted. On the contrary, as expected, the case of no ventilation applied, i.e. H1, corresponds to the best recorded performance for the *iliakos* space, with 59.1% of time within the comfort zone.

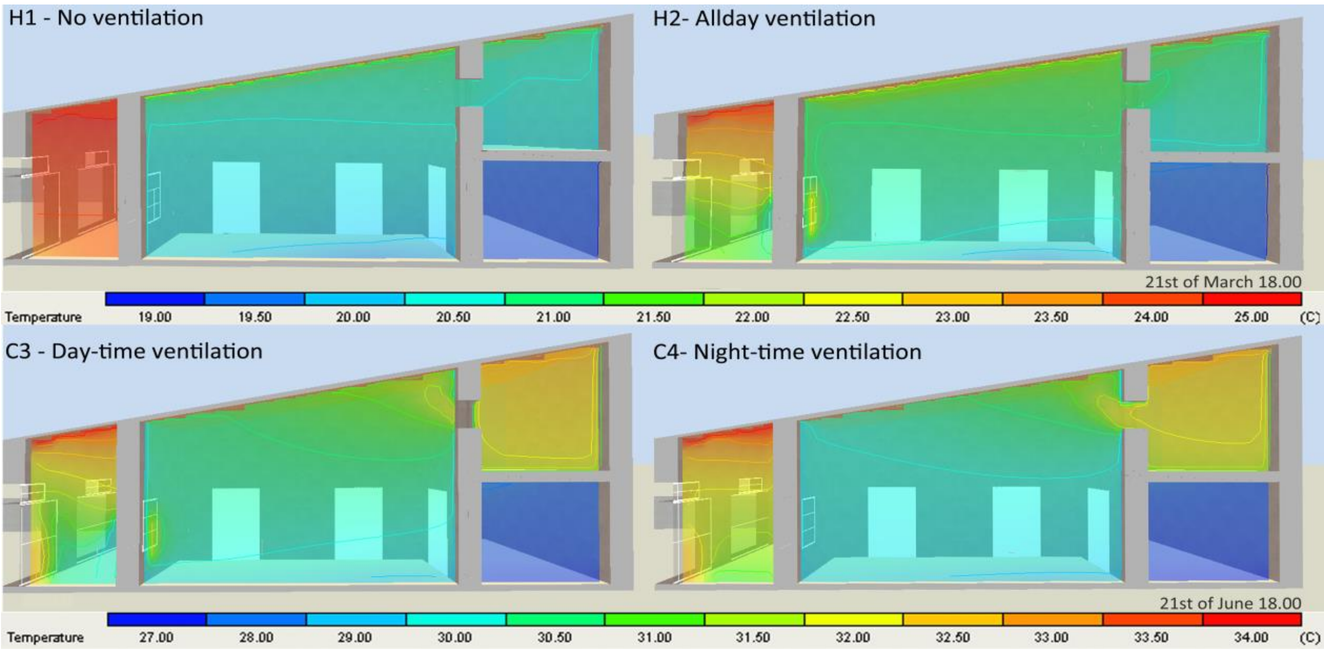

Figure 3. Temperature distribution across the building in cases H1, H2, C3 and C4

During the cooling period, the *iliakos* functions as a semi-open space, thus it is more susceptible to daily temperature fluctuations of the exterior environment. The application of night-time ventilation i.e. C4, increases the thermal comfort performance of the *dichoro* and *sente* (with 88.5% and 53.5% of time within the comfort zone respectively) compared to the daytime ventilation strategy i.e. C3 (80.6% and 47.9% respectively). In the case of night-time ventilation, openings are kept closed during the day when outdoor temperature rises (Fig. 3, C4), while greater air change rate during the night enhances convective heat loss from mass elements and dissipates the heat outdoors. In this case, maximum air temperature levels are maintained in lower levels (Fig. 2). The results on the effectiveness of night-time ventilation in heavyweight buildings in Cyprus are in line with other researches [10].

4. CONCLUSIONS

The present study discusses the impact of contemporary architectural interventions and occupant interactions with the building elements on ventilation. The intervention under investigation is the conversion of south adjacent semi-open spaces into indoor spaces during the heating period, in the Mediterranean climate of Cyprus, focusing on the optimum window-operation pattern. The research indicates that occupants' behaviour has more impact on thermal comfort during the heating period rather than on the cooling period. More specifically, during the heating period, when *iliakos* functions as a solar space, the opening of the windows of the *dichoro* is recommended as it allows heat flow towards the inner spaces. Such heat flow significantly affects the *dichoro,* while air temperature levels in the *sospito* and *sente* are barely affected. During the cooling period, when the *iliakos* functions as a semi-open space, night-time opening of the *dichoro* windows records the best performance as the induction of cool external air cools down the building envelope. The *sente* is also positively affected by the application of night-time ventilation during the cooling period. The *sospito* offers thermal comfort for the vast majority of time, regardless of the ventilation strategy applied.

In summary, the research findings highlight that occupant interaction with the building envelope offers great potential for energy savings and comfort establishment in naturally ventilated heritage buildings. Considering that occupants' behaviour assimilates significant intangible values of social, environmental and identity aspects, the importance of documenting and conserving original occupants' interaction with the building elements is brought forth. By extension, it is deduced that enriching conservation practices with energy efficiency aspects entails actions in two key directions; firstly, the identification of the environmental design principles of heritage building envelopes and secondly, awareness raising regarding energy related occupant behaviour. In this way, all values of cultural significance are taken into consideration with the scope of merging culture and energy performance into creating meaningful and sustainably inhabited heritage environments.

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USING AND IMPROVING ENERGY MODELS

Modelling impact of collections on indoor climate and energy consumption in libraries and archives

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Abstract *– COMSOL Multiphysics was used to model the moisture uptake and release for library and archival collections in response to variations of temperature and relative humidity (RH) in their environment. These results were coupled to the modelling of indoor climate and energy consumption in collection storage spaces with the use of the WUFI®Plus software. The study revealed the crucial impact of air-tightness of the building on the indoor climate stability and the humidification and dehumidification loads required to provide selected climate control classes. In the adequately air-tight storage spaces, sizeable paper collections were found to diminish the energy consumption by at least 22%. For the 'cool storage' conditions, optimal for the preservation of library and archival materials, the impact of the collection on the energy consumption was reduced due to high average RH levels which required considerable dehumidification year round. The research was supported by Grant PBS2/A9/24/2013 from the Polish National Centre for Research and Development.*

Keywords – Hygrothermal modelling; indoor climate; energy consumption; libraries and archives; moisture buffering

1. INTRODUCTION

In recent years, considerable attention has been given to managing indoor environments in museums, libraries and archives in a responsible manner, particularly in terms of reducing energy use and carbon emissions [1, 2]. Indoor microclimates are an outcome of many factors, of which construction materials used, air-tightness of the building envelope, its thermal insulation, installed climate control systems of ventilation, heating, humidification or dehumidification, and the collections housed in the building are the most important. A lot of effort has been put into assessing energy consumption in the specific buildings while taking into account different indoor climate control scenarios (the recent publications comprise refs. [3-5]). And yet, all approaches to modelling the indoor climate lack any precise estimations of the buffering effect by hygroscopic heritage objects housed in a building. Only approximations have been used so far to tackle this issue ([6, 7] and references quoted therein).

In this study, WUFI®Plus and COMSOL Multiphysics software codes were used to investigate the buffering effects of paper collections in libraries and archives on the indoor microclimate conditions [8, 9]. WUFI®Plus allows fully coupled heat and moisture transport problems to be modelled for different building components, such as exterior or interior walls, ceilings and floors. Additionally, the software takes into account the heat and moisture sources and sinks located inside rooms, including ventilation, heating, cooling, dehumidification and humidification processes. The simulations can be further used to determine energy consumption under selected scenarios of microclimate control, based on recommendations or specifications for managing environmental conditions for heritage asset collections. WUFI®Plus however, has limitations in simulating objects other than walls or ceilings, for which heat and moisture transport proceeds through more than one surfaces. In such cases, COMSOL Multiphysics turns out to be useful, as it can precisely simulate heat and moisture transport in objects of complex geometries. In fact museum, library and archival collections comprise objects of complex forms absorbing water vapour from the surrounding environment through many surfaces.

2. METHODOLOGY

The general approach to investigating the buffering effect of cultural heritage objects on indoor microclimate in this work is divided into two steps. First, a detailed numerical simulation of water vapour uptake or release by heritage objects of given dimensions, is performed with the use of COMSOL Multiphysics. The results of the simulation constitute an input into the WUFI®Plus modelling, as the second step of the procedure. The buffering impact of collections on the indoor climate, and on the energy consumption for cooling, heating, humidification or dehumidification, are investigated in the second step, depending on the selected climate control scenario.

2.1 Collections investigated and climate control scenarios

For the purpose of approximating paper collections in archives or libraries, a statistical book was created basing on the measurements of sizes of 384 books from the storage of the National Library in Warsaw. The average obtained dimensions were 261 × 186 mm^2. Thickness can take any value, to represent the required number of books placed next to each other on a bookshelf. For such statistically determined book dimensions, a numerical simulation of water vapour sorption was carried out using COMSOL Multiphysics. A relative humidity (RH) step from 30% to 70% was considered. The following material properties of paper were used: density of 690 kg/m^3, water vapour permeability of 9.6E-11 kg/msPa, measured in specimens imitating a book in the direction parallel to the paper sheets, surface emission coefficient of 3E-8 kg/m^{2}sPa, sorption isotherm measured at 24 °C and described by the Guggenheim-Anderson-de Boer three-parameter sorption equation with the constants v=5.23%, c=15.03, k=0.6 [10]. Sorption of water vapour by a real book in response to the same RH step change was measured gravimetrically and the results agreed very well with the numerical simulation.

In computer simulations of books placed next to each other on a bookshelf, only two of six book surfaces are assumed to significantly absorb/desorb water vapour from the surrounding space. Close packing of books on the bookshelves and book covers block the water vapour penetration through two side surfaces, and the book spine and the bookshelf itself isolate the back and bottom surfaces of a book. Since WUFI®Plus cannot model any two-dimensional (2D) sorption process, the statistical book was represented by another cuboid, with the same volume and only one side open to water vapour transport.

The surface of this new side is the sum of two surfaces of the initial statistical book. The obtained dimensions of the new 'equivalent' book are 447×109 mm^2. This change has led to the shortening of time needed for the material to reach the new equilibrium moisture content, in response to a step change of RH. To correct this effect, the original diffusion coefficient was systematically decreased. A perfect agreement between the 'true' 2D water vapour diffusion and sorption in the books, and their 1D approximation was achieved when the diffusion coefficient was divided by 1.5 that is to say was taken to be 6.4E-11 kg/msPa. Such 1D model of a statistical book with the modified diffusion coefficient was implemented in the WUFI®Plus simulations.

Four climate control scenarios based on the ASHRAE specifications for classes of climate quality in museums, libraries and archives were analysed [11]. First, the ASHRAE highest class of climate control AA was considered reflecting the conventional 'ideal' option, and a single value RH target of 50% with conservative tolerance of variations of ± 5% was selected. The ASHRAE B class of control was selected as the second case, in which RH was allowed to vary between 40-60%. This class of control is a moderate-cost strategy in historic buildings – also in use by museums – of limited potential for tighter climate control. At the same time, class B constitutes little risk to most paintings or artefacts and no risk to most books. International Institute of Conservation IIC and ICOM Conservation Committee recommended the 40 – 60% RH range as acceptable for loaning objects containing hygroscopic material (such as canvas paintings, textiles, ethnographic objects or animal glue) to international exhibitions [12]. The ASHRAE class of control C, in which RH was assumed only to stay within the 25-75% RH range all year round, was selected as an option in which just high risk extremes are prevented. In all three climate control scenarios described, the temperature was maintained at a constant level of 21 $^{\circ}$C all year round to ensure human comfort. The ASHRAE 'cool storage' recommendations optimal for the preservation of library and archival material, were the last climate control scenario. The RH range between 30 and 50% and natural yearly temperature cycle, but not dropping below 10 $^{\circ}$C, was assumed.

2.2 Modelling of indoor climate

A typical storage space of $14 \times 15 \times 2.5$ m^3 (volume of 525 m^3) in a historic building housing a library or an archive was considered. The building envelope was modelled with the following materials (interior to exterior): walls – cement plaster (0.015 m), ceramic brick (0.51 m), sandstone (0.1 m); floor – stone (0.05 m), cement base (0.05 m), reinforced concrete (0.3 m); celling – cement plaster (0.015 m), reinforced concrete (0.15 m), mineral wool (0.05 m), cement finish plaster (0.05 m), asphalt roofing felt (0.005 m). The water and heat transport properties for these materials were taken from the WUFI®Plus database.

Basing on a typical capacity of storage spaces for paper collections, it was assumed that the storage room housed shelves of the total length of 1780 m. Books of statistical dimensions of 447×109 mm^2, placed next to each other on the shelves, took up 16% of the room space. Half of that space occupancy, 8%, was also considered in the simulation.

Natural ventilation of the storage space, typical of most historical buildings, was assumed. Two aspects controlling the natural ventilation – the air tightness of a building and its pattern of use – are reflected in the air changes per hour (ACH). Five libraries studied in the UK showed a range of ACHs between 0.28 and 0.93 h^{-1} [13]. Two extreme values of 0.3 and 0.9 h^{-1} were considered for the climate control scenarios in which temperature was maintained at the human comfort level of 21 °C, therefore, in which the conditions are suitable for people visiting the storage rooms or working in them.

In contrast, low ACH of 0.04 h^{-1} was assumed for the 'cool storage' conditions as they can be established at low running costs if the storage space is kept tight and the human traffic and work is kept to a minimum. Such ACH level was estimated in a storage facility at Vejle, Denmark, in which the concept of passive climate control through air tightness of the building supported by the auxiliary dehumidification was implemented [14]. A statistical climatic data for Krakow were taken as outside weather conditions. The energy required to remove or add 1 kg of water by dehumidification (desiccant wheel) or humidification was assumed to be 1.3 and 0.6 kWh, respectively. The moisture content in the building shell or paper was assumed to correspond to 60% RH at the start of the simulation. To avoid the effect of this initial condition on the results, two yearly cycles were considered in the simulations, whereas the results analysed come only from the second year.

3. RESULTS

3.1 Buffering effect of the collections

Figures 1 and 2 show the indoor RH in an empty room and in the same room when paper collections of increasing volumes were introduced, for two different ACH values and the constant temperature of 21 °C. The stationery heating regime bringing the indoor temperature to a human comfort level caused low RH indoors in cold periods as the cold air outside is drawn in and heated. As a result, the ASHRAE lowest class of climate control D (RH below 75% all year round) was attained in the empty room. The buffering effect of the paper objects begins to be meaningful only when ACH is lower than 0.3 h^{-1} in which case the minimum RH in winter is brought within the boundaries of ASHRAE class of climate control C when the amount of paper stored is sufficient. Increasing ACH to a level of 0.9 h^{-1} rises the rate of outdoor air ingress into the building, which decreases the impact of the paper collections.

For the building with ACH=0.04 h^{-1} and the "cool storage" climate conditions, the indoor average RH levels are around 60% RH. Therefore, dehumidification needs to be continually operated to ensure the required RH range between 30 and 50% RH. The buffering effect of the paper collection only minutely reduces the maximum RH level in the summer (Fig. 3) and therefore plays an insignificant role in bringing climate to the optimal conservation conditions selected.

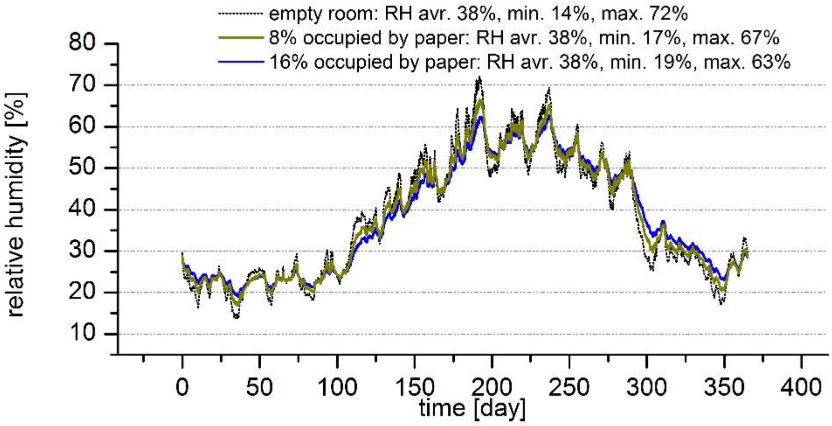

Figure 1. Buffering of indoor climate by paper collections for ACH=0.3 h^{-1} and temperature of 21 ˚C.

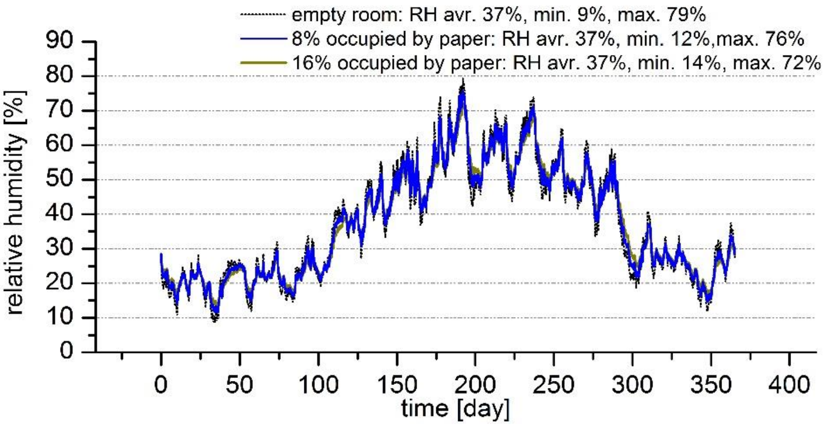

Figure 2. Buffering of indoor climate by paper collections for ACH=0.9 h^{-1} and temperature of 21 ˚C.

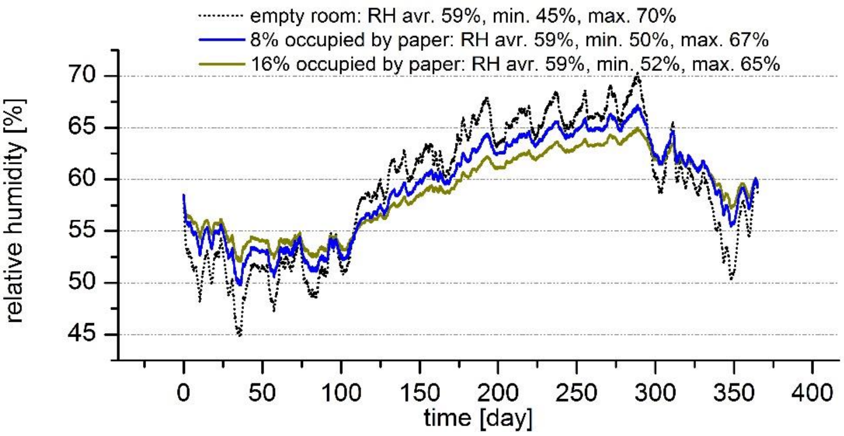

Figure 3. Buffering of indoor climate by paper collections for ACH=0.04 h^{-1} and the natural yearly temperature cycle between 10 and 21 ˚C.

3.2 Energy consumption under various climate control scenarios

The energy demands for dehumidification and humidification calculated for various climate control scenarios and ACHs are collected in Tables 1 and 2.

Table 1. Energy consumption for humidification (Hu) and dehumidification (De) of a 210 m^2 storage space with varying volume of paper collections, for different climate control scenarios and ACH levels.

Percentage of storage space occupied by paper	ASHRAE AA (45-55% RH)		ASHRAE B (40-60% RH)		ASHRAE C (25-75% RH)	
	Hu [kWh]	De [kWh]	Hu [kWh]	De [kWh]	Hu [kWh]	De [kWh]
ACH=0.3 h^{-1}						
0	1981	530	1446	236	227	0
8%	1796	417	1306	142	175	0
16%	1625	335	1168	76	127	0
ACH=0.9 h^{-1}						
0	6063	1831	4499	975	932	33
8%	5499	1523	4082	757	779	1
16%	4974	1274	3690	585	658	0

Table 2. Energy consumption for humidification and dehumidification for the "cool storage" climate control scenario (210 m^2 of storage space).

Percentage of storage space occupied by paper	"Cool storage" (30-50% RH), ACH=0.04 h^{-1},	
	Humidification [kWh]	Dehumidification [kWh]
0	0	469
8%	0	429
16%	0	394

The data in Table 1 confirms entirely the expectation that maintaining the ASHRAE rigorous climate control scenario AA is the most demanding energetically whilst the ASHRAE most relaxed climate control class C practically does not require energy input when the storage space contains paper collections of sufficient volume. The data reveal the crucial impact of air-tightness of the building, reflected in the ACH values, on the humidification and dehumidification loads required to provide selected climate control classes. The total energy consumption is reduced by a sizeable paper collection by at least 21% when compared with the empty space (the worst case of the climate control class AA combined with high ACH of 0.9). Lower reduction of 16% in the energy consumption is caused by the collection in the case of the 'cool storage' conditions as the moisture buffering by paper has merely a smoothing effect on the yearly variations of the indoor RH around high average level of approximately 60% (Fig. 3). Therefore, a considerable dehumidification all year round is required to maintain the desired 30-50% RH range.

4. CONCLUSIONS

Although a lot of effort has been put into assessing energy consumption to maintain stable indoor microclimate in the memory institutions preserving cultural heritage collections, so far heat and moisture buffering by the stored collections has not been integrated into the simulations. This study analysed quantitatively the impact of paper collections on indoor climate and energy consumption in libraries and archives by implementing a model of a paper 'wall' equivalent to the library collection in the simulations. The results indicated that the collections can have a visible although not significant effect on stabilising the relative humidity, by absorbing and releasing moisture, only when air exchange rates are low. However, the impact of collections on the humidification and dehumidification loads and the related energy consumption crucially depends on the climate control scenarios and need to be assessed individually for each specific case.

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A new Tool for accurate Energy and Comfort Assessment of Historic Building

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Abstract – *Through a case study building equipped with an advanced monitoring system, the reliability of modern dynamic tool is analyzing by the assessment of energy and comfort performance of building thermal model. A new calibration strategy tailored for historic building is presented.*

Keywords – Historic building; calibration; Standard Assessment Procedure (SAP); comfort assessment; EnergyPlus,

1. INTRODUCTION

For historic buildings the resulting reliability of retrofit is even more uncertain because the prebound effect [1], the uncertainty into performance estimation and investment cost are even higher than other buildings. However, this paper puts forward the hypothesis that more can be done to preserve heritage while reducing energy consumption, utility costs, and environmental impact. Results reveal that the key to the development of optimal retrofit measures is the correct assessment of the operational (pre-retrofit) performance of the building considering also comfort conditions and occupancy behaviour.

Although modern dynamic energy modelling tools are very flexible, they have some limitation on describing a specific building and system [2]. It is therefore important to verify the reliability of the developed models before the retrofit design and currently several research groups are working on the development of model calibration procedure. Other important aspect in retrofit design, even more important that energy performance, is the comfort assessment, therefore there is the need that the tools used for the design should be calibrate to accurate predict also comfort condition in the building. In this paper we present a strategy to calibrate the building by considering both energy and comfort assessment.

2. METHODOLOGY

The methodology presented here it is implemented to be a general tool to use in the contest of historical buildings, but it could be easily adapted to existing buildings. The historic buildings are characterized by many uncertainties: ancient materials, construction layers, variable occupant behaviour, and thermal response due to massive walls with solar exposure. An accurate estimation of energy conservation measures can be obtained only if the actual building energy behaviour is captured by the model. The methodology represents an advancement of recent published work of the author [3]. Here only the new developments are presented addressing the improvements achieved and discussion on open research points while refers to the more extensive work for more details on the model development process and experimental activities connected.

2.1 Model approach

The EnergyPlus simulation engine is used in this research. No interfaces were used, commercial or otherwise, to interact with the text-based input files other than communication with software tools written by the authors. The choice was to retain as much physical modelling as possible, therefore the models physical dimensions, material constructions, schedules, loads, and HVAC systems are consistent with actual building according to data gathered during audits, including manually operable (simulated) windows, a heating system with radiator, and an air flow network (AFN) to account for natural ventilation. This model strategy fits into our general strategy because we are interested to evaluate the thermal response of each zone and each surfaces considered. In this way the, interior heat gains, occupancy profiles of each zone could be easily schedule in more realistic way and the comfort and energy assessment could be analysed in more details.

2.2 Calibration procedure

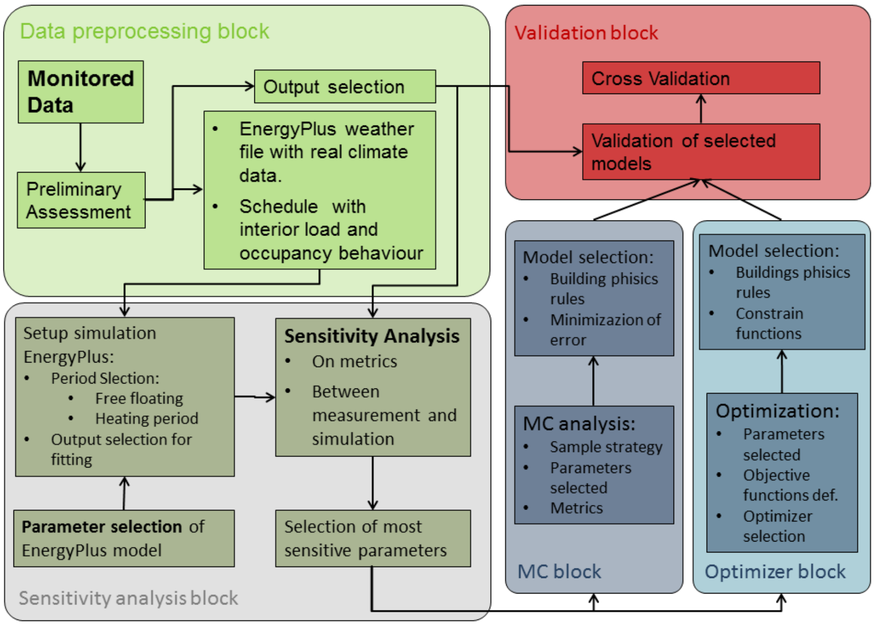

Figure 1. Calibration Procedure Diagram

The calibration procedure is resumed in six main blocks as presented in Fig. 1.

In the “data pre-processing block” the tool has all necessary capability for data period selection and raw analysis: sensor node extraction, plot functions, data filtering and interpolation. In this phase of the procedure weather data are elaborated both to extract the main features of the local weather condition for one or multiple years and to create custom EnergyPlus weather file. Monitored data are analysed to create evented based and time series schedule input files for the simulations. Other important choices are the variables for the calibration, two configurations are presented: Method A considers that the calibration should be in respect to indoor air and surface temperature, and Method B considers that the calibration should be in respect also to the indoor relative humidity.

In the “sensitivity analysis block” the parameters of the models are classified in respect to their capability to influence the calibration with respect to the metrics selected. Fixing the others to their nominal values is useful to reduce the dimension of optimization that will follow in the second step of the calibration procedure. This sensitivity analysis objective is called factor fixing (FF). A powerful method that supports this objective is the Elementary Effect Method (EEM). The EEM implementation in the statistical software package R was used.

In the calculation block two alternatives are implemented. The Monte Carlo technic allows exploring the uncertainties that remain in order to analyse the model variance. Moreover a multi criteria optimization algorithm is implemented since it allow to optimize several objective functions in contradiction at the same time without the need of combining them into one single-objective scalar function, which introduce some problems for no convex part of the Pareto front. The result of the optimization is a set of near optimal solutions that approximate the Pareto front of the objective space. Those solutions could be used to select different model configuration which simulate the building behaviour. The second approach is selected in this procedure by using a model with only the sensitive parameters.

In the validation block the tool provides several functions that help select the best parameter sets based on predefined criteria, reconfigure models to produce time series plots for a specific configuration and period of year, and analyse the model’s performance by comparing it to measured data.

2.3 Metrics

Root mean square error (RMSE) was considered as a metric since it is a good overall measure of model performance. Considering F_{ei}, the model estimate at time i; and F_{oi}, the observation at time i; the subscripts e and o correspond to model-estimated and observed quantities, respectively, the subscript i refers to the i-th hour of the day, N the length of time vector of measure and simulation. RMSE (1) is also a generalized metric without the need to apply a post-normalization that makes the metrics time dependent, as CV-RMSE [4]. The advantage of normalization is giving the possibility to enrich the objective function with variables of different nature, like energy and temperature, but is not necessary in the presented procedure. The final metric adopted by the procedure is the sum of RMSE calculated in each fitting (2). For Method A there is one objective function while for Method B there are two objective functions, one for the temperature RMSE and one for the relative humidity RMSE. This simple formulation allows considering the contribution of each zones and surfaces to the overall error of the model and offers the possibility to compare different time period.

$$RMSE = \left[\frac{1}{N-1} \sum_{i=1}^{N} | \Phi_{ei} - \Phi_{oi} |^2 \right]^{\frac{1}{2}} \tag{1}$$

$$RMSE_{TOT} = \sum_{i=1}^{N} RMSE_i \tag{2}$$

2.4 Performance assessment

The calibrated model is used also to evaluate the performance of the building, to compare its capability with other strategy of assessment and with billing consumption data properly disaggregated and corrected using heating degree days (HDD). Standard assessment procedures are compute by using PHPP and EnergyPlus model accordingly developed. This comparison allows estimating the prebound effect of the standard calculation for the buildings considered, using static and dynamic, to assess the capability of the calibration procedure to increase the reliability of dynamic tool to analyse the energy performance of the building. The comfort assessment is performed by calculate Fanger model using ISO 7730 method on monitoring data and comparing the results of the EnergyPlus simulation considering different model configurations. Two EnergyPlus model configurations are analysed, one uses FDM algorithm and the other the HAMT algorithm. This choice allows comparing the capability of thermo hygrometric balance to the traditional used thermic heat balance in describing indoor microclimate and comfort condition.

2.5 Case study, equipment and material used

At the end of the sixteenth century D'Accursio Palace, began to show the consistency of its current form. The office building represents a common example of the reuse and retrofit of historic buildings in city centers across Europe. The four-story building is approximately 775 m2 per floor, with an oil heating plant supplying hot water for a hydronic radiator system. The materials of the palace are typical for the area: brick for the load-bearing structure, sandstone for the decorative pieces with wood beams, sheathing, and roof tiles. The thickness of the exterior walls varies from 30 to 100 cm, depending on floor considered and orientation. A Zigbee wireless monitoring system was installed in the building in order to record information about indoor and outdoor microclimate, wall thermal response, occupancy behaviour and electric energy consumption at floor and plug level. A weather station was mounted on the rooftop of the building. Solar radiation data and cloud cover index were obtained from Solargis and all data were verified against those from the local weather station installed on the rooftop of other building at 1.2 km of distance.

3. RESULTS

3.1 Model calibration

A detail overview of the results is presented using time series plot for Method A and B, Fig. 2.

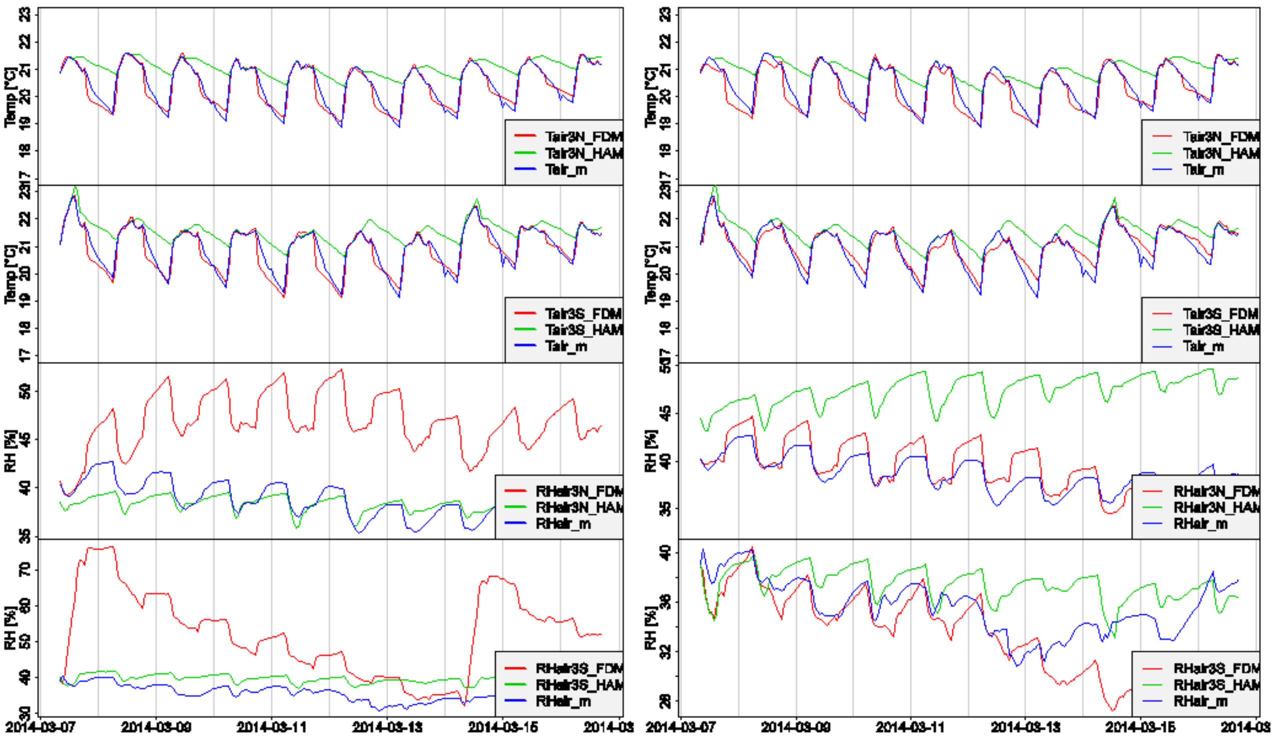

Figure 2. Model Calibration using Method A (left) and Method B (right). Each Figure shows the comparisons between monitoring data and two simulation setup in two room of the building, one facing north (3N) and the other facing south (3S) at the third floor. Finite Difference Method (FDM) and Heat & Moisture Method (HAMT) are presented.

Temperature profiles are well represented by FDM but not from HAMT using both calibration method. Surface temperature are not reported here but not vary from what it was presented in [1]. Even if the RH has not strong influence on heating demand for the building considered, it has an impact on comfort assessment and an even bigger importance for the methodology in general since the control of the RH is one of the main objectives of conservation guideline. The two zones presented are selected since allow to analyse the reasons of the discrepancy of RH profile: The room 3N is empty in the period selected while room 3S is occupied only on Friday (March 7 and 14) where the biggest discrepancy is detected. Using Method B the reliability of the FDM model increase considerable and it could predict well both occupied and not-occupied zones. The reliability of HAMT is not increased and the reasons could be related to a not proper description of the material characteristic of the building and to the fact that the sensitivity analysis doesn't include other sensible parameters.

3.2 Comfort assessment

As first step of the assessment was to compare the Fanger comfort index calculated within EnergyPlus with ones calculated using monitoring data and ISO 7730. Even using the same condition for people thermal description and same view factor angles for the calculation of the mean radiant temperature an offset of average PMV=0.3 it was observed that could be related to the different implementation. Therefore it was decided to calculate the comfort index from the simulation using ISO 7730 on simulation output. The comfort assessment is presented in Fig. 3, where Fanger index are calculated for the two model considered before and after the calibration. The influence of RH on Comfort assessment is more evident in the EnergyPlus output and could be estimated to be a difference in PMV= 0.18, difference in PPD =3. The resulted estimated comfort is more representative of the office analysed since from our questionaries' some occupants feel uncomfortable.

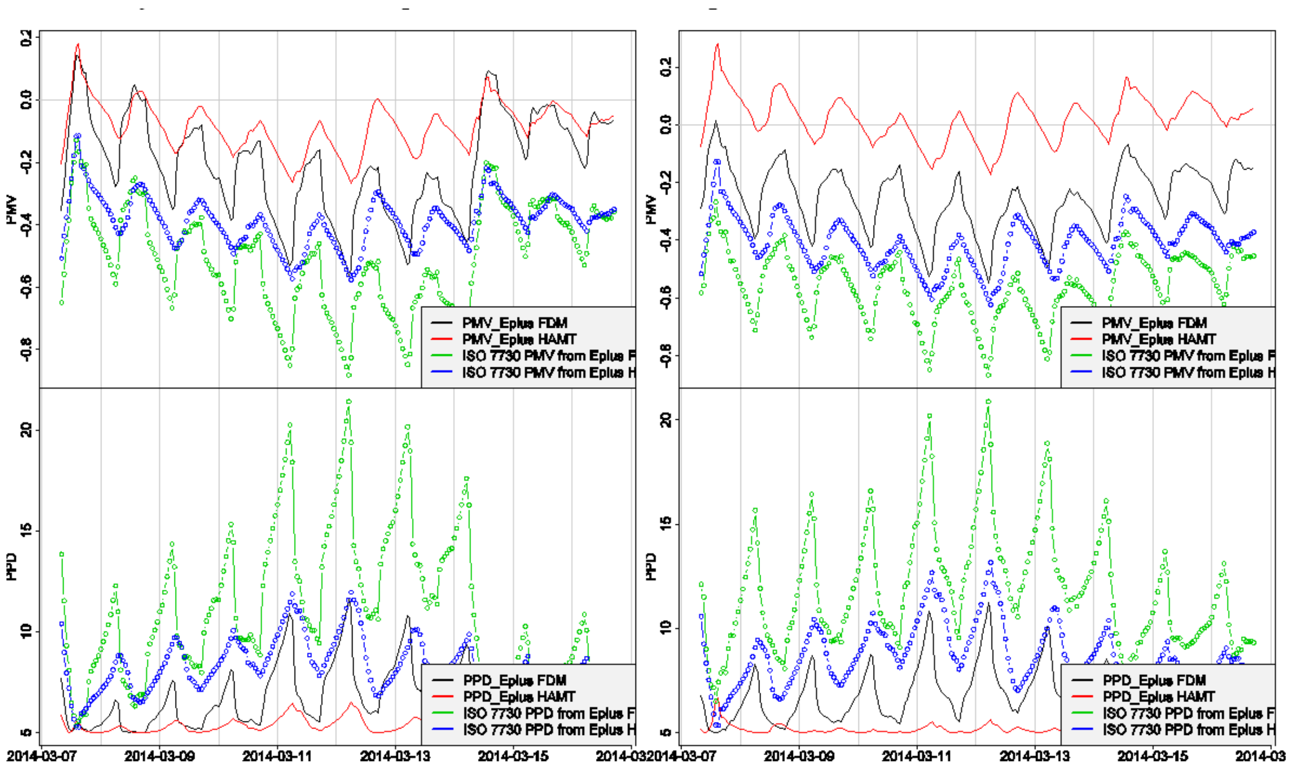

Figure 3. Comfort assessment using calibrated models: Method A (left) and Method B (right) considering room 3S. PMV/PPD are calculated both using Eplus Fanger model and ISO 7730.

3.3 Performance assessment

The Table 1 resumes all the energy calculation performed in this research. It is interesting to show that the new Method B do not improve or make worse the energy assessment. It is expected that bigger improvements will be produce where cooling system is used.

Table 1. Comparison between different strategies of performance assessment. SAP represent the Standards Assessment Procedure which is regulated by law.

Performance Assessment	***Calculation method***	***Heating Consumption [kWh/m2a]***	***Prebound effect [%]***
Real energy consumption	Estimated from 4 Year bills	73,1 ± 8:5	-
SAP	PHPP	120.7	64
SAP	EnergyPlus	106.7	45.9
EnergyPlus	reference model	65.9	9
EnergyPlus	Method A	75.5	3.5
EnergyPlus	Method B	75.5	3.5

4. CONCLUSIONS

It was demonstrated that the problem of prebound effect could be even bigger in the historic buildings stoke that the average value of building stoke. For example for the building considered is 64%. As discussed in other paper [1] introduces uncertainty into the process of performance assessment of buildings with consequences on economic viability of refurbishment and policy objective [5]. In historic building the consequence are even worst. The methodology and the tool developed allow solving the problem and it was demonstrated that it is possible to increase the reliability of model regarding the comfort assessment.

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TRAINING AND EDUCATION

Historic Scotland’s approach to training and education for energy efficiency in traditional buildings

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Abstract – *Over the last ten years Historic Environment Scotland has conducted significant research into insulating traditional buildings. Following on from this work is the need to deliver education and training. This paper looks, firstly, at those to whom such training should be delivered. It will also consider the different forms which education and training can take. When delivering training to professionals, for example, it is vital to explore in detail considerations around moisture movement. For the delivery of training to contractors Historic Environment Scotland has developed a series of full sized replicas of building elements on which appropriate techniques can be demonstrated. Education for building owners is primarily focused on shorter presentations to raise awareness of key issues. Electronic learning modules around energy efficiency work, are also under development. These approaches combined ensure all those involved in improving the energy efficiency of traditional buildings have adequate knowledge and skills.*

Keywords – Training; education; insulation; fabric; retrofit

1. WHY SPECIFIC TRAINING AND EDUCATION IS NECESSARY

Whilst there are a wide range of existing training and education programs concerned with the installation of energy efficiency measures, few out with those described in this paper cover, in any detail, the specific requirements of traditionally constructed buildings. There is a significant body of evidence which shows that such buildings require a different approach to the retrofit of energy efficiency measures [1]. This is due to the specific characteristics of mass masonry construction, notably in terms of moisture transport through building fabric. Most traditional building materials allow for an element of moisture transfer through their structure as a result of mechanisms such as capillarity and permeability to moisture vapour. Many also have the capacity to hold moisture hygroscopically. Restricting the movement of moisture through traditional building fabric has been proven to lead to various decay mechanisms occurring. This is notable where, for example, Ordinary Portland Cement mortars and renders, which restrict the diffusion of moisture, cause decay in stone and brick walls [2]. The ability of traditional buildings to allow moisture to diffuse through its fabric means that when insulation work is planned for traditionally constructed buildings any methods and materials which are used must allow this dynamic to continue [3]. It is these specific characteristics which lead to the requirement for training and education in this area. If the standard approach to retrofitting such buildings is taken, which generally involves the use of materials such as phenolic and other closed cell foams as well as vapour barriers, the risk of moisture being trapped in building fabric and causing decay is substantial. Historic Environment Scotland has, therefore, looked to develop programs of training and education to support the use of methods and materials which allow moisture movement to continue thus helping reduce the likelihood of decay in traditional buildings.

Figure 1. Historic Environment Scotland have held many outreach and training events for all those involved in the process of improving the energy efficiency of traditional buildings to highlight why a different approach to mainstream construction in necessary.

2. RESEARCH AND KNOWLEDGE BASE FOR TRAINING

The research base which Historic Environment Scotland has developed through ten years of technical research into methods and materials for improving the energy efficiency of traditionally constructed buildings is substantial. This has seen a wide range of measures installed in buildings which were monitored to measure both the level of improvement in thermal performance [4] and, in a number of cases, levels of moisture to show both surface and interstitial condensation [5]. Measures installed as part of these tests have included works to all building elements including internal and external wall insulation, improvements to windows and insulation in floors and roof spaces. The results of these tests have been written up in the form of case studies and a guide to improving energy efficiency in traditional buildings [6]. Additionally a number of technical papers have been commissioned focussing on various aspects of the thermal upgrade of traditional buildings including the performance of sealed double glazed units [7] and the pre improved thermal performance of mass masonry walls [8]. These technical papers, case studies and guides reflect a considerable amount of research work which underpins the training and education described in subsequent sections of this paper. The importance of such a knowledge base cannot be under estimated. It provides both the substance for the training and also gives credibility to Historic Environment Scotland as the developer and deliverer of training and education in this area.

3. RECIPIENTS OF TRAINING

It is essential to the success of any strategy regarding education and training that the groups who will receive the training are well defined prior to its development. It has become clear during the development of the educational material delivered by Historic Environment Scotland that all those who are involved in the delivery of energy efficiency measures in traditionally constructed buildings require training if this is to be successful. For this reason it is important to consider who is involved at all stages of the process of improving energy efficiency in traditionally constructed buildings [9].

Firstly, there is always a building owner responsible for commissioning the work to be undertaken. This may be an individual home or business owner or an organisation which has ownership of a larger estate of buildings such as a local authority or multinational business. There may also be someone providing advice to the building owner prior to work commencing in the form of a government appointed advisor or, in some cases, representative of a charity or company. Following the decision to undertake energy efficiency improvements in some cases a designer or professional is involved in specifying the work in the form of an architect or surveyor. Lastly, come the contractors who are installing the energy efficiency measures onto a building.

The form which the training and education of these key groups takes is considered in detail in subsequent sections, what should be noted at this juncture is that it is crucial that all those involved in the process receive sufficient training to allow them to make the correct decision regarding methods and materials of improving energy efficiency in traditional buildings. If those involved at all stages are not cognizant of the differences in how traditionally constructed buildings handle moisture movement they will be unable to make informed decisions about how best to improve the thermal performance of their buildings. It is clear, therefore, that all those involved at every stage of improving energy efficiency in traditional buildings require to be trained and educated. This requires a multiplicity of training methods rather than a one size fits all approach and it is this which will now be considered.

4. AWARENESS RAISING FOR BUILDING OWNERS

Building owners are most often the starting point for energy efficiency improvements to traditional buildings. The education of building owners by Historic Environment Scotland takes two broad forms. Firstly, a range of written materials have been made available, both online and in print, to raise awareness of issues surrounding energy efficiency and traditional buildings. At the most basic level an eight page leaflet gives introductory information. More detail is given in the *Short Guide, Fabric Improvements for Energy Efficiency in Traditional Buildings* [6]. Also available to building owners are the case studies, technical papers and other pieces of work which form the evidence base on which the other literature is based demonstrating that the approaches being advocated rest on sound research foundations.

Coupled with written resources is a series of outreach events for building owners. Typically these will be of shorter duration than training delivered to contractors or professionals ranging from brief 20 minute awareness raising sessions to longer lectures of one or two hours. It is clearly impossible in such a short time to go into significant detail around issues such as how insulation may affect condensation in a mass masonry wall, what is crucial is that building owners are aware of potential issues and can then raise these with professionals or contractors with the result that better work will be commissioned. In the coming year Historic Environment Scotland will be partnering with the Energy Saving Trust, the government appointed body responsible for providing guidance for energy efficiency improvements, to deliver webinars online for building owners. This will help ensure that information reaches a greater number of people than face to face events and also that this is available to those in remote areas where it may be impossible to hold face to face events.

5. TRAINING OF ADVISORS

There are a number of organisations in Scotland which provide advice to building owners regarding energy efficiency work in traditional buildings. Most notable is the aforementioned Energy Saving Trust. This advice giving stage is a crucial part of the process whereby building owners plan the installation of energy efficiency measures in traditional buildings. However, those giving the advice often have little knowledge of the performance of traditional construction and the specific needs of such buildings when retrofit of insulation is taking place. The training of those in advisory roles is, therefore, crucial to the success of any integrated approach to ensuring traditional buildings are improved in a manner which will not cause damage and decay to building fabric.

This requirement has led to Historic Environment Scotland developing training specifically for those in an advisory role. The first stage of this process was the creation of National Occupational Standards for the delivery of energy efficiency advice in older buildings [10] under the auspices of a Sector Skills Council. One of the major points of disagreement during the setting of these standards was the length of time it should take a candidate to meet the standard. It was ultimately concluded that three days duration provided the right balance. The setting of this standard was an integral stage in the overall process of training and educating those giving advice. It provides a framework on which a qualification has been developed and which will be delivered from October 2016 in Historic Environment Scotland's new facility, the Engine Shed.

In addition to the development of the aforementioned qualification Historic Environment Scotland has worked with the Energy Saving Trust to develop a bespoke training course for their staff who deliver advice to the public on insulating buildings. This course, which is 2 days in duration, is delivered around three times a year by Historic Environment Scotland staff at locations throughout Scotland and provides those in an advisory role with knowledge of the performance of traditional buildings and their thermal upgrade.

6. TRAINING OF PROFESSIONALS

For many works involving energy efficiency upgrades in traditional buildings the services of a professional, either an architect or a surveyor, will be commissioned to specify and design the work. As with all those involved in the process the training of professionals is integral to the success of any comprehensive strategy to improve energy efficiency in traditional buildings. The training of professionals requires a subtly different approach to that of advisors or building owners as they will have a high degree of pre-existing knowledge regarding building fabric, although not necessarily regarding traditional construction. With this in mind the training of such groups delivered by Historic Environment Scotland often focusses on short, intense continuing professional development sessions ranging in duration from an hour to a whole day. Such training focusses on technical aspects of the installation of energy efficiency measures and may also provide indicative details of such measures. As professionals are likely to be involved in more complex works than advisors or home owners their training naturally goes into more detail regarding issues such as condensation risk assessment methodology for example. The provision of resources for professionals out with the delivery of face to face training is also important. This further demonstrates the need for a strong knowledge base underpinning any training and education strategy for the retrofit of traditionally constructed buildings. It is expected that e-learning will form a part of future training for professionals and, to a lesser extent contractors, but the development of this is yet to begin in earnest.

7. TRAINING OF CONTRACTORS

The training of contractors who install energy efficiency measures into traditionally constructed buildings is also of considerable importance. To support this Historic Environment Scotland has developed full sized sections of building elements to demonstrate energy efficiency measures in practice. Currently there are five of these to demonstrate the installation of internal wall insulation, suspended timber floor insulation, warm and cold roof insulation and improvements to windows. These allow contractors to see how measures are installed in a practical way and allow issues to be shown which are hard to articulate through the use of lectures alone. For example, the gap which should be left between roof space insulation and sarking boards is readily demonstrated and allows contractors to see in practice what is described in theory.

It is important, however, when considering the training of contractors not to neglect the theory as well as practice. It is vital that all those involved in the retrofit of traditional buildings understand why a different approach is required as considered at the outset of this paper. An important recent development in this area has been CITB, the sector skills council for the construction industry in the UK, creating a qualification for contractors. It can be seen, therefore, that the inclusion of both theoretical and practical considerations is central to the successful training of contractors in the retrofitting of traditional buildings.

Figure 2. The use of full size replicas of building elements is used by Historic Environment Scotland in the training of contractors.

8. CONCLUSION

This paper has sought to provide a summary of the approach which Historic Environment Scotland takes to the delivery of training and education related to the improvement of energy efficiency in traditionally constructed buildings. It has been shown that a strong knowledge base, founded on technical research, is crucial to underpin any training and education strategy. This provides material for its delivery, resources to support those who have undertaken the training afterwards and also credibility for the organisation delivering such training in terms of being leading experts in their field. This paper has also shown the importance of a comprehensive and integrated strategy to the delivery of training and education which covers all those involved at each stage of the process including building owners, professionals, those giving advice and contractors. Only by taking such an integrated and comprehensive approach can a training and education strategy be truly successful. It is important to recognise, however, that the same approach to training cannot be taken for all groups. Each has their own specific requirements for training and Historic Environment Scotland has developed different approaches for each. Other points of note include the importance of the development of standards as shown through work regarding National Occupational Standards for those giving advice and the translation of these into a qualification. It is hoped that this paper, reflecting strategies used successfully by Historic Environment Scotland, can stimulate the development of similar approaches to the training and educating of those involved in the thermal upgrade of traditional building fabric throughout Europe and beyond.

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Cornwall Council - skills training and energy saving initiatives

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Abstract – *Traditional buildings are complex and work in different ways to new buildings. They are often hard to heat but need to be upgraded with 'breathable' as opposed to 'air tight' solutions. Well intentioned alterations to improve energy efficiency often harm original historic fabric and create unhealthy living environments for occupants. Perceived difficulties in upgrading older buildings lead many developers to prefer demolition and new build to conversion.*

Cornwall Council has been using externally sourced funding to authentically repair traditional buildings in its historic towns and show how they can be sustainably repaired and upgraded without damaging their character and with health benefits to occupants.

This paper will briefly describe how this has been achieved through:

- *Traditional skills training and energy monitoring programs*
- *Production of web based energy saving guidance*
- *Embodied energy and life cycle comparisons of converting local historic buildings as opposed to demolishing and building new.*

Keywords – Retrofitting; skills training; coordinated local approach

1. INTRODUCTION

Cornwall is a remote county in South West England. Over the last 16 years Cornwall Council has successfully sourced national heritage led regeneration funding and implemented traditional repair schemes in its historic towns. These were mainly though Heritage Lottery funded Townscape Heritage Initiatives (THI's), four year multi funded grant schemes with partnership funds over £1 million pounds [1]. Grants of up to 75% were offered to around 30 buildings on each scheme for quality traditional repairs using local materials, reinstating missing architectural detailing and bringing vacant buildings back in to use.

12 heritage led regeneration schemes have been successfully implemented in Cornwall between 1998 and 2013. In addition Camborne, Roskear and Tuckingmill THI finishes in June 2016 and a new scheme in the historic market town of St Austell will start in 2017. Completed schemes have created £25 million pounds of investment (including £8.2 million private investment) in the historic towns through a combined Cornwall Council contribution of £1.7 million. The later schemes have progressed

pioneering traditional skills and monitored energy saving measures which have benefited the local construction skills base and influenced local retrofitting proposals.

2. TRADITIONAL SKILLS TRAINING AND ENERGY MONITORING

Traditional buildings in Cornwall were robustly built with locally sourced stone and slate to withstand extreme local weather conditions. This produced a distinctive local character which is now under threat. There is a long standing shortage of specifiers and installers who understand traditional buildings and traditional building skills are rarely taught in colleges. Local contractors often prefer to replace rather than repair original building fabric and to demolish and build new rather than convert.

Traditional buildings with solid wall construction make up 25% of the UK building stock. Upgrading them to reduce energy consumption and carbon emissions is a generally accepted principle. Retrofitting schemes, however, often use external non permeable 'air tight' insulation that prevents solid walls from 'breathing'. This can cause water ingress, condensation and mould growth as well as obscuring original materials and details. Creating sealed environments is potentially damaging to occupants health and there is a need to balance insulation and ventilation. Tenant interviews on THI funded schemes revealed windows were rarely opened, a concern as Cornwall is a radon affected area.

To address these issues a THI in the Cornish settlements of Camborne, Roskear and Tuckingmill [2] has funded and promoted high quality traditional repairs, organised training days for local contractors and Architects and given local college students work experience traditionally repairing historic buildings funded by the THI (Fig.1).

Sympathetic ways of upgrading traditional construction have been installed on THI funded buildings. Performance of products used have been monitored by local Renewable Energy and Carbon Management students as part of their coursework. So far monitoring has taken place on upgraded original timber single glazed windows (Fig.2) and natural breathable internal insultion (Fig.3). Results have been added to an 'Improving Energy Efficiency in Cornish Historic Buildings' guide [2]. This web based guidance produced by Cornwall Council illustrates local examples of good practice, provides updated costs and lifespans of products and includes web links to enable further research. The guide has been formally endorsed by Cornwall Council and links to wider local policy and guidance. It is used early in the planning process and before Building Regulation applications to influence the quality of local retrofit schemes. The guidance concluded that retrofitting historic buildings required a 'whole building' approach taking on board location, construction, condition, effectiveness of building services, heritage value, significance and occupant behaviour.

Figure 1. THI funded timber repair training day, Rosewarne House. The top and bottom photos on the right show a discreet trickle ventilation detail for timber sash windows produced with local carpenters as part of training days. This provides health benefits by providing secure ventilation without damaging the character of the window.

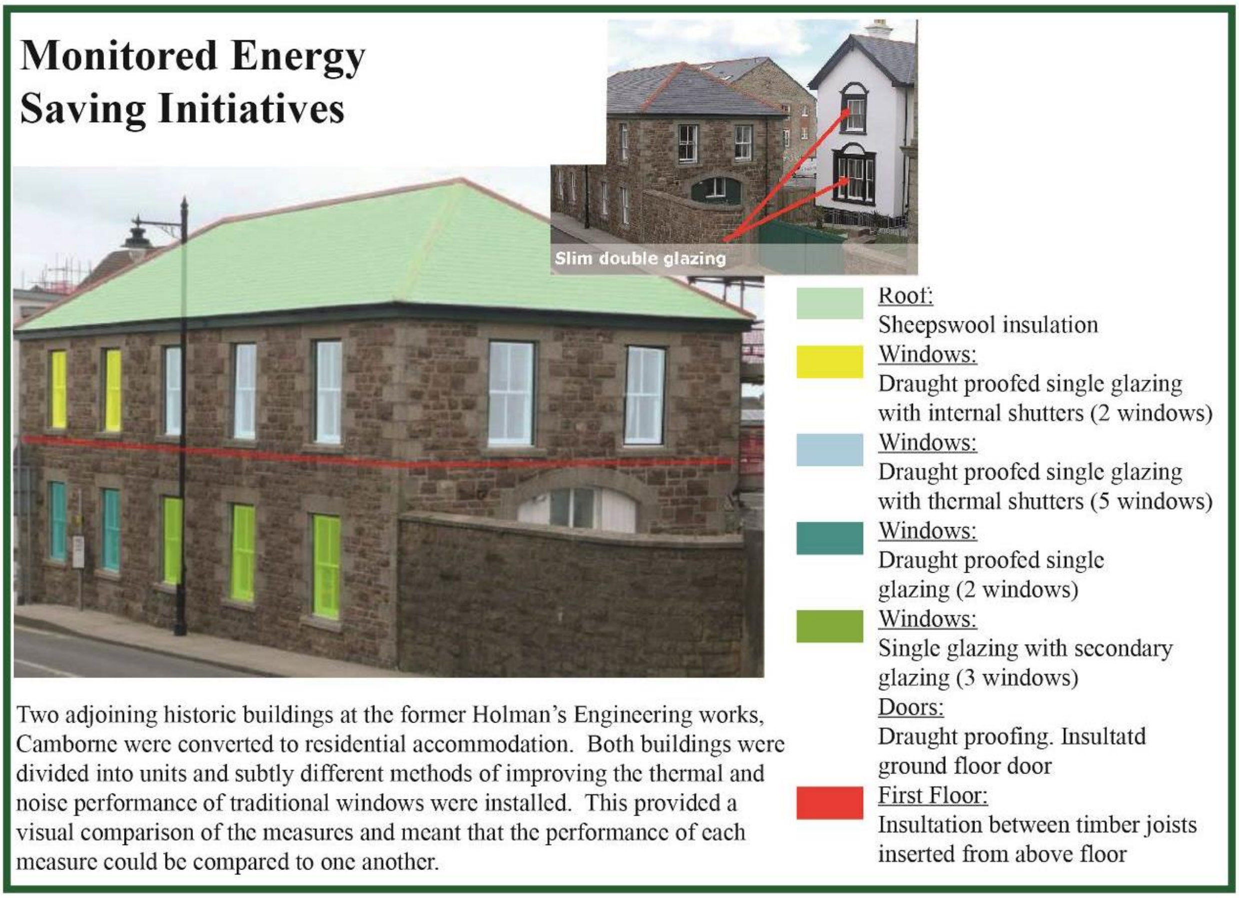


Figure 2. Example from 'Improving Energy Efficiency in Cornish Historic Buildings' guide, showing how timber single glazed sash windows can be upgraded without altering their character by installing draughtproofing, secondary glazing, internal timber shutters and slim double glazing. Monitoring showed that all of these methods effectively reduced heat loss, reducing energy bills by 15% and £100 a year for occupants as well as providing good noise protection. The building was not listed and without grant aid unsympathetic pvc windows could have been installed which would have damaged character.

The aim of these initiatives is to show that repairing rather than replacing original fabric retains original character and costs less. Good, regular repairs help the performance of traditionally built buildings which can then be upgraded in ways that do not damage their character. THI funded schemes provide easily accessible reference points for local developers, contractors and Architects to see how this has been achieved while the web based guidance provide a basis for discussion and negotiation through feedback on performance, cost and lifespan of products used.

These initiatives so far have provided 24 training events for 534 local builders, professional agents and college students, 'live' training opportunities for over 100 local college students, good practice monitored energy saving methods to 40 building units and led to inclusion of traditional building repair skills, sympathetic retrofitting details and energy monitoring as part of local college construction and renewable energy courses [2].

3. MONITORING OF ROSEWARNE HOUSE STABLE BLOCK CONVERSION

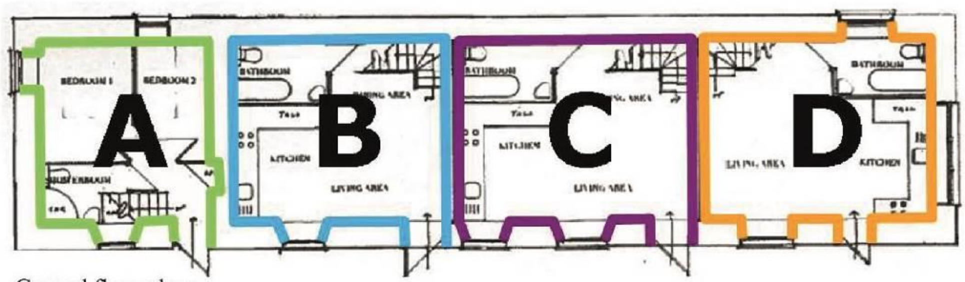
3.1 Introduction

A stable block with solid local stone walls at the rear of a grade 2* listed building is being converted to four separate cottages (Fig.3). Cottage A is being upgraded conventionally with internal non permeable Celotex PUR closed cell dry lining. The other three cottages are being internally insulated with different types of natural breathable insulation. Cottage B is being insulated with woodfibre board and clay plaster, Cottage C with ecoCork plaster and Cottage D with Cork board. 60mm insulation was fixed to internal walls and 20mm to window reveals to counter cold bridging. Monitoring will compare products analysing:

- Whether breathable internal insulation effectively increases thermal performance of solid walls, reduces damp problems and maintains good air quality.
- The relative life cycle impact of retrofitting historic buildings compared to demolishing and building new. A retrofitted building's thermal performance will usually be worse than that of a new building leading to higher in use energy and emissions. The analysis looks to what extent this is mitigated by the lower embodied energy and carbon of the retrofit and how this is affected by choice of materials.

Heat Flow measurements to date compare Cottage A with Cottage D (with normalised floor areas) and provide estimates of the embodied in use and overall energy and carbon of the conversion compared to a similar sized new building built in masonry/ cement construction.

Stable Block during conversion | Cork Board Cottage D | Section through Stable Block



Ground floor plans

(green)	**Conventional Celotex:**	non permeable rigid polyisocyanurat (PIR) foam insulation http://www.celotex.co.uk
(blue)	**Woodfibre board:**	natural softwood made from timber offcuts from local sawmills https://mikewye.co.uk/product-category/natural-insulation/pavatex-wood-fibre-insulation-systems/fibre-insulation-boards/
	Clay plaster:	hygroscopic natural plaster which can reduce mould and transmission of airbourne bacteria and viruses http://clay-works.com/specifications/specfications-overview/#
(purple)	**Secil ecoCORK plaster:**	breathable lightweight lime render with natural cork aggregates https://www.mikewye.co.uk/wall-insulation/#ecoCORK int
(orange)	**Cork board:**	vapour permeable insulation with good acoustic properties made from natural and renewable cork https://www.mikewye.co.uk/wall-insulation/#Cork EWI
(yellow)	**Woodwool board:**	rigid roof boards made from wood pulp https://www.mikewye.co.uk/product/pavatherm-thermal-board

Key to internal insulation trialled

Figure 3. Monitored internal insulation, Stable Block, Rosewarne House. Thermal monitoring uses Hukseflux heat flux plates, thermocouple temperature sensors and Enviromon data logges [3]. Air Quality monitoring uses EVM-7 all in one environmental monitors [4].

3.2 Monitoring

The 600 mm thick stable block walls have granite facing stones with a central core of stone, earth and air voids making an accurate thermal resistance estimate difficult. Presuming the stone is granite and the earth/stone core ratio range is 20/80 to 80/20 then a steady state U-value calculation would estimate the R value of the stone wall to be 0.37 to 0.65 W^{-1} K m^2, giving a U-value of 1.5 to 2.7 W K^{-1} m^{-2}. Steady state calculations for finished walls after adding insulation give U values of 0.31 – 0.34 for Cottage A, and 0.74 to 0.94 for Cottage D.

Heat flux measurements were carried out over several days in a same manner to other research [5,6], using thermistors pressed to the interior and exterior surfaces to measure temperatures T_{in} and T_{out}, together with a Hukseflux HP5 heat plate [3] on the interior wall surface to measure the heat flux Q. The data were analysed in the manner of Biddulph and co-workers [6]. By modelling walls as two thermal resistances R_1 and R_2, linked to an internal wall heat capacity C, with the initial temperature of the wall interior parametrised as $T_{m,init}$. A maximum likelihood estimation, using the mle() function in R was used to find the best fit values of these parameters. Temperature measurement plots and real and modelled heat flow measurements are shown in Figure 4.

Results show Cottage D walls have a thermal resistance of 2.65 W^{-1} K m^2, and a U-value of 0.39 W K^{-1} m^{-2}, while those of Cottage A are 2.96 W^{-1} K m^2 and 0.34 W K^{-1} m^{-2}. A bare wall U value measurement of Cottage A before insulation was 1.3 W K^{-1} m^{-2}. This reduced U value difference impacts on the relative life-cycle impacts of the two type of construction. An estimate of embodied and in use carbon and energy use (including demolition and disposal) was made comparing the cottage conversion to a similar sized new building using a process LCA with data from the Bath Inventory of Carbon and Energy [7] and a simplified building physics model [8] based on SAP. It was assumed, following Moncaster and Symons [9],that the demolition life cycle part included in the total for the new build accounts for 21% of embodied carbon and 5% of embodied energy. Results are summarised in Figure 5.

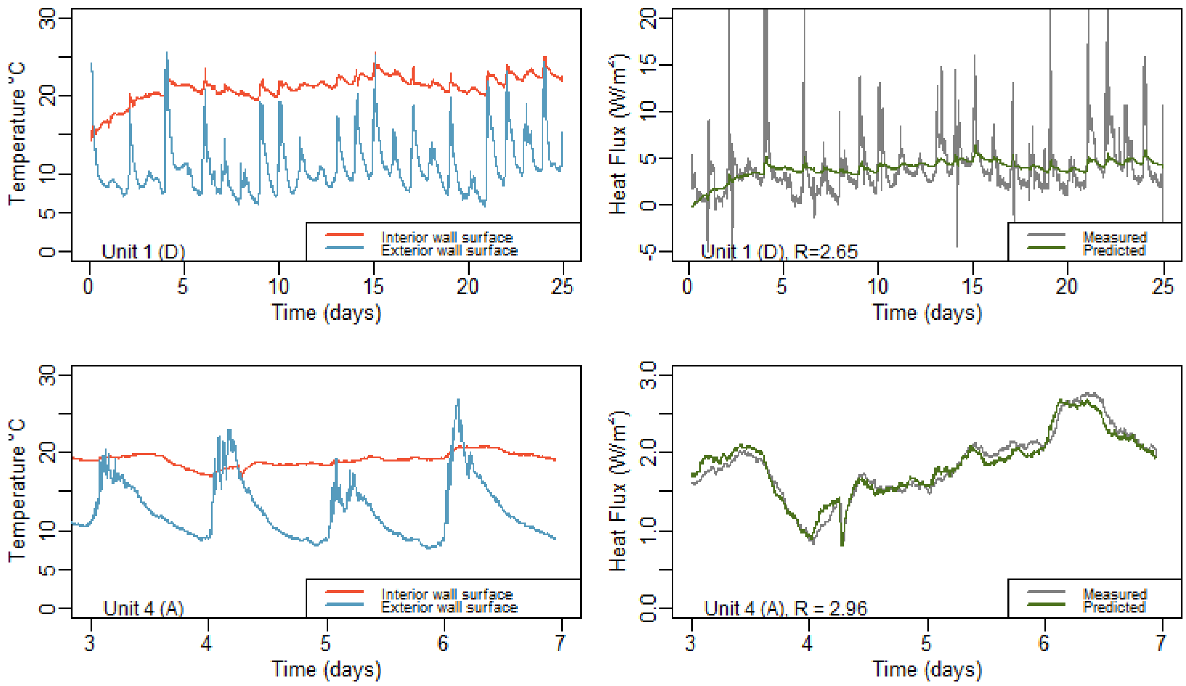


Figure 4. Left panels show interior and exterior wall surface temperatures of the two retrofitted cottages. Right panels show modelled (green) and measured (grey) heat fluxes through the walls of these units

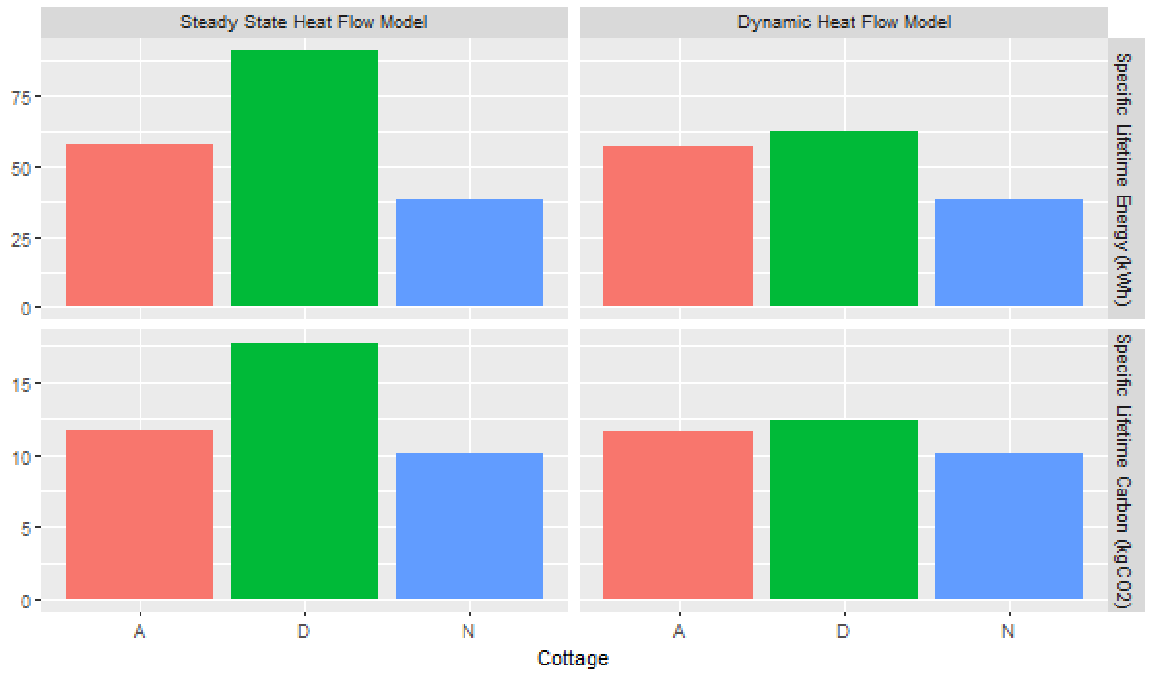


Figure 5. Summary of the specific lifetime (50 year) energy and carbon of the two retrofitted units (A nd D) and of a conventional new-build (N) of the same size, under steady-state and dynamic heat flow models.

4. CONCLUSION

- The dynamic nature of heat flow through the thick solid walls shows that lifetime carbon emissions of the retrofitted cottages are comparable to those of the new build, even for cottage D where a less thermally insulating cork layer was used. Using this dynamic treatment significantly reduces lifetime emissions assumptions.
- Further, the natural product retrofit has scope to achieve lower emissions than either the modern material or new build options if space and water heating were switched to an electrical form, as the carbon intensity of electricity in coming decades is expected to reduce.
- U values of solid walls, used for SAP energy performance calculations and Building Regulations are often lower than anticipated making energy efficiency calculations of solid walls inaccurate. Breathable insulation is essential to a solid walled buildings long term survival and all breathable internal insulation monitored worked effectively.
- Cork boards and plasters used in Cottage D, as well as all roofing slates were imported from Portugal and Spain. Carbon intensities supplied by DEFRA[10] show that the additional transport emissions due to this distance of travel are less than 1% of the lifetime building emissions, and thus not a major consideration.
- Monitoring is not fully complete with full analysis of thermal and air quality results expected in July. A final summary will be available for the conference in October.

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INTERVENTIONS: SYSTEMS AND INDOOR CLIMATE

An evaluation of three different methods for energy efficient indoor climate control in Skokloster Castle

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Abstract *– Climate change is expected to result in a warmer and more humid climate in northern Europe. Historic buildings with none or primitive climate control will face higher risk of bio-deterioration – mainly due to mould, rot and insects. There is a lack of experience of how different methods for energy efficient indoor climate control compare to each other in practical applications. The objective of this study was to evaluate and compare the relative performance of conservation heating, dehumidification and adaptive ventilation in a historic building. The investigation was carried out during three years at Skokloster, an unheated Baroque castle in Sweden suffering from problems due to high indoor relative humidity. The results show that the initial draught proofing of the rooms had a positive effect on the indoor climate which reduced the need for active climate control. Dehumidification was the most energy efficient method.*

Keywords – Adaptive ventilation; dehumidification; conservation heating; preventive conservation; mould

1. INTRODUCTION

Many historic buildings require active indoor climate control to reduce risks related to high relative humidity (RH). RH is the most important parameter for a range of deterioration mechanisms which are relevant for cultural collections. In buildings with little or no demand for thermal comfort there are three principal technologies available for lowering RH: heating, dehumidification and adaptive ventilation. In this study these three technologies are evaluated in terms of their effect on the indoor climate and their energy use.

Climate change is likely to increase the risk for mould growth in unheated historic buildings in northern Europe [1]. Unheated historic buildings which, today, have had no or manageable problems with mould growth might have to install active humidity control to avoid serious problems in the future. At the same time, there is a need to reduce the energy used by buildings to curb greenhouse gas emissions. Climate change thus calls for adaptation measures that are as energy efficient as possible.

Although RH affects both mechanical damage and bio-deterioration, it is common in historic buildings that the upper target for RH is set to avoid deterioration in the form of mould growth, which is considered unacceptable. The target is commonly set as a constant value, despite the fact that mould germination and growth is dependent on both RH, temperature (T) and exposure time [2]. To control the upper limit for RH based on both RH and T in combination to avoid mould growth is therefore a way to minimize energy use.

Conservation heating (CH) is the most common technology in northern European countries for lowering RH and has been extensively tested in practice [3]. By using a hygrostatic control instead of thermostatic control it is possible to keep a stable RH and also to reduce energy use [4]. The main drawback with CH is that there will be a T gradient within the heated space, which might result in unfavourable microclimates, e.g. behind paintings on cold exterior walls. Elevated T during the summer period can also be a comfort problem with CH.

Dehumidification (DH) is achieved either with condensation or adsorption DH. Adsorption DH is more efficient at low T and therefore favourable in unheated buildings during winter. The main drawback with DH is the practical difficulties to install and operate the machinery if there is no existing ducting. As DH lowers the absolute humidity there can be problems with increased moisture transport through the building envelope. Larsen [5] simulated the energy use of DH and CH and concluded that DH was more energy efficient unless the building envelope was very leaky (ACH <1,7).

Adaptive ventilation (AV) in historic buildings has been tested in a number of recent studies [6][7]. The idea is to ventilate when there is higher absolute humidity indoors than outdoors. To be effective, a reasonably tight building envelope is required. AV, which is an interesting low-energy alternative for indoor climate control, has not yet been extensively studied and applied. It is therefore of interest to understand how well it works in comparison with the other technologies.

A long-term comparison of the different technologies in practical use, controlled in a way to minimize energy use, has not been carried out before [8]. Hence, the objective of this paper is to evaluate and compare, in situ, the relative performance of CH, DH and AV in a historic building.

The study was carried out at Skokloster Castle, a unique Baroque palace museum. The major part of the collection, which is dominated by objects from the 17th century, is still on display in their original historic setting. A series of detailed inventories beginning in 1716 reveal the status of individual objects and if they have been moved around between the rooms. The castle has been a state run museum since 1967. It is mainly open during summer, but there are occasional guided tours also in wintertime.

The indoor climate due to the heavy and relatively leaky building envelope is characterized by high thermal inertia and a high and unstable RH. The upper floors of the castle have been unheated for centuries. A few rooms on the ground floor are permanently heated to provide thermal comfort for staff and visitors. An increase of problems with mould growth, especially in rooms facing north, has called for preventive indoor climate control. In the 1990s it was decided that to reduce the risk for mould growth it would be beneficial to increase the air exchange rate. The chimneys, packed with centuries of old bird’s nests, were cleared out in order to increase the infiltration of outdoor air. The doors in rooms with mould problems were kept open to provide more ventilation.

In 2008-2010 an extensive measuring campaign was performed to determine the impact of the building envelope on the indoor climate and to assess indoor climate-related risks [9]. There were two main results. On an average absolute humidity indoor and outdoor was about the same, which implies that there were no sources of moisture except from infiltration. Among the rooms there were considerable differences regarding the stability of RH. A conclusion was that draught proofing the rooms would decrease the amplitude of RH fluctuations without increasing the average RH level. This measure would decrease the risk for mechanical damage of the objects without increasing the risk for bio-deterioration. It was also suggested that relying only on passive climate control would not be sufficient to eliminate the risk for future mould growth, as evident in fig. 1.

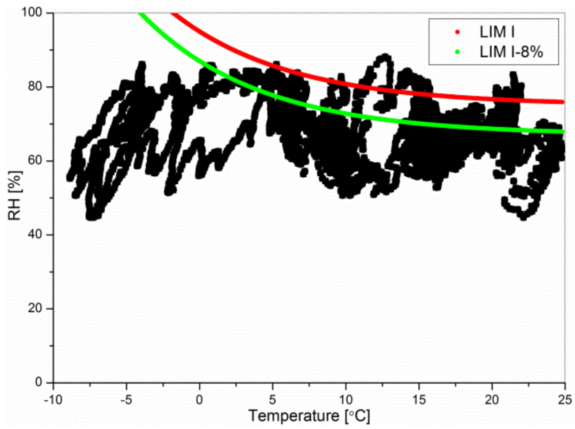

Figure 1. Left: Skokloster Castle. Right: T and RH in "grå rummet" (Grey Room) during the reference year. The red line shows the isopleth LIM I, values above which indicate a risk for mould growth. The green line shows LIM I-8% which gives a conservative safety margin.

1.1 Method

Three rooms known to have problems with bio-deterioration due to the indoor climate were chosen as case study rooms. The active measures were rotated annually according to table 1. Three similar rooms with no active climate control were used for reference. Rooms CS1, CS2, RF1 and RF2 are facing north-northeast and CS3 and RF3 are facing south-southwest. T and RH were monitored in all six rooms for all three years and energy use was monitored in the case study rooms.

Prior to the first year of the study it was decided that all rooms had to be draught proofed in order to make the active climate control more efficient. The windows were renovated and the doors and dampers were closed. CH was installed with four direct electric heaters with a total power of 800 W. An adsorption DH, *Fuktkontroll DA-250*, was used, with a maximum power of 1400 W and dehumidifying capacity of 1.1 kg/h (20 °C, 60% RH). The dry air was supplied through vertically directed nozzles making sure that no historic objects were directly exposed to the dry airstream. The heaters and the DH were controlled with hygrostats, with set points for T and RH set according to the Lowest Isopleth for Mould for susceptible building materials (LIM I) as described by Sedlbauer [10]. A safety margin of 3% RH was used during the first year. In the second and third years a safety margin of 8% RH was used. AV used a 110 W fan to control the incoming air. The outgoing air was led through a valve mounted in the draught proofed chimney. The fan was controlled by the ratio between indoor and outdoor water vapour partial pressure [11]. The fan was running only when the ratio was larger than 1.1.

Table 1. Case study and reference rooms and associated rotation of climate control measures.

Reference rooms		**Case study rooms**		**Measure**		
Number	*Room*	*Number*	*Room*	*Year 1*	*Year 2*	*Year 3*
RF1	Blå rummet	CS1	Grå rummet	DH	AV	CH
RF2	Bryssel	CS2	Florens	AV	CH	DH
RF3	Gröna sängkammaren	CS3	London	CH	DH	AV

2. RESULTS

Table 2 shows that the need for active control has been so low during all three years that there are only small differences between the rooms, both between the case study rooms and between case study and reference rooms. The combination of a low demand for active control, existing differences in hygrothermal behaviour between the case study rooms and variations in outdoor climate between the years makes it difficult to compare the different methods. Still some observations can be made.

After year one it was evident that the indoor climate in CS1 had improved significantly even though the dehumidifier had not run for more than a few hours, probably due to the draught proofing. It was decided to lower the control level by an additional 5 % RH, which means that for year two and three a safety margin of 8 % RH below LIM I was used (shown in the table in row $\text{Mould}_{\text{LIM I-8}}$). The draught proofing of the rooms has had a positive effect on the case study rooms in terms of a more stable RH, as indicated by the standard deviation from the 30-day moving average of RH (SD30). On the reference rooms the effect is less clear but these rooms were also more stable before draught proofing as can be seen in the statistics from the monitoring campaign in 2009-2010 referred as the reference year in table 2.

The energy use for all three control methods has been low. DH has used the lowest amount of energy, in total 534 kWh for all three years. CH has used 957 kWh and AV 742 kWh. The load for AV has been more or less constant regardless of room and year. The load for CH and DH has been highest in CS3, which also is the leakiest room. DH and CH has successfully kept T and RH below the mould growth limit LIM I, except in one occasion during year one when the CH in room CS3 was unable to lower RH during a rapid weather change with warm and humid air. AV has lowered the mixing ratio (MR), i.e. mass of water vapour to mass of dry air, in comparison to the reference rooms and also to the other case study rooms but the mould risk has not been significantly lowered in comparison to the reference rooms; however the mould risk has been low in all rooms anyway. The SD30 fluctuations are significantly higher (25-30%) in the rooms where AV was installed.

Table 2. One year data from all rooms and all three years. Two different thresholds are used to make a fine grained assessment of the risk for mould growth. The reference year is from a monitoring campaign in 2009-2010.

	Case study rooms															
	Reference year				**Year 1**				**Year 2**				**Year 3**			
Room	*CS1*	*CS2*	*CS3*	*Out*	*CS1*	*CS2*	*CS3*	*Out*	*CS1*	*CS2*	*CS3*	*Out*	*CS1*	*CS2*	*CS3*	*Out*
Measure					*DH*	*AV*	*CH*		*AV*	*CH*	*DH*		*CH*	*DH*	*AV*	
Avg RH [%]	71	68	68	80	65	64	64	77	66	67	65	79	65	67	65	79.5
Avg T [°C]	8.0	8.5	8.6	6.8	10.5	10.0	11.3	8.0	10.0	10.3	11.0	8.1	10.2	9.6	10	7.2
Avg MR [g/kg]	5.4	5.2	5.2	5.5	5.6	5.3	5.6	5.4	5.4	5.6	5.7	5.6	5.4	5.5	5.3	5.3
SD30	6.0	6.1	5.9	12.3	3.6	4.8	5.4	15.1	4.8	3.8	4.9	14.9	2.9	2.8	5.6	14.6
Energy [kWh]					32	249	431		231	277	443		249	59	262	
Mould$_{LIM\ I}$ [%]	3	3	3		0	0	1		0	0	0		0	0	1	
Mould$_{LIM\ I\text{-}8}$ [%]	32	11	14		4	2	20		9	2	1		0	0	10	
	Reference rooms															
Room	*RF1*	*RF2*	*RF3*		*RF1*	*RF2*	*RF3*		*RF1*	*RF2*	*RF3*		*RF1*	*RF2*	*RF3*	
Avg RH [%]	68	70	63		66	69	60		68	70	61		68	69	60	
Avg T [°C]	8.2	7.8	9.7		10.2	9.8	12.1		10.1	9.7	12.0		9.4	9.0	11.4	
Avg MR [g/kg]	5.3	5.2	5.3		5.5	5.5	5.6		5.6	5.7	5.7		5.4	5.4	5.4	
SD30	4.2	5.2	5.2		3.5	4.2	5.2		3.4	4.6	5.3		2.7	4.0	5.2	
Mould$_{LIM\ I}$ [%]	0	0	0		0	0	0		0	1	0		0	0	0	
Mould$_{LIM\ I\text{-}8}$ [%]	11	13	5		5	22	3		6	18	4		13	12	2	

Energy measurements showed that the CH and DH were active mainly during the summer period. This period with increased mould risk was studied more closely in order to assess the impact of the active control. Table 3 shows the data for three summer months, July to September, for all three years.

It is evident from table 3 that year 1 had a beneficial outdoor climate during the three month period, resulting in a low mould growth risk in all rooms and an extremely low energy use in the case study rooms. There is a small mould risk in the reference rooms during year 2, except in RF3 which always has a low mould risk due to heat gain, either from sunlight or the heated rooms below. DH and CH effectively reduces the mould risk during this period. AV consistently gives the lowest MR but increases RH fluctuations compared to the other methods. The difference in MR between CH and DH is insignificant which is consistent with the low energy use for DH, only 116 kWh in total for the summer months. AV used 182 kWh and CH 342 kWh.

Table 3. Three months data, July-September, from all rooms all three years.

	Reference year				Year 1				Year 2				Year 3			
Case study rooms																
	CS1	*CS2*	*CS3*	*Out*	*CS1*	*CS2*	*CS3*	*Out*	*CS1*	*CS2*	*CS3*	*Out*	*CS1*	*CS2*	*CS3*	*Out*
Measure					*DH*	*AV*	*CH*		*AV*	*CH*	*DH*		*CH*	*DH*	*AV*	
Avg RH [%]	68	60	61	76	61	57	53	72	65	63	57	76	65	65	59	77
Avg T [°C]	18.6	20.1	20.0	15.5	18.9	19.1	20.7	15.7	18.5	19.8	21.0	16.7	18.7	18.8	19.6	15.6
Avg MR [g/kg]	9.2	8.8	8.9	8.2	8.4	7.9	8.1	7.8	8.8	9.2	9.1	8.9	8.8	8.8	8.4	8.4
SD30	4.5	4.0	4.7	16.8	3.7	4.2	4.4	18.2	3.7	2.0	3.5	16.9	2.1	2.1	4.2	15.9
Energy [kWh]					3	70	3		50	112	71		227	42	62	
$Mould_{LIM\ I}$ [%]	1	0	0		0	0	0		0	0	0		0	0	0	
$Mould_{LIM\ I\text{-}8}$ [%]	51	2	5		1	0	0		18	0	0		0	0	6	
Reference rooms																
	RF1	*RF2*	*RF3*		*RF1*	*RF2*	*RF3*		*RF1*	*RF2*	*RF3*		*RF1*	*RF2*	*RF3*	
Avg RH [%]	66	63	61		61	57	52		66	62	56		69	64	57	
Avg T [°C]	18.9	19.4	20.2		18.8	19.6	21.1		18.8	19.9	21.4		17.7	18.8	20.4	
Avg MR [g/kg]	9.1	8.9	9.1		8.4	8.2	8.2		9.1	9.2	9.0		8.7	8.7	8.9	
SD30	3.4	3.6	4.4		3.4	3.8	4.1		2.3	3.0	3.6		2.5	3.2	3.9	
$Mould_{LIM\ I}$ [%]	0	0	0		0	0	0		0	0	0		0	0	0	
$Mould_{LIM\ I\text{-}8}$ [%]	23	6	5		0	0	0		19	2	0		50	12	2	

3. DISCUSSION AND CONCLUSIONS

In spite of an ambitious and systematic approach the comparative investigation did not provide the conclusive differences or patterns one would have expected. DH has been most energy efficient and also most effective in terms of reducing mould growth. AV has had a positive impact on mould risk and the associated energy use has generally been low, although it has on the other hand increased short term variations of RH which are important in regard to mechanical damage.

The total amount of energy used is so low that the difference hardly can be important for decision-making in the case study building. Draught proofing has had a beneficial effect on RH stability and to some extent also on mould risk. However the indoor climate is only just below the risk zone and active control is necessary to reach an acceptable risk level.

The present paper can only give a general overview. Future publications will provide a more detailed analysis of the performance during those time periods when active climate control was needed.

4. ACKNOWLEDGEMENT

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Energy impact of ASHRAE's museum climate classes: full scale measurements in museum Hermitage Amsterdam

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Abstract – *The indoor climate of museums, often housed in historical buildings, is important for collection preservation and thermal comfort. Among many guidelines, ASHRAE's chapter on the museum environment is widely known and used. Recent decades, the notion of an optimal museum environment has evolved to 'the more stable, the better', resulting in the fact that museums often chose the most strict climate class, and even beyond, allowing no fluctuations at all. This study provides insight in the energy impact of museum climate classes. A full-scale measurement campaign was conducted at museum Hermitage Amsterdam and during one year, every week, one of the following climate classes was tested: reference (21 °C / 50 % RH), ASHRAE class AA, ASHRAE class A. The results show that conditioning stricter than needed comes at a price: class AA saves 50%, and class A saves 63% compared to the reference situation.*

Keywords – Energy savings; museum; historic building

1. INTRODUCTION

The indoor climate conditions of museums, archives, galleries and libraries are of utmost importance to provide adequate conditions for preserving the objects [1]. This also holds for historical buildings if the interior and the building structure itself are of cultural significance [2]. Therefore, indoor climate guidelines are developed as for example ASHRAE's indoor climate classes for Museums, Galleries, Archives and Libraries. Besides, the indoor environment should provide thermal comfort to the visitors and staff.

ASHRAE's chapter on the museum indoor climate includes a table providing specifications for short term and long term fluctuations and permissible levels of both temperature and relative humidity [3]. The table is organised into climate classes ranging from class AA (precision control) to class D (relaxed control). A vast amount of practical and theoretical knowledge forms the basis of these specifications[4]. Besides the specifications, every class has its own description of a risk profile for the collection. E.g., class AA yields no risk of mechanical damage to most artefacts and paintings, class A yields only a small risk to highly vulnerable objects. Classes AA, A and even B are presented as 'precision control', but with different relaxations.

Without profound knowledge it is very difficult to make an educated decision on which climate class fits best to a particular museum, especially museums housed in historical buildings. Many museums therefore chose the most strict indoor climate class (AA), supposing this to be the overall optimum solution. However, conditioning the indoor climate of museums according to a strict climate class results in huge energy consumptions, especially museums housed in historical buildings. Moreover, historical building structures suffer from side effects like moisture vapour condensation during the winter season [5]. Also, it has been shown that the desired strict indoor climate in most historical buildings, despite the complex HVAC systems, is not realized [6]. Moreover, no evidence has been found that these less strict indoor climates result in collection damage [6].

Recent years, energy efficiency has become an important issue for museums, storage rooms, libraries and historical buildings as energy bills keep increasing [7]–[10]. On the other hand, there is a lag of insight in the relation between climate class and energy consumption. Therefore, this study provides insight into the energy saving potential of ASHRAE's climate classes compared to a strict indoor climate without fluctuations.

This study comprises full scale dynamic measurements of the HVAC system and indoor climate conditions of a state-of-the-art museum: The Hermitage Amsterdam (Amsterdam, the Netherlands). The museum is housed in a 17th century building that is completely transformed and refurbished in 2009. Various setpoint strategies were tested: reference situation comprising 21 °C and 50 % RH, ASHRAE class AA, ASHRAE class A. These strategies were sequentially tested, each for one week, and repeated from June 2015 until February 2016. Measurements are still on-going.

Section 2 presents the methodology, including a description of the case study museum, data acquisition and testing of ASHRAE's museum climate classes. Section 3 presents the results, and section 4 the discussion and conclusions.

2. METHODOLOGY

2.1 Case study: Hermitage Amsterdam

Museum Hermitage Amsterdam is a sister of museum the State Hermitage in St. Petersburg, Russia. The museum is located in Amsterdam, The Netherlands. The Hermitage Amsterdam has no own collection, but displays loan exhibitions: The artworks mainly belong to museum the State Hermitage in St. Petersburg, but also to other museums. The museum is housed in a late 17th century building. During the past centuries, many changes were made to the building. The most recent renovation dates from the years 2007-2009 when the building was transformed into a state-of-the-art museum (see Fig. 1): the historical building envelope was conserved and insulated from the inside, all other construction parts were newly built, floor heating was applied in the non-exhibition areas, an all-air HVAC system was installed that conditions the exhibition areas. The employed indoor climate specifications were 21 °C and 50 % RH, resulting in an extremely stable museum indoor environment (observed fluctuations were ± 0.5 °C and ± 1 % RH), but unfortunately also high energy cost.

This study focusses on 'de Keizersvleugel', which is the exhibition wing on the right side in Fig. 1a. The exhibition wings consist of a main hall and adjacent cabinets (Fig. 1b). The ceilings of the exhibition cabinets adjoin the technical areas that are located at the top floor. The ceiling of the main exhibition hall partly consists of a large glass roof with interior sun blinds that are almost permanently closed. The museum is opened seven days per week from 10 h to 17 h.

Figure 1. a) Aerial view of museum Hermitage Amsterdam. b) Cross section of one exhibition wing.

2.2 Data acquisition

The exhibition room of interest is equipped with four sensors that are connected to the Building Management System (BMS): Hanwell Radiologgers ML4106 combined T and RH measurement providing T accuracy of ± 0.2 °C and RH accuracy of ± 2 %. The logging interval of the indoor measurement data is 16 min. The four sensors are attached to the four walls of the exhibition room at a height of 2 m. The average of these four sensors has been used for setpoint control.

The measurement campaign of the AHU is shown in Fig. 2.

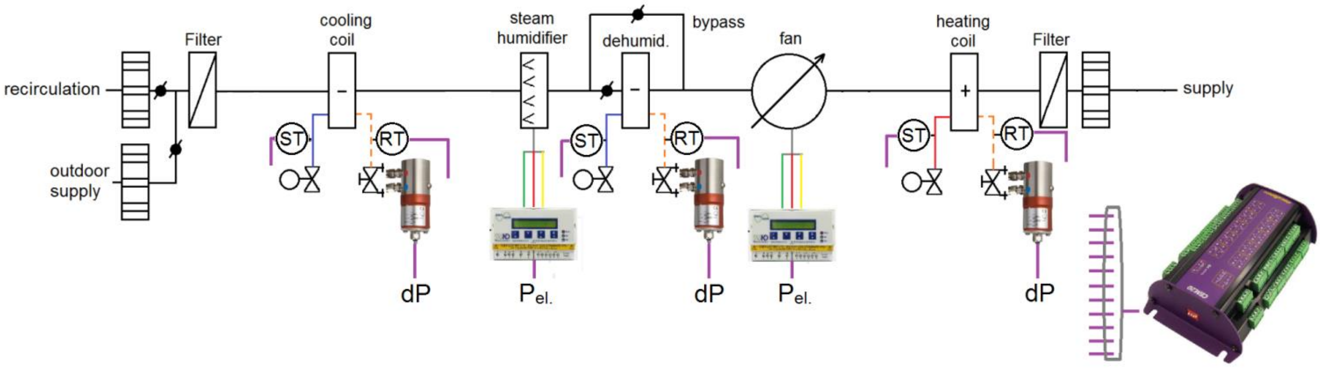

Figure 2. Measurement setup of the main exhibition room's AHU. All signals are indicated by purple lines and were sent to the data logger. Coil measurements included temperatures of the supply water (ST), return water (RT) and pressure drop of the water flow over the balancing valves (dP). Electric power consumption was measured of the steam humidifier and fan ($P_{el.}$).

The energy consumption of heating, cooling and dehumidification was calculated based on the energy exchange between the water side and air side of the coils according to,

$$P = \dot{m}_{w} Cp_{w} (T_r - T_s) \quad (1)$$

where P [kW] is the power, $\dot{m}_{w}$ [kg/s] is the water mass flow, Cp_{w} is the specific heat of water (4.0 kJ/kg.K for a mixture of 75 % water and 25 % glycol), T_r [°C] and T_s [°C] are the temperatures of the return and supply water flows. The water mass flow was calculated from measurements of the pressure drop over the balancing valves according to,

$$\dot{m}_{w} = \frac{K_v}{36}\sqrt{\Delta P} \quad (2)$$

where $\dot{m}_{w}$ is the water flow [kg/s], K_v is the coefficient of flow (from manufacturer's tables), ΔP is the pressure drop over the balancing valve [kPa]. The pressure drop was measured using TA Hydronics' TA Link (see Fig. 2) with an inaccuracy of < 1 kPa and measuring range of 0-100 kPa.

The temperatures of the supply and return water flow of the coils were measured by Grant thermistors with an accuracy of ± 0.1 °C. The measuring tips were positioned at the external surface of the piping, directly under the insulation material.

The electric power consumption of the fan and the steam humidifier was measured using the ND Metering Solutions, Rail 350 (see Fig. 2), with a resolution of 10 pulses/kWh.

The measurement data were logged at an interval of 30 s by a Grant dataTaker® DT85. The data were sent via File Transfer Protocol once a day to a server located at the university.

2.3 Testing Ashrae's museum climate classes

The museum's indoor climate control system was accessed via the BMS. This system included all controller settings and measurements of the indoor climate. The control system was adapted to be able to implement ASHRAE classes AA and A.

Table 1 specifies T and RH settings of the tested indoor climate strategies. The reference situation, as used by the museum in normal operation mode, which does not include any permissible fluctuations, whereas ASHRAE classes AA and A specify a range for T and RH. The range for T was determined by comfort requirements [9], because these are more strict than the collection requirements as presented in the ASHRAE chapter, see Fig. 3 for an illustration.

ASHRAE defines short term (daily) and long term (seasonal) permissible fluctuations for these classes. The average setpoints may be the annual averages that the collection has been exposed to, or 21 °C and 50 % RH for loan exhibitions. The latter was used in this study. Moreover, class A includes two options: (i) fluctuations of ± 5 % RH and seasonal adjustments of 10 % RH up and 10 % RH down; (ii) larger fluctuations of ± 10 % RH without seasonal adjustments. The latter was used in this study.

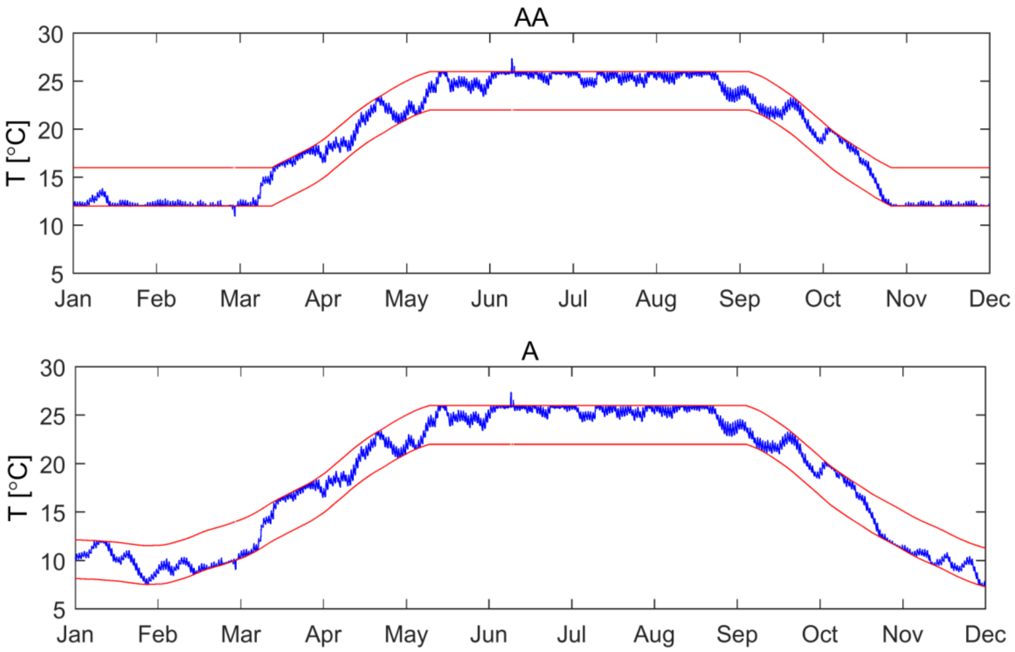

Figure 3. The indoor temperature according to ASHRAE's classes AA and A [11]. The red lines indicate the lower and upper limits and the blue line is the indoor climate with permissible fluctuations. It is clear that temperature should be determined by thermal comfort requirements instead of collection conservation requirements during opening hours.

Table 1. T and RH settings of the tested indoor climate strategies.

	indoor climate strategies		
	reference	*class AA*	*class A*
T [°C]	21	20-22*	20-22*
RH [%]	50	45-55	40-60

**Adjusted to 19.5-21.5 °C during winter and 20.5-22.5 °C during summer.*

The indoor climate strategies were tested, each for one week, in the following order: reference, class AA, class A, class AA, reference. This scheme was repeated from June 2015 until February 2016. Tests are still on-going.

3. RESULTS

Fig. 4a presents the general results: the relative energy consumption of ASHRAE's classes AA and A compared to the reference situation. Class AA saves approximately 50 % compared to the reference situation and class A saves approximately 63 %.

Fig. 4b shows the specific annual energy consumption per square meter of the museum. Fan energy remained unchanged of course. Relaxing the indoor climate specifications (from REF to class A) has resulted in significant energy savings for dehumidification. Note that dehumidification was realized by deep cooling. As a result, heating energy has been reduced significantly, because heating was predominantly required in the reference situation for post-heating the air after dehumidification. On the other hand, reduction of dehumidification (deep-cooling) resulted in increased sensible cooling. Steam humidification even proofed to be unnecessary for class A. The total energy consumption may be reduced from 1050 kWh/m^{2}y (REF) to 400 kWh/m^{2}y (class A).

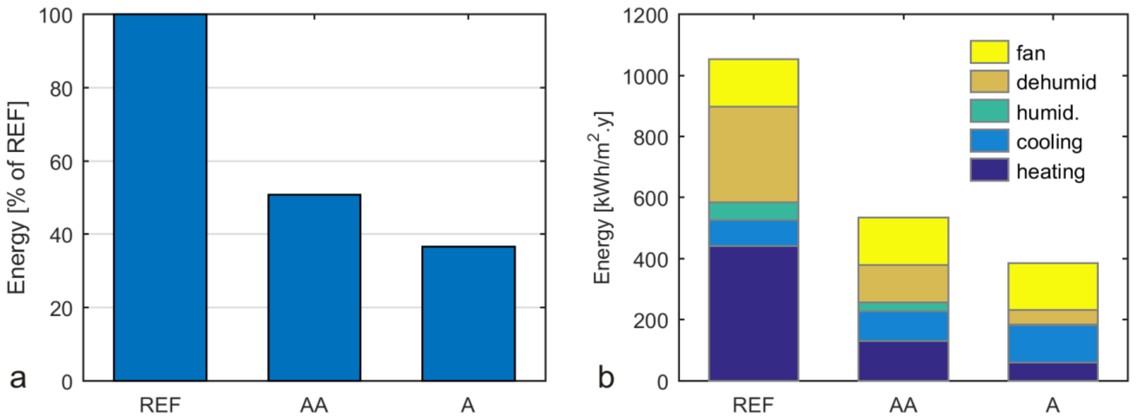

Figure 4. a) Energy consumption of ASHRAE classes AA and A relative to the reference situation (including fan energy). b) Annual energy consumption per square meter specified for heating, cooling, humidification, dehumidification and fan.

4. DISCUSSION AND CONCLUSIONS

The results from Fig. 4a imply the law of diminishing returns. This effect has been identified earlier by Mecklenburg [12] who concluded, based on measurements at several buildings of the Smithsonian Institute, that energy consumption as function of permissible RH fluctuation follows an exponential decay curve. I.e., switching from a very strict situation to class AA (± 5 % RH fluctuation) will save more energy than switching from class AA to A (± 10 % RH). Therefore, the results of this study comply with earlier results.

The results in Fig. 4a also show that the relative savings are tremendous for museums like the Hermitage Amsterdam, which may be characterized as an air-tight and well insulated building type. Kramer et al. [11] have shown in a simulation study that relaxing the indoor climate specifications will relatively save the most energy in museums with modern building envelopes, although absolute savings will be the highest in museums with poor building envelopes. This appears to comply with the results from this study given the high relative savings.

Further research is required to include class A with seasonal adjustments (40 % RH ± 5 % RH during winter and 60 % ± 5 % RH during summer) besides the tested class A without seasonal adjustment (50 % RH ± 10 % RH). Moreover, comfort requirements are only applicable during opening hours, whereas collection requirements determine temperature setpoints during closing hours. However, in this study, temperature setpoints were determined by comfort requirements 24 hours per day, due to the inflexibility of the control system to differentiate between opening and closing hours.

The main conclusions of this study are: (i) relaxing the indoor climate specifications results in energy savings, particularly if the current situation comprises a very strict indoor climate, but be aware of the law of diminishing returns; (ii) the most significant savings result from decreased dehumidification; (iii) much more effort should be spent at determining the indoor climate specifications during the design process, because conditioning museum indoor climates more strict than needed, just because we can, or because a lack of knowledge, will result in significant energy waste, and consequently unnecessary high energy cost.

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Evaluation of different wall heating systems in historic monuments – Aspects of Energy and Conservation

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Abstract – *There are many different ways of heating in historic houses – radiative, air, or convective heating, high- and low-temperature systems, local and area heating. Four different heating systems with high suitability for historic buildings were chosen and compared in long-term measurement campaigns. Two low temperature area wall heating systems – prefabricated clay elements with serial pipes as well as a wall heating system with parallel pipes – were installed and two radiative high temperature systems – a radiative plate heater and a Temperierung system that heats the base of the wall with copper pipes underneath the plaster. These systems were installed in four nearly identic rooms, but experience from the measurements has shown the difficulties with a direct comparison. So this project also shows the special problems when dealing with comparative measurements in historic buildings with their inhomogeneous and often unknown wall construction. In the end all four systems were compared to a reference system (convective electric heater) room by room. For the specific examined case at Benediktbeuern both low temperature area wall heating systems and the radiant heater showed similar or only very slightly elevated energy demand like the convective system. The high-temperature Temperierung heating system had an about 1.5 times higher energy demand. All wall heating systems were favorable in terms of comfort and preventing damp damages.*

Keywords – Historic building; energy consumption; wall heating; Temperierung; conservation

1. BACKGROUND AND GOAL

Saving energy in different branches of industry and private households is the declared objective of the federal government and is in the public and private sector a pioneering topic. Energy efficient renovation methods and developments in the field of HVAC technology are essential topics for the renovation of traditional buildings. In the modern construction sector a large number of innovative approaches have been followed, solutions and investigations of heating technologies in historic buildings were so far rather neglected. The type of heat distribution here has a significant influence on the preservation of a historical building, but on the other hand also on the energy efficiency of the systems and the indoor comfort of the user or residents. This is why the present investigations aim to compare low-temperature wall heating to high-temperature radiant heating. The investigations were conducted on a real old building with various and at the same time innovative heating systems in parallel under comparable conditions.

2. COMPARATIVE INVESTIGATIONS OF THE WALL HEATING SYSTEMS

The investigations took place at the Fraunhofer Centre for Conservation and Energy Performance of Historic Buildings in the Alte Schäfflerei (Old Cooperage) of Benediktbeuern Monastery (Fig. 1). The building is dated to the year 1760. In the north-building in each of four rooms on the ground floor with a similar size, one of the heating systems has been installed. The rooms had to be converted for the actual test set-up to improve the comparability of the study. One of the main aims of the measurements and comparative studies was to compare the heat-flows of the individual heating systems through the outside walls. It was envisaged that the boundary conditions to the other adjacent rooms should be as far as possible adiabatic. The rooms are conditioned to identical air temperature, therefore adiabatic situation between these rooms is reached. The walls towards the staircase in the south, to the youth hostel in the north as well as the floor and the ceiling have been equipped with different insulating materials in order to keep the heat losses as low as possible. For the desired comparison from an energy point of view it was necessary to make the four rooms as far comparable as possible. Therefore extensive measures were carried out, e.g. thermal insulation of the floors of the measuring rooms with 25 cm glass of glass granulates, masking the existing window with a tinted sun protection foil and introduction of controlled forced air ventilation, etc. (details in [1]). The experimental setup consists of 4 measuring rooms. All rooms are equipped with numerous temperature, humidity and heat flux sensors. All installed heating systems are run with hot water. Hot water flow rate, feed line and return line temperature are measured to measure the energy that is sent to the four (wall) heating systems.

Figure 1. Left: The "Alte Schäfflerei" (old cooperage) at Benediktbeuern Monastery, after façade restoration in 2015. The measurement rooms are on the ground floor in the left building part (behind the scaffolding), the so called Northern-Building. Right: Ground plan with different examined wall heating systems in the four measurement rooms.

In room 1 a special radiant heater was installed in the window niche. The water-filled steel heat body is structured in two hydraulically connected heating parts. The hot water passes through serial, first through the front heating part, then through the rear. In addition there is some thermal insulation applied on the back of the heater towards the wall. So there is a large part of heat emission from the front plate while radiation heat losses in the direction of the outer wall are reduced.

The room 2 is equipped with the wall heating system I. Between the wall and the heating system a special wire mash mat is located (a geotextile with an artificial air-gap of 2 cm between 2 layers of glass fibre fleece). The water passes through the mounted heating tubes parallel, called theTichelmann-principle. The tubes are covered with lime plaster.

Room 3 is equipped with a Temperierung system, a special wall heating system that is very common in heritage preservation in Germany. Two copper heating pipes in the base area of the outer wall and a second loop at height of the window parapet heat the wall and thereby the measuring room. The system is installed at a small distance over the ground and under the window parapet in the outside wall. Großeschmidt [2] emphasizes many positive effects of this building component heating, while among others Künzel [3], Krus and Kilian [4] in their articles consider that this building component might lead to higher use of energy when used for heating and not for conservation purposes only.

The wall heating system II in room 4 is an assembly of prefabricated joinable elements of clay mortar, which was prepared with straw and other natural ingredients. Embedded within it are multilayer composite pipes, which are connected in a serial way after installation [5]

In comparison, measurements of the 4 rooms with identical electric heaters it turned out that there was a big difference in energy consumption, although meticulous care had been taken to make the rooms comparable and isolated from outer influences. Therefore it was decided to compare the wall heating systems to convective heating by electrical heaters, each room by itself. For comparison measurements of four identical electric radiators with a maximum heat output of 2200 W have been chosen. The wall heating systems are supplied by district heating and controlled via building automation system to a set point of 20 °C air temperature. The supply air pipe of the ventilation system is passed through the chimney from the roof to the measuring rooms and blows outside air into the measurement rooms. The supply air is regulated in all measurement rooms to 9 m^3/h, which corresponds to an air exchange rate of $n = 0.2\ h^{-1}$.

The sensors are installed according to a measurement concept (Fig. 2 left). The positions of the sensors vary slightly due to the different dimensions of the rooms; in principle, however, the arrangement in the various measurement rooms is equal. To measure the height distribution a measuring pole with a number of sensors was positioned in each room at a sufficient distance from all walls, to reduce an influence of the walls on the sensor (Fig. 2 right). At the space-enclosing walls, the surface temperatures are measured at different heights. Additional sensors are located on the outer walls, a heat flow plate to determine the heat flow and PT100 sensors at the geometric thermal bridges between walls and ceiling or floor.

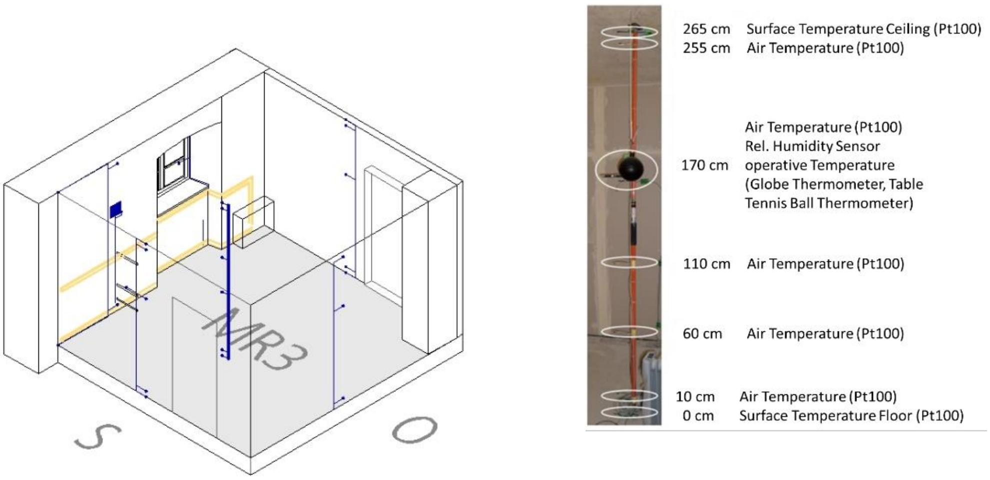

Figure 2. Positioning scheme of monitoring sensors using the example of measuring room 3 (left) and a typical measuring pole with attached sensors in different heights (right).

3. RESULTS

Before the hydronic heating systems has been installed reference measurement with electric heating were made in each room. It showed that despite the extensive measures to improve the comparability of the four measurement rooms, supposed identical, they still strongly differ in their thermal behaviour and energy consumption, up to about 45 % difference from each other (Fig. 3). The conclusion from these first reference measurement was that a direct comparative assessment of the installed heating systems in the historic building "Alte Schäfflerei" was not possible. Instead of comparing the rooms to each other directly (shown schematically in Fig. 3, right), the energy consumption of the respective measuring room with wall heating system is compared to the same room itself by electric heating as a reference system.

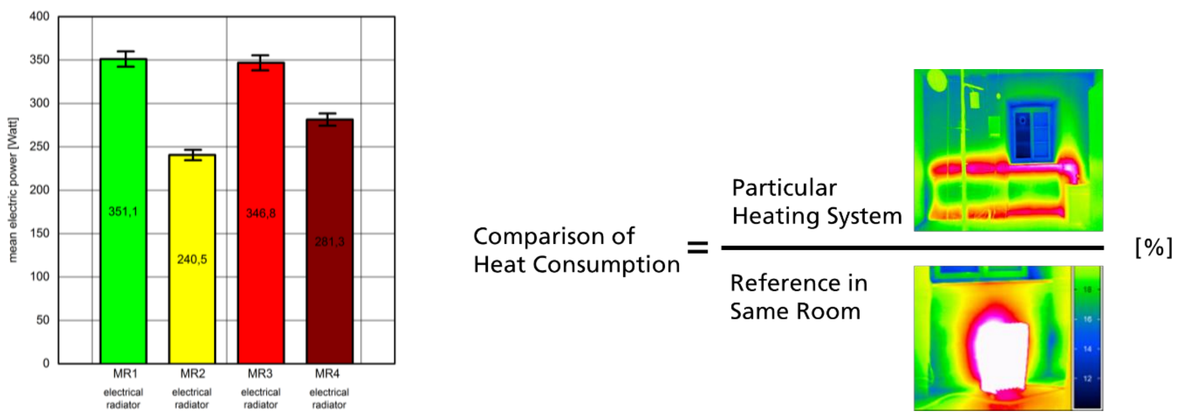

Figure 3. Results from the zero measurement of the four measurement rooms at Benediktbeuern with electric heaters (left) and schematic representation of the conducted benchmarking by reference measurement in the same room (right).

For this, the temperature-related heating power of the different wall heating systems was measured and compared to the respective reference system, an electric heater without wall contact. Periods of about 3 weeks with similar outdoor climate conditions are used for this comparison and several parameters and corrections are included in the assessment, e.g. outdoor temperature conversion, etc.

In Fig. 4 the energy consumption of the hydronic heating systems is compared with figures referenced to the electrical heating energy consumption. Also the specific errors of measurement for each wall heating system are shown. The electrical reference have a slight reduced heat loss through the walls with additional wall heating systems by the additional insulating effect of the wall constructions of wall heating systems. The electric heating reference measurement was therefore adjusted in relation to the insulating effect of the wall heating systems in two rooms (MR2 and MR4) with a correction factor. Almost all investigated wall heating systems show a similar energy consumption as compared to the heating with a conventional, convective electric heater. Only the Temperierung heating installed as building component warming (MR3) had a significant higher energy consumption than the reference electric radiators.

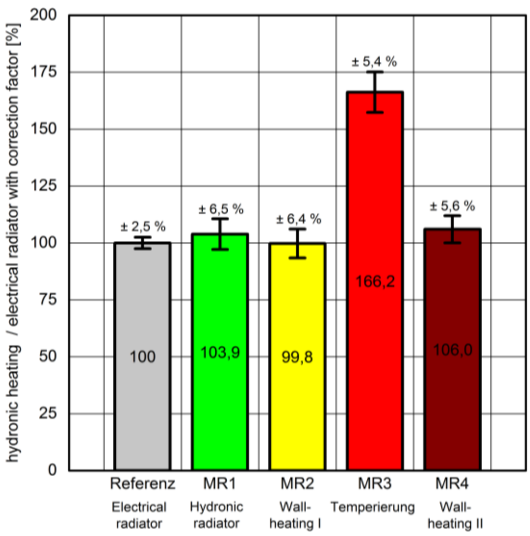

Figure 4. Ratio of the energy consumption of the specific (wall) heating system in relation to convective electrical radiators (reference system) in %, using the corrected electrical energy consumption. These values are presented for the specific measurement setup at the four measurement rooms at the "Alte Schäfflerei" at Benediktbeuern monastery.

4. EVALUATION OF THE RESULTS AND SUMMARY

The present study show how complex comparative energy studies in real buildings are. Despite huge efforts to produce comparable conditions, like using rooms of the same size, defined heating, mechanical ventilation, insulation to adjacent rooms, insulation of the floor and the ceiling, external shading during the measurement period, no use of the spaces by residents at the time of experiments. Still numerous and partly unknown uncertainties affect the measurement results massively. Basically, the boundary conditions must be defined in comparative studies, uncertainties and limitations on transferability must be clearly identified. All comparative measurements that take place in real buildings should be considered in terms of their uncertainties and informative value therefore with great caution.

For this reason, here, a new approach has been chosen and the normal test procedure has been changed in a way, that the energy consumption of the built-in wall heating systems for each room were compared to a reference heating with an electric heater, which was placed in the window niche in the same room and turned on in a different time period while the wall heating was turned off.

For the comparative determination of the energy consumption we tried to have constant boundary conditions during the two test phases, which in practise is of course only possible to a certain extent. The parameter used for the comparison have been calculated daily and averaged over several weeks for the specific case of the four measurement rooms at the “Alte Schäfflerei” (Fig. 4). With these average values the comparative assessment of each heating system has been calculated, based on the reference heating systems in the respective room with all its specific boundary conditions. Also the uncertainties in the measurement and calculation have been assessed (details see [1]).

For the room 1 with the radiant heater the measured energy consumption is very close to the electric reference heater. The radiant heater has been designed with an insulated backside. But inconsequently it is not insulated at the sides of the radiator. For this reason, the air space in the niche behind the radiator is heated, too. Therefore, the rear insulation brings no larger energy savings here.

The room 2 with a wall heating covering almost the entire surface and mounted with special wire mash mat has a slightly increased energy consumption compared to the measurement with electric radiators. Due to the direct heat transfer from the heating pipes to the wall without convective heat transfer resistance from inside air to the wall surface a higher heat loss is to be expected. Considering, however, the given heat resistance of the additional wall heating layers, this effect is nearly compensated. The result is an almost the same energy requirement as with a conventional radiative heater.

For room 3 containing the Temperierung system with in wall mounted heating pipes, a much higher energy consumption is shown in comparison to the electric convective heater. This is mainly caused by the direct heat transfer inside the wall with a local high temperature. However, heated components at the wall-socket can have positive effects for the protection and conservation of historic buildings by preventing damages from damp (like mould) in this critical area. This can make Temperierung a meaningful solution for rooms with special climate requirements or endangered building components. However, it is less suited for energy saving heating to human comfort temperatures for example in office or residential buildings.

Room 4 with a wall heating system made out of prefabricated clay panels covering also almost the entire outside wall surface has mainly a similar behaviour like the wall heating system in room 2. Without the wire mesh that was used in room 2, the area wall heating in room 4 has a slightly lower heat transfer resistance, and consequently a slightly elevated energy requirement is given compared to the other wall heating system and also reference heating. Yet it is nearly in the same area of energy consumption like the convective heaters for this specific measurement setup at the “Alte Schäfflerei” at Benediktbeuern monastery.

Generally, beside the energetic requirement, other possible positive effects should be considered when choosing a specific heating system like for example the increase of human comfort. The wall heating systems showed a reduction of height stratification of the air temperature compared to convective heating which leads to improved comfort.

In addition, wall heating or building component heating can be especially advantageous for historical buildings for preventing moisture damages. Therefore it can be an interesting alternative to conventional heating systems. By heating critical points of the construction, the risk of damages for example caused by rising damp or surface condensation (like mould) can be reduced. Here in particular, the Temperierung wall heating has to be mentioned as a means of damage prevention when the primary goal is conservation, not heating for comfort. As the investigations have shown, for this system possibly higher heat losses have to be taken into account, so energy efficiency and conservational benefits should be weighted for each individual case of application.

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Domestic Hot Water Systems – constant with changes

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Abstract – *Piped hot water in New Zealand homes is comparatively recent, yet in the past decades energy efficiency has improved. A historic review examines hot water generation, storage and distribution from 19th century batch production (e.g. stove-top pot) to the piped systems fuelled by gas or electricity found in almost all houses by the 1960s. Unlike many other services, heritage hot water systems can be, and often are, replaced with modern, more energy efficient plant. Data on energy use, based on extensive monitoring, are used to provide a comparison of the different systems based on age and thermal performance to support decision making – when is it worth replacing an old, inefficient system with a more modern system? It is suggested that adding insulation or water efficient appliances to an old electric cylinder is likely to be cost effective, and only when replacing a cylinder is additional expenditure on thermal performance beneficial.*

Keywords – Domestic water heating; electricity; natural gas; wood; coal

1. INTRODUCTION

Today the provision of hot running water is considered a fundamental household requirement, yet only it is only since the 1960s that almost all New Zealand houses have had a constant hot water supply. Although there is good historical evidence of the use of hot water, the methods used to supply it are less well documented. This paper examines the supply of hot water since the arrival of Europeans in the early 1800s through to the energy use of systems found in modern households.

Historically the provision of hot water divides into two broad categories:

- batch production, often based on carrying cold water to a pan or other holder above a fire; and
- constant production, piped water flowing into a device heated by electricity, gas or solid fuel.

This paper focuses on the energy use of constant production and related technical issues using results from the Household Energy End-use Project (HEEP) random sample of 400 dwellings [1].

2. UNTIL PIPED WATER

Early European settlers made use of natural sources of water – ponds, lakes, streams or rivers. Until piped water, hot water was provided by a 'batch' process, based around a container placed on the coal or wood stove, or hung over an open fire [2]. Even into the early 1900s, batch heating was widely used as water had to come from on-site or nearby. For example, the 1906 designs for workers' dwellings included on-site water storage tanks fed from roof water collection [3].

The kettle or pot provided hot water for dish washing or drinking. Larger quantities of water for washing of clothes or humans took more effort. The once-a-week family bath required the heating of large amounts of water, transporting it to a portable bath and then removal once the family had washed [3]. A Saturday night bath meant all would be clean for attendance at Sunday church.

Specialised, dedicated water heating equipment was coming – the ‘copper’. This large copper container when full held from 10 to 20 gallons (45 – 90 litres) of water, and was normally permanently mounted in a cast iron, concrete or brick stand in the laundry or wash-house. The copper was filled with water, a fire lit underneath, and after some time clothes could be ‘boiled’ with homemade (in later years, store-brought) soap. The used water then had to be manually removed. The direct contact between the flames and the cold copper surface resulted in inefficient combustion leading to excess particulates which clogged the chimney and polluted the atmosphere.

Later purpose-built heaters could be free-standing, such as the batch-feed chip heater, or part of the stove such as the piped ‘push-through’ heater, provided with water from the rain water tank [4].

3. PIPED WATER

Piped water was laid to at least the main central city areas (Dunedin, Wellington and Auckland) by the mid-1860s, taking another 20 years before it was available in nearby suburbs and a further 40 years before it was usual outside main urban areas. This was not long after piped water became available in England, with basins not common there until after 1918 [5].

By 1917 an NZ school domestic science course taught “no modern house is complete without a hot water service connection with the kitchen range” [6]. The key features, shown in Figure 1, were:

1) A cold water tank placed at a high level, either on or near the roof
2) An iron boiler or iron pipes ("wetback") providing a large heating surface at the back of the fire
3) A cylinder for storing hot water; and
4) The necessary pipe connections.

The term ‘wet-back’ describes a heat exchanger fitted at the rear of an open fire or stove for providing hot water [7] or “a wood or coal stove, incorporating water-heating capability” [8] In Australia the comparable term would be ‘auxiliary water heater’ [7] or in England ‘back boiler’ [9].

By the 1923 second edition of the domestic science course, the kitchen range was inadequate: "A distinct improvement in the above service can be made by having an additional boiler behind the dining room or sitting-room fire. Then the household is rarely if ever without a plentiful supply of hot water" [10]. These features are still found in the majority of NZ dwellings – albeit fuelled by electricity rather than pipes in the back of the kitchen range.

Even today, some 7% of water heating energy comes from a “wetback” [1].

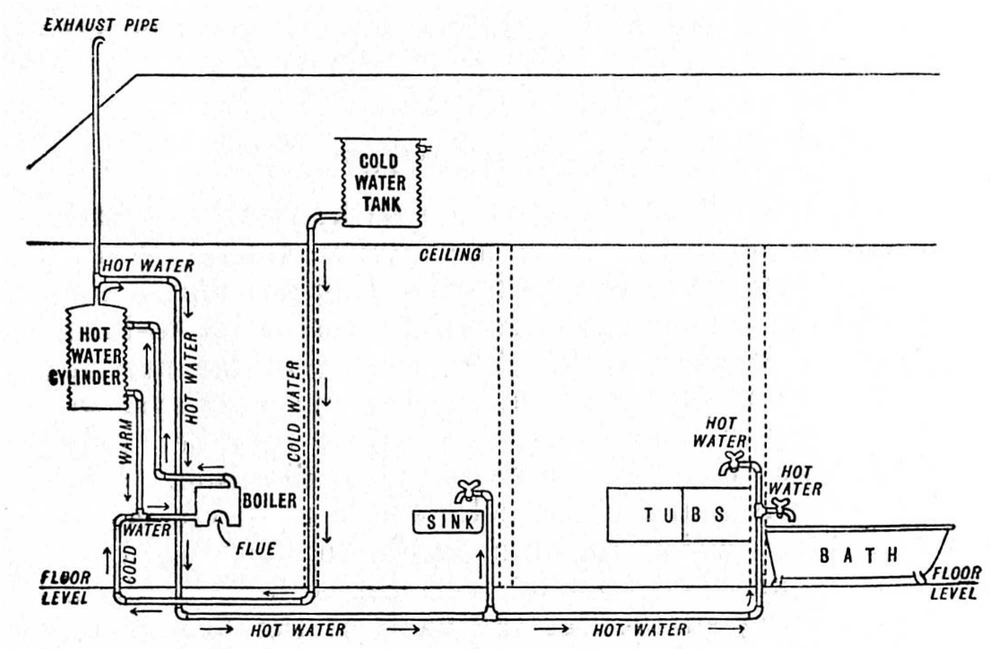

Figure 1. Low pressure household hot water system (1923) [10]

3.1 Electric hot water system

Although electric hot water systems had been patented in many countries by 1910, the modern NZ storage cylinder traces its ancestry to Lloyd Mandeno's 1915 heater made for the nation's first all-electric house. He "made the hot water container of heavy gauge galvanised iron and fitted two elements, one 350 W and one 500 W. This sat in a larger container, around which he packed a 6 inch thick layer of screened pumice for insulation before placing it under the roof above the ceiling, with short drops of concealed pipe leading to the sink and the bathroom" [11]. The fatal flaw did not become obvious for a couple of years, when the galvanised iron corroded through and the hot water followed [12]. The solution, a corrugated copper cylinder, remains the basis for the modern low pressure electric cylinder [11]. The pumice insulation was later replaced by cotton ("flock") then by a foam insulation – most recently polyurethane.

Table 1. Electric hot water cylinder standards

Cylinder Grade	Standard Number	Title of Standard	Standing Losses kWh/day	
			135 l	180 l
A	NZS 4305:1996	Energy Efficiency – Domestic Type Hot Water Systems	1.4	1.6
A	NZS 4602:1988	Low pressure copper thermal storage electric water heaters	1.4	1.6
B	NZS 4602:1976	Low pressure thermal storage electric water heaters with copper cylinders	2.8	3.2
C	NZS 720: 1975	Thermal storage electric water heaters with copper cylinders	2.8	3.2
D	NZS 720: 1949	Thermal storage electric water heaters	2.75	3.3

Table 1 lists electric hot water cylinder Standards from 1949 to 1996 with the maximum standing losses (kWh/day) for 135 litre and 180 litre cylinders. The letter grades (D through A) represent the levels of cylinder standing losses. The worst possible cylinder lacks any insulation (i.e. bare metal) and fails the D-grade requirements. In the HEEP sample, 17% of the electric cylinders were A-grade; 37% B-grade; 8% C-grade; 33% D-grade and 5% could not be allocated a grade [1].

3.2 Gas hot water systems

Coal gas was first made in Auckland in 1862, and by the end of that decade gasworks were operating in Wellington, Christchurch and Dunedin. By 1900 there were gasworks in 30 locations nationally, increasing to 56 by 1918 then declining to 46 by 1940 and to 33 by 1965. Natural gas was discovered in 1959, but it was not available until 1971 for residential customers [13].

The first 'geyser' (or califont) was produced in England in 1868 and the design evolved over the next thirty years. The early geysers could not stand high internal water-pressure, so one was required at each point of use [5]. Apart from the smell of burnt gas, there was always the possible excitement of an explosion if the gas failed to light [14].

The first 'multi-point pressure geyser' was produced in 1899. It was not until the invention of the thermostat controlled hot water storage tank that competition between many would-be-users of the gas heated water could be managed [5] The modern continuous flow (also called tankless or instantaneous) gas water heater combines modern metallurgy and electronics to provide greater reliability, safety and the ability to service up to three outlets. Experience with wetbacks in solid fuel stoves may well have led to similar products being developed for gas stoves [15].

4. CHANGING HOT WATER SYSTEMS

Although regular censuses of population and dwellings were carried out from 1858 [16], it was not until 1945 that a question was first asked about hot water supply. The question was last asked in 1996. The precise question has changed over time, but a general overview can be obtained.

In 1945 over a quarter (26.9%) of households reported that they had no means of hot water service. In 1956 11.6% of households lacked hot water service, falling to 5.9% in 1961, to 1.1% in 1966 and to just 0.4% in 1996 (4,917 of 1,276,332 'Private Occupied Dwellings').

Even in 1945, 88% of households had either a bath or shower – suggesting one of these amenities was present in some of the 15% of households lacking a hot water service. By 1966, the last time this question was asked, either a shower or bath (or both) was found in 97.7% of households.

From 1966 the Census focused on the fuel used and it was mostly electricity. In 1966 84.3% of households used electricity to provide hot water. This increased to 89.5% in 1971 and to 92.5% in 1976, stayed at this level for the 1981 and 1986 Censuses, but fell to 88.1% in the 1996 Census as natural gas increased its market share.

5. ENERGY USE

HEEP was a multi-year, multi-discipline, New Zealand study that monitored all fuel types (electricity, natural gas, LPG, solid fuel, oil and solar energy used for water heating) and the services they provide (space temperature, hot water, cooking, lighting, appliances etc) in a national random sample of about 400 houses, with 440 hot water cylinders. Full details of the research, including house selection, monitoring and analysis methods are provided in [1].

HEEP included measurements of room temperatures as well as hot water temperature. Hot water system standing losses (energy used to maintain water temperature) were calculated in two ways. For those systems where a period of house vacancy with no water use could be identified, the standing losses during those periods were used. Where a vacant period could not be found, standing losses based on the energy use profile were used.

Table 2 gives cylinder standing losses by grade for 135, 180 and 270 litre electric storage cylinders grouped based on the Standards in Table , plus ‘Wrapped’ for those with added cylinder wraps. The 135 and 180 litre gas cylinders do not have grades. The ‘Cylinder Thermostat Temperature’ represents the water temperature as delivered, while the ‘Average Cylinder Temperature’ takes into account the mixing of cold and hot water as the tank recharges.

Table 2. Electric storage cylinder standing losses by size and grade [1]

Nominal Size & Grade	Total Energy (kWh/day) ±SD	Standing Loss (kWh/day) ±SD	Count
Electric - 135 litres (30 gallons)			
A or B	6.5 ± 0.4	2.1 ± 0.1	51
C or D	7.2 ± 0.4	2.8 ± 0.2	56
Wrapped	6.4 ± 0.5	1.8 ± 0.1	9
Other	12.6 ± 1.4	3.7 ± 0.3	19
Electric - 180 litres (40 gallons)			
A or B	7.8 ± 0.4	2.2 ± 0.1	76
C or D	7.8 ± 0.6	2.7 ± 0.2	28
Wrapped	7.6 ± 1.1	2.1 ± 0.3	10
Other	14.2 ± 1.7	3.7 ± 0.3	14
Electric - 270 litres (50 gallons)			
A or B	8.1 ± 1.3	3.0 ± 0.4	8
C or D	6.1 ± 1.8	2.6 ± 0.2	2
Gas cylinders			
135 litres (30 gallons)	14.1 ± 1.5	4.1 ± 0.3	15
180 litres (40 gallons)	17.3 ± 2.0	4.2 ± 0.4	9

Table 2 shows that ‘A or B’ grade cylinders have lower standing losses than the ‘C or D’ group, but 135 litre wrapped cylinders losses at 1.8 kWh/day are even lower. The 180 litre wrapped cylinders have average losses of 2.1 kWh/day. Data in Table shows standing losses for electric systems are, on average, about 33% of the total household energy use and that gas systems' energy use is about twice that of electric systems, but other data shows that this is partly due to increased water use [1].

6. DISCUSSION

This paper has provided a brief review of the methods used to produce hot water in New Zealand homes from the 1800s to the early 2000s. These include batch production (heating in a pot, kettle or other container); add-ons to open fires or solid fuel stoves ("wet backs"); and more recently constant production electric or gas, storage or instantaneous water heaters. Census data from 1945 to 1996 shows the changing importance of different fuels, highlighting the modern predominance of electricity.

The results of a national study of household energy use (HEEP) provide energy use data for constant production systems by heating fuel (electricity and natural gas) and storage cylinder size (135, 180 and 270 litres). This data can be used to examine possible energy savings from replacing an inefficient older cylinder with a modern cylinder, or adding (where appropriate) an insulating wrap.

To replace an existing 180 litre, low pressure cylinder with a new A-grade insulated cylinder costs of about NZ$1,500 (€ 900). Assuming the standing losses are reduced from 3.7 kWh/day (Table 'Other' cylinder) to 2.2 kWh/day (Table 'A or B' grade), at 0.3071 NZ $/kWh (€ 0.18/kWh) the annual savings of NZ $168 (€ 101) would give a simple payback of under 9 years. Decreasing the standing losses by a further 25% gives a 6½ year payback, suggesting replacement is of limited cost benefit. Unfortunately cylinder replacement can often be required at times of urgency, so it is important to ensure the highest efficiency cylinder replaces the older, inefficient cylinder. As it is only the marginal additional cost of the higher performance cylinder that then relates to energy efficiency, the cost benefits are higher and the payback shorter.

Adding additional cylinder insulation in the form of a wrap would cost about NZ $50 (€ 30) plus labour, giving a simple payback of under half a year. Where an old, inefficient cylinder is in use, this action should be undertaken as a matter of course.

The data suggest benefits from controlling hot water use. The 180 litre 'Other' cylinder uses 10.5 kWh/day (14.2 – 3.7). If this could be reduced by 25% through the use of water-efficient equipment (e.g. low flow shower heads) the annual savings would be nearly NZ $300 (€ 180). Water management leads to shorter payback times as well as energy savings.

The HEEP research also found that hot water energy use is not solely determined by the cylinder or fuel type. The design of the hot water system, including the distribution (pipe size and thermal insulation) and installations (e.g. high or low flow shower heads) need to also be taken into account. This paper has not discussed occupant-controlled issues of hot water usage such as occupant shower time or bath use patterns, the selection of water efficient appliances or the replacement of old, inefficient or poor pipes. In cases where an old cylinder is apparently incapable of meeting the existing hot water requirements, some reduction in hot water demand may make the cylinder viable as well as reducing energy demand.

Deciding whether a modern cylinder and/or low-flow fittings or appliances should be used in in a historic building is a complex question, requiring consideration of more than just the efficiency of the water heating system, the pipework and the installations. Understanding the history of the development of hot water heating and the energy efficiency of comparatively modern systems can provide useful knowledge to help support this decision.

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INTERVENTIONS: MATERIALS

Energy efficiency in traditional and historic buildings: keeping it simple

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Abstract *– The thermal refurbishment of older structures is often perceived as being complex and difficult. Modern construction practices do not lend themselves well to a more nuanced approach to work on traditional building fabric. Work by Historic Environment Scotland has shown that technically appropriate interventions, applied proportionately and in the spirit of the original construction, can yield substantial savings in terms of cost and operational energy. Simple fabric measures can be implemented using existing construction skills, and are largely passive, ensuring a minimum burden on the occupier for ongoing servicing and maintenance. Heritage protection legislation is often cited as a barrier; this is not the case. It is there to manage change appropriately, not prevent it, and proportionate measures developed by HES can balance the need to upgrade older buildings without damaging their cultural and amenity value. Technically appropriate measures using the right materials can also have lower embodied carbon and product lifespans similar to that of the building itself.*

Keywords – Traditional and historic buildings; sustainable refurbishment

1. BACKGROUND AND CONTEXT

1.1 Traditional and historic buildings

In Scotland, historic buildings are described as those that have statutory protection, and they make up approximately 3% of the domestic total. Generally these structures date from before 1919 and are made up of traditional materials assembled in a fairly standard way. Such buildings are normally made up of solid masonry walls, approx. 600mm thick, suspended timber floors, timber windows with single glazing, and pitched slate roofs, as well as provision of chimneys and flues. However, not all buildings built before 1919 are considered 'historic', 20% of Scotland's housing stock was built before 1919 using the same materials and techniques, but do not have protection, however, they can be considered as being technically the same. This type of building is perceived as being difficult to refurbish; the phrase 'hard to treat' is often used; until recently there was little research or information on addressing thermal improvements to traditional buildings. The Scottish Building Regulations accept that this type of building has different technical characteristics to more modern ones, and includes in its definition 'vapour open construction' as being characteristic of the pre 1919 housing stock [1]. In Europe the term 'Historic Building' is applied in a number of ways, sometimes including all structures built before 1939. Historic Environment Scotland (HES), an agency of Scottish Government, is tasked with oversight and leadership in the sector and were aware that guidance was needed in the refurbishment field, looking beyond the needs of historic buildings alone.

1.2 The requirement for thermal upgrade

The requirement for thermal upgrade buildings of all periods is well established in European and national law; and the EPBD obliged member states to measure improvements in the housing stock. The Scottish Government has also set a high standard for carbon reduction in the Climate Change Act of 2010 and there was specific attention paid to the pre 1919 building stock and how they could be improved. Noting the technical difficulties experienced with some retrofit programmes in England, there has been a focus by HES on establishing what measures will suit buildings of traditional construction. HES were supported by Scottish Government in a programme of research and trial work to demonstrate durable and effective interventions to older properties that commenced in 2010. It was established early on that in fact historic or traditional properties were not the poorest performing in energy terms. The thick walls that characterised Scottish traditional construction generally meant that U-Values were better than many models and assumptions suggested, and this was validated by a programme of in situ testing by Glasgow Caledonian University for HES [2] .

1.3 The HES approach to refurbishment

While there has been a lot of refurbishment activity on older buildings all over Europe, much of it has not been sympathetic to aesthetics or the host fabric; while thermal improvements may have been realised there was loss of historic material and often a compromise of the architectural composition. In addition there have often been issues of damp, mould and poor internal environments. A recent study by English Heritage in 2015 has shown that work carried out on traditional terraces in England in 2012 resulted in damp and other issues after only a few years [3]. The HES work would seek to approach the refurbishment of older buildings with a different mind-set – one of sympathy with the existing fabric. Traditional and historic fabric, if maintained and improved with the right materials and skills, can be very durable, but the wrong measures will quickly degrade and damage building fabric. To validate this new approach HES established a set of pilot projects that would trial and evaluate a range of insulation measures that were appropriate for older structures. This project took account of the following factors:

1.3.1 Perceptions regarding national protection legislation

Protection for historic buildings, referred to in Scotland as ‘Listing’, contrary to perceptions, does not seek to prevent change, but to manage it appropriately, maintaining the special character of a building and not using materials that cause damage to the fabric. The measures trialled by HES were designed to be appropriate for most historic structures, that is the changes required to install the measures would generally be acceptable to planning authorities and HES. In some cases change is not possible, and historic material cannot be disturbed, but the numbers of such structures in Scotland is very small.

1.3.2 Embodied energy considerations

While reducing energy losses through the fabric was the main focus of the projects, consideration of the embodied carbon of the new work, and the carbon costs of materials going to landfill was also considered. It is the opinion of HES that a lot of refurbishment activity results in excessive quantities of waste and the loss of durable construction materials which could be reused. This resulted in a refurbishment approach that generally improved the performance of existing building elements as opposed to their removal and replacement.

1.3.3 Cover a representative range of housing stock

The HES pilots were carried out on a range of traditionally built domestic properties; all were domestic in scale and reflected the range of Scottish building types. They included works on rural cottages, tenement flats and some non-domestic buildings of traditional construction. Some of these pilot buildings had heritage protection, but many did not. This wide range of building types will allow the lessons to be applicable to a large number of homes and owners in Scotland and elsewhere.

1.3.4 Proportionate interventions

It is the view of HES that for interventions to be durable and replicable they should be simple in design and modest in extent. That is to say the law of diminishing returns, should apply – modest interventions are the most effective. Working on an existing building to achieve parity with modern performance standards was not felt to be cost effective, but that older and historic structures should be improved where reasonably practicable.

1.3.5 Technically compatible measures

It is an established principle in building conservation that matched or similar materials are used in new work, not just to achieve visual continuity, but to ensure the building fabric continues to operate technically as designed. In many traditional and historic buildings this means maintain the vapour open nature of the construction. This is sometime called the 'need for older buildings to breathe' and is a well-established principle in building conservation [4]. Maintaining this important dynamic will allow the dispersal of water vapour during periods of peak loading and was always a consideration in the pilot projects.

1.3.6 Modelling hygrothermal risk

In refurbishment there is always a consideration of condensation risk, especially where walls are being insulated. Condensation risk assessment is often carried out using procedures outlined in BS 5250 and ISO 13758, sometimes called the Glasser Method. While this well-established procedure is relevant for many types of modern structures, it has limitations for traditionally constructed buildings, and is stated as not being suitable for masonry buildings. While condensation risk analysis was commissioned for some projects, its results did not reflect site conditions and sometimes set out a requirement for vapour barriers. HES work, and analysis by The Sustainable Traditional Buildings Alliance (STBA) have allowed a questioning of the outcomes from this method and its use in solid wall insulation contexts and especially the perceived requirement for vapour barriers [5]. In all the HES projects there were no vapour barriers.

1.3.7 Indoor air quality and health

Many refurbishment projects on older buildings in recent years have not always yielded the benefits sought. Much refurbishment work, by reducing air leakage, has also reduced ventilation rates significantly. This has resulted in high internal humidity levels, with condensation and mould forming. While bad in themselves, they can also be considered a proxy for other health effects. This area was considered in more detail by Historic Scotland in 2011 [6]. In all the HES projects, while the building fabric was improved, some degree of fortuitous ventilation was maintained. This was achieved through the retention of open chimneys, and underfloor vents. Timber windows were always retained, with a degree of draught proofing, but exclusion of all draughts was not desired.

2. THE PILOT PROJECTS

From the project start, 3 properties were selected each year. The owners of the properties were supported with a HES Grant and technical input. Work was carried out on 15 properties over a five year period, and a range of thermal upgrades were installed, following the approach set out above. The exact nature and focus of the interventions varied, but followed similar themes of intervention – that is generally improving the performance of existing elements of a building essentially using vapour open materials. As the properties were widely dispersed in Scotland, skills and experience varied, so the focus had to be on basic and durable measures that could be easily adopted. This required a high level of oversight and training in the techniques and materials used; while it could not be said that any of the materials were new, they were certainly being used in a new way. Additional projects have also been delivered on ways of heating older properties, but they are not considered in this paper.

2.1 The interventions

2.1.1 Work to floors

In most traditional buildings in Scotland there is a suspended timber floor at ground level. These were insulted by the application of a wood fibre board between the floor joists. The original floorboards, if lifted carefully, were able to be laid back in place and re-fastened. Of all the measures trialled this was considered the most effective; perceptions of thermal comfort are significantly increased if feet are not losing heat through a floor. Where there was a solid concrete floor this was replaced with an insulated lime concrete floor.

2.1.2 Work to windows

In heritage circles work to windows is often thought to be a sensitive topic, however, following a programme of lab trials and site work it was demonstrated that a range of upgrade options were available depending on the specific circumstance of the building, and the condition of the existing window [7]. Upgrade options included the use of roller blinds, restoration of traditional shutters; secondary glazing and new slim profile double glazed units in the existing timber of the window.

2.1.3 Work to roof spaces

While insulation to roof spaces and attics is relatively straightforward, attention to detail was required. The choice of insulation material, depth of the insulation and suitable levels of ventilation into the roof space were all relevant considerations. Insulation of the roof slopes was preferred, as that kept the roof space as a warm roof, and good results were obtained with wood fibre board. When insulation was applied to the ceiling, giving a cold roof space, issues of ventilation needed consideration. In one case a misunderstanding over the roof construction led to insufficient ventilation with resulting condensation and significant mould growth. This was resolved with additional roof vents.

2.1.4 Work to solid walls

It is considered by HES that solid wall insulation (SWI) should be the last area to be tackled, and that IWI should not oblige the removal of traditional or historic linings. The approach was taken to improve the existing material as opposed to its removal; this meant less waste to landfill, reduced embodied energy considerations and less disruption to the occupant. This more mild approach is partly possible due to the thickness and thermal mass of solid walls in Scotland; At 600 mm thick, sometimes more so, they have a degree of thermal resistance (approx. 1.2 W/m^2K) so any improvement did not have to be a great as that needed for a double skin of brick as, for example, is encountered in London. Generally internal wall insulation was favoured for the pilot projects taking the form of blown materials injected behind the existing plaster lining. This allowed the retention of existing linings (decorative or otherwise), was relative inexpensive, and was fairly quick to deliver. Such materials included blown polystyrene beads, blown cellulose, and a water based foam.

2.2 Quantifying the thermal improvements

In order to demonstrate the improvements made, in situ measurements were taken of the thermal performance of the walls and other fabric areas. This was done with in situ heat flux meters and a U-value was calculated. This allowed pre and post intervention information for the areas measures to be compared. A report was prepared from each project by the monitoring contractor to allow and assessment of the insulation and refurbishment measures to be made. While these are published separately as Historic Scotland Technical Papers, the information was also incorporated in the full report for each project. As a summary for this paper, average values for building elements pre and post intervention are given in Table 1.

Table 1. Average pre and post intervention U-Values from HES projects

Fabric Element	U-Value/heat transfer co-efficient (W/m²K)		
	Pre intervention	*Post intervention*	*% reduction*
Timber floor	2.4	0.7	71%
Timber windows	5.4	2.0	62%
Attic roof slope	1.0	0.13	87%
Attic ceiling	1.4	0.20	86%
Masonry walls	1.1	0.41	63%

2.3 Assessment of the measures

Many of the measures were relatively new, or consisted of existing materials used in a new way. In order to demonstrate that not only were there thermal improvements, but that the measures were not causing damage, a programme of monitoring was established to establish or track any changes. This was achieved with relative humidity loggers set within the masonry of the solid wall. Logging of the relative humidity at the pilot sites showed that there was no sustained increase in relative humidity in walls, and internal conditions in all the refurbished properties remained good. In two cases, external factors (due to plumbing problems) led to water ingress and limited flooding; however with the vapour open materials selected for the upgrades the building fabric was able to dry out with no long term damage.

2.4 Feedback from occupants and industry

The views of residents were taken into account when planning the interventions, and feedback was taken once the refurbished property had been occupied for several months. In all cases the feedback was very positive and while a full survey of the energy consumption for the pilot stock has yet to be made, early indications are reductions in energy use and an improvement in indoor air quality. The contractors who carried out the work were positive, once they were familiar with the measures. One of the later projects, carried out with a housing association in Perth, achieved sustainability recognition with a Green Apple Award in 2015. This work is described in The Historic Scotland Refurbishment Case Study 20 [8].

2.5 Education and dissemination

The pilot projects would only have value if the lessons and techniques learnt were disseminated within the construction and insulation industry. For each pilot there was a report from the monitoring staff as well as extensive site records and photographs that followed the construction phase of the project. This material was used to write up a report on the project, called a Refurbishment Case Study, this report sought to describe in simple language what was done, what it cost and any key learning outcomes. In addition, to summarise the measures that were tested into a single document, HES published written guidance in 2012, in the Short Guide Series, called *Fabric Measures for Energy Efficiency in Traditional Buildings* [9]. A new version is being developed to describe the new measures proved since then, and to validate the earlier works after the passage of time.

2.6 Skills and training issues

While most of the measures were straightforward in nature, ensuring that designers and contractors were comfortable in their specification and installation required dialogue and oversight. However, it was clear that once a contractor had finished the works, they were comfortable to repeat it again in a non-trial situation. Developing qualifications and training in sustainable retrofit was an important part of the project, and forms another paper in this conference.

3. CONCLUSION

The Historic Environment Scotland pilots have shown that with the right approach to traditional and historic building fabric good levels of thermal improvement can be achieved with simple and durable measures. Allowing the traditional building fabric to function as intended, without the use of vapour barriers has proved to be a successful strategy and one which not only gives technical benefits but allows respectful and appropriate upgrades. In Scotland the heritage protection regulations are about managing change appropriately, not preventing it, and the pilots also show how thermal efficiency can be compatible with reduced carbon emissions from traditional and historic buildings.

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Comparison of different systems for internal wall insulation with reversible application for historic buildings

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Abstract *– Internal wall insulation is a method of retrofitting that can be an interesting option for historic buildings. However, from the point of view of building physics it is a critical solution that can lead to damages if not applied in a correct way. Also the impact of conventional ways of application can be rather destructive for valuable historic surfaces including paint layers and thus evidence from many centuries.*

Here a comparison of internal wall insulation, that is currently applied and tested in a historic building dating from 1760, is presented. With this new reversible attachment different products of internal wall insulation are tested and compared. This includes mineral capillary active insulation, high performance insulation using aerogels, conventional systems and material from renewable resources. The criteria for the comparison are both from a building physics point of view and practical aspects like effort of application, practicability, usability and price to insulation improvement ratio.

Keywords – Internal wall insulation; reversible application; retrofitting

1. BACKGROUND

The investigations presented in this paper were performed at the Fraunhofer Centre for Conservation and Energy Performance of Historic Buildings. It is located at the "Alte Schäfflerei" (Old Cooperage) in Benediktbeuern Monastery. The building is dated to the second half of the 18th century (Fig. 1). The Fraunhofer Centre deals with the preservation of built heritage and historical materials and structures of buildings. It focuses on the improvement of energy consumption and different aspects of monument preservation. Tradition and innovation complement each other. One of the main concepts is to develop solutions in close exchange with people working in the building sector and together with the Bavarian State Office for Preservation of Monuments. The described research objectives aim for long-term solutions that are compatible with the needs of historic monuments and traditional buildings. With the different research projects the "Alte Schäfflerei" aims to be an open centre for communication with building professionals and building owners alike as a "vitreous construction area".

The ongoing research project „internal wall insulation" focuses on innovative solutions for internal wall insulation in existing buildings as well as the further development of existing products for the preservation of historic monuments. Especially the question of reversibility is one of the primary considerations of the researchers and conservators. Over the years interior surfaces in historic buildings often have accumulated multiple paint layers such as colourful coatings which in some cases also served ornamental purpose. These layers are material evidence of the past and shed light on the prevailing tastes of each period. When installing interior insulation panels, workers usually cover these painted surfaces with adhesives that pull off and destroy this historic evidence when panels are later removed.

Figure 1. The "Alte Schäfflerei" in Benediktbeuern monastery accommodates the Fraunhofer Centre for Conservation and Energy Performance of Historic Buildings (left). On the upper floor innovative insulation materials are reversibly applied and their hygrothermal performance is examined (right).

For this reason, the goal of the project is to develop reversible solutions for the installation of internal wall insulations that are simple to apply and cause as little damage to the valuable historic building materials and surfaces as possible. For the examination of different insulations various protective systems are considered: laminated interlayers, which are easily strippable, elevated drywall installation with Japanese tissue paper on top of the historic interior plaster in order to protect the original surfaces. Not only for historic buildings, but also for existing buildings with periodical renovation measures these innovative reversible solutions may be useful.

2. CHOICE OF INSULATION SYSTEMS

In the examinations at Benediktbeuern mineral capillary-active materials and conventional systems are included, but also high-performance insulations using aerogel, which allow very slim setups, as well as material from renewable sources [1]. These criteria are important also in the field of monument preservation. New solutions always have to be compatible with existing historical building materials. Thin and highly efficient systems are appreciated in order to avoid changes in the appearance and proportions of historical buildings. Insulation materials from renewable sources are more similar to historic materials and therefore sometimes easier accepted for preservation by building owners and conservation professionals. Examples of the examined systems at the "Alte Schäfflerei" are classic curtain wall systems with mineral wool, cellulose infill systems and perlite-fill as well as an internal wall built, consisting of hollow bricks filled with perlite. As high-performance insulation materials aerogel-boards and aerogel-plasters have been applied, as renewable and traditional materials cattail- (i.e. Typha) and reed-board. Basically the systems can be divided in permeable and capillary-active insulations versus diffusion resistant ones. All in all ten different kinds of insulation were installed (Fig. 2) and suitable sensor systems were added to them (Fig. 3). Each system covers a wall section of roughly ten square meters and includes a window opening. Thus researchers can examine potential issues concerning the reveal of the window and the joints for different orientations.

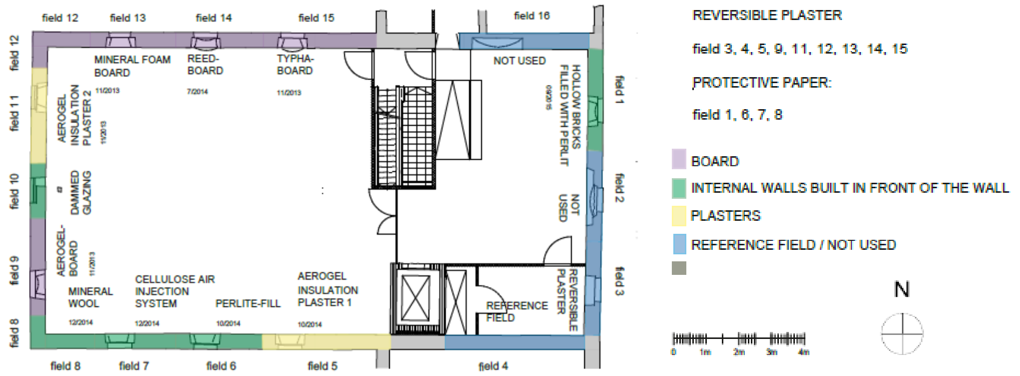

Figure 2. Floor plan of the upper floor of the "Alte Schäfflerei" with different insulation systems.

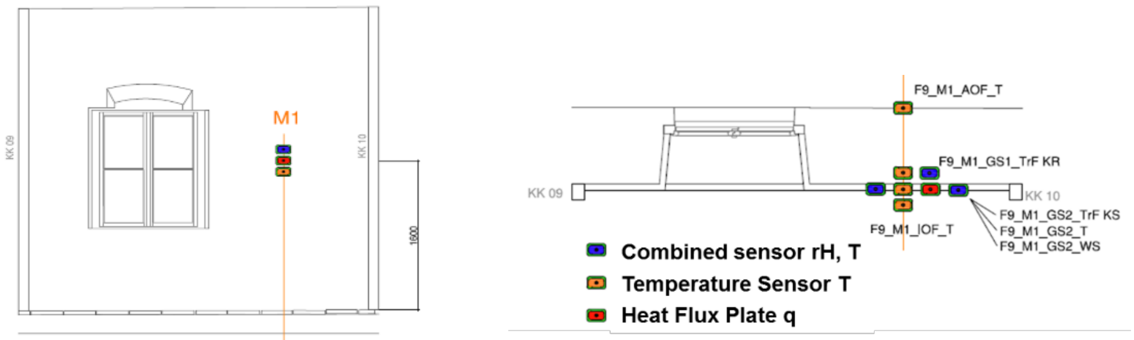

Figure 3. Example of a test area with typically installed sensor technology. View from inside (left) and in horizontal cross section (right).

3. ASSESSMENT OF THE IMPACT OF DRIVING RAIN AND LAYOUT OF THE INTERNAL WALL INSULATION

To reduce the risk of damages on the historic building fabric, two strategies are pursued. On the one hand, before the installation all systems have been tested by hygrothermal simulations with regard to their suitability for critical boundary conditions, for example the water absorption of external plaster due to driving rain. On the other hand an extensive monitoring on critical spots in the construction, for example on original wall surfaces or beam ends is carried out to recognize potential risks in time for starting arrangements to prevent damages. With the aid of two dimensional calculations capabilities for internal wall insulation systems are analysed. This is used also as a suitability test for the insulation systems. Thus damages due to moisture can be eliminated and avoided before on-site operation. For the calculations the knowledge of all hygrothermal properties is required. They partly originate from the material database of WUFI®, but some also had to be determined experimentally. As basis for the boundary conditions climate data from the meteorological station in Benediktbeuern are used. The indoor climate is calculated with 20 °C and 50 % relative humidity as the test room is also conditioned to this indoor climate. The systems are calculated for a westward direction as this orientation is affected most by driving rain. Left side of Fig. 4 shows an implemented wall setup using the example of capillary active mineral foam insulation.

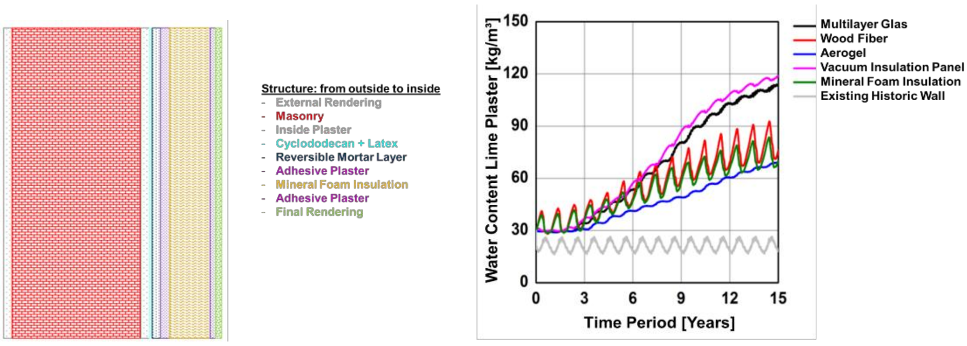

Figure 4. Implemented wall construction using the example of mineral foam insulation in WUFI®-2D (left) and calculated development of the water content of the interior lime plaster for different insulation systems (right).

Due to the fact that the hygric material properties of the original wall façade were insufficiently known the water absorption coefficient of the external plaster was measured before by “Karsten Pipe”. There is a big fluctuation range of the A-value (1.8 – 7.7 kg/m²√h) because different plasters have been used for reparation works at the façade. As a consequence an averaged value of 4.2 kg/m²√h was taken as initial situation for the simulation. By taking measurements of the heat flow rate and temperature the U-value of the original wall could be determined as about 1,1 W/m²K. Based on the fact that the initial moisture content in the different materials corresponds to equilibrium moisture content of 80 % RH, the water content in the interior lime plaster increases constantly in every calculation of the chosen systems (Fig. 4, right). This concerns particularly systems which are diffusion tight, like vacuum insulation panels or multilayer glazing. That’s why none of these diffusion tight systems were implemented in this way. The existing uninsulated wall shows a lower water content than the walls with internal wall insulation systems. The reason for the increase in moisture content is the high water absorption coefficient of the external plaster. Rainwater is absorbed and transferred by capillary transport into the depth of the masonry. To tackle this, e.g. a hydrophobic paint coat on the outside of the building is recommended when applying internal insulation under comparable boundary (weather) conditions like at Benediktbeuern.

Due to the additional diffusion resistances of the insulation systems and the temperature reduction at the original inner surfaces, a very low and slow drying takes place compared to the situation without insulation. Additionally because of the lowering of the overall temperature of the masonry, drying to the outside is reduced, too. In order to avoid damages on the surface of the lime plaster and the historic paint layers the A-value, i.e. the water uptake, of the external plaster has to be reduced therefore. Application of water repellent agents, the use of hydrophobic coatings or the application of a new plaster system are possibilities to reduce the absorption of water. Therefore calculations were conducted to identify the required A-value for the outer coating. With an A-value of 0.5 kg/m²√h or less no more long-term increase of total moisture content occurs. For the two diffusion resistant systems (VIPs and multilayer glazing) with this A-value the result is even a lower of water content, because of the lack of moisture diffusion from inside. The exterior façade has now been renovated with a slightly hydrophobic coating system in 2015, about 1.5 years after the application of the first insulation systems.

In order to estimate whether the installation of the internal wall insulation can be conducted without damage risk a worst-case scenario insulation with a diffusion tight system (VIP insulation) was simulated with a renovation of the façade not before four years after the installation of the systems. In these simulations the influence of the built-in moisture was included. Fig. 5 shows the course of the water content for the lime plaster in different phases: steady-state situation before (green), application of internal wall insulation with built-in moisture from installation of the systems (red) as well as after the reduction of the water absorption coefficient of the external plaster (blue). It is visible that after the application of the insulations a strong wetting of the original internal lime plaster occurs. With a reduction of the outside water absorption coefficient after 4 years to 0.5 kg/m²√h, for one year an increase of water content occurs until a slow drying takes place for the inside lime plaster. Fortunately, the maximum capillary saturation level lies below 50 %, far away from critical area.

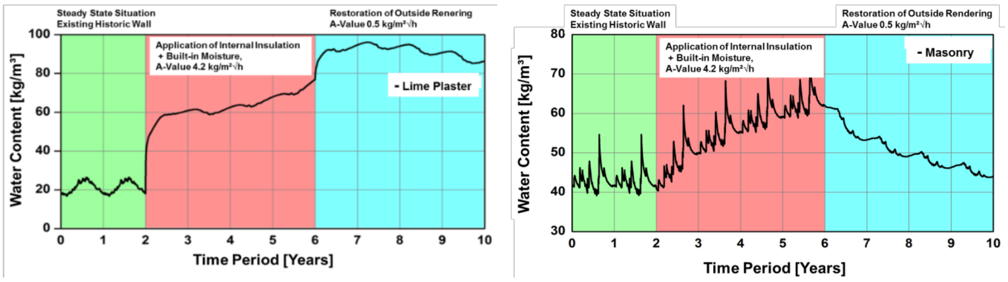

Figure 5. Worst-case simulation with a diffusion tight internal wall insulation system (VIPs). Simulated development of the water content of the internal lime plaster (left) and the masonry (right) in the different phases if a renovation of the façade with a slightly hydrophobic coating (A-value = 0.5 kg/m²√h) would take place only after 4 years.

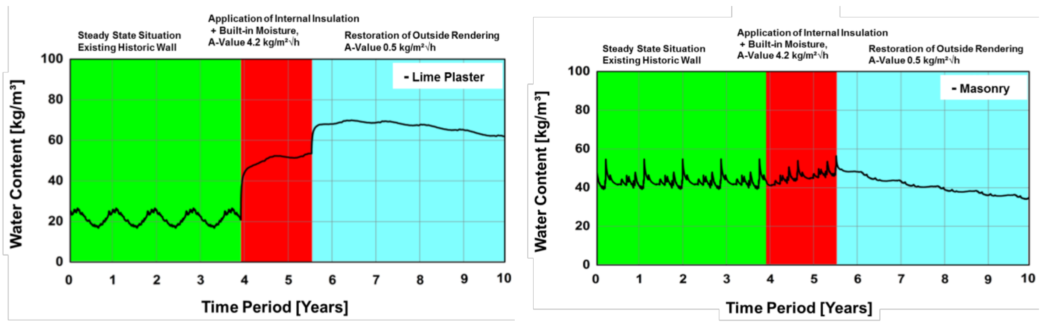

Figure 6. Worst-case simulation with a diffusion tight internal wall insulation system (VIPs). Simulated development of the water content of the internal lime plaster (left) and the masonry (right) in the different phases related to the real renovation of the façade in 2015 with a slightly hydrophobic coating (A-value = 0.5 kg/m²√h) after 1.5 years.

In reality at about 1.5 years after the application of the first internal wall insulation systems the façade of the “Alte Schäfflerei” has been restored with a slightly hydrophobic coating. In accordance with this new situation, the simulation has been run again to assess the real impact of the current measures at Benediktbeuern, as shown in Fig. 6. The increase in moisture was much less in the phase after installation of the internal wall insulation (red phase). The construction now seems to work well, as can be recognized by the constant reduction in moisture content in the phase “Restoration of Outside Rendering” (blue) shows.

4. FIRST MEASUREMENT RESULTS

In Fig. 7 the temperature courses behind different insulation systems are shown. One example for each category (high-performance insulation, curtain wall system, renewable and capillary-active insulation) has been chosen as typical representative. These are aerogel insulation plaster (4.5 cm, λ = 0.028 W/mK), perlite-fill (8 cm, λ = 0.05 W/mK), Typha (cattail) board (9 cm, λ = 0.055 W/mK) and mineral foam board (10 cm, λ = 0.042 W/mK). Additionally the particular thermal resistance value of each insulation system is denoted, which arises mostly from thermal conductivity and thickness of the insulation. As expected, during summer time there are minor differences between these systems, in contrast to the winter time with heating activity (scaled up in Fig. 7, right). The comparison of the position of the curves shows the same succession as the thermal resistance, as should be expected. The higher the thermal resistance, the less energy loss and the lower is the resulting temperature behind the internal wall insulation.

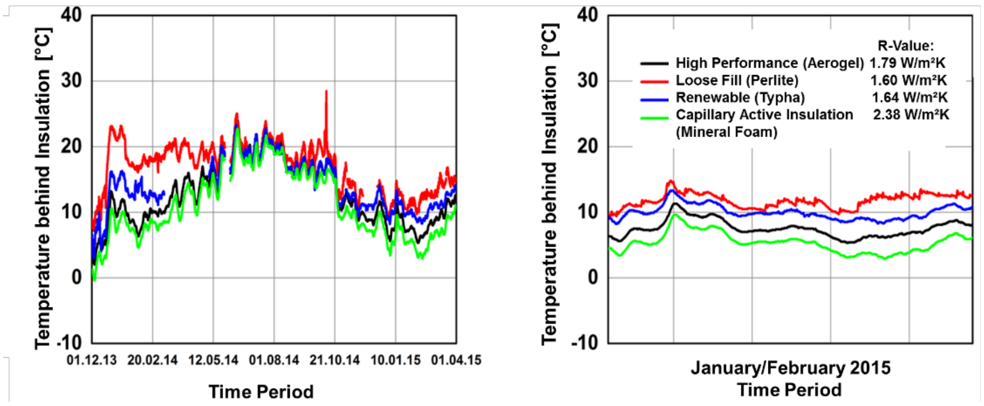

Figure 7. Course of the measured temperature behind the insulation for different insulation categories for the period from December 1st 2013 to April 1st 2015 (left) and in detail for January/February 2015 (right).

The following Fig. 8 shows the course of the measured heat flows behind the insulation. The curve for the insulation with perlite-fill begins in November because of the installation at this later date. During the first winter period little differences exist except for one. Although the perlite-fill possesses the least thermal resistance, the wall insulated therewith shows a noticeable lower heat loss.

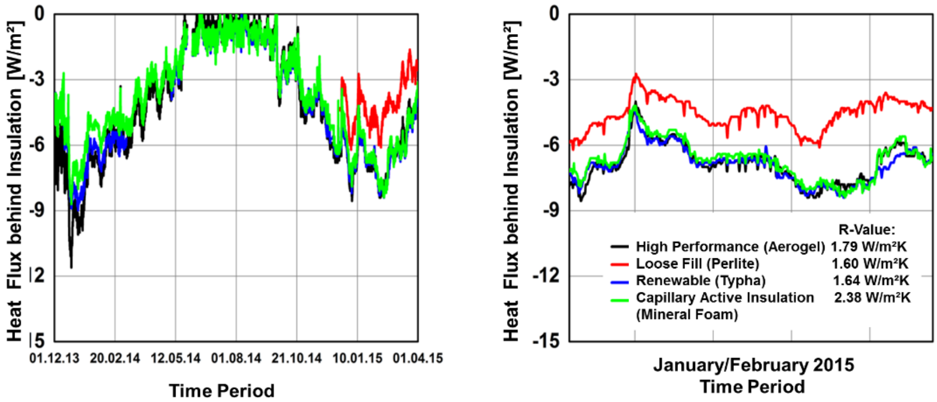

Figure 8. Course of the measured heat flow behind the insulation for a choice of each insulation category of the whole measured time period (left) and in detail for January/February (right).

This effect can be explained with a look at orientation. The façade that is insulated with Perlite is straightened southward. Because of the solar radiation on the south façade higher external surface temperatures occur, leading to lower heat losses.

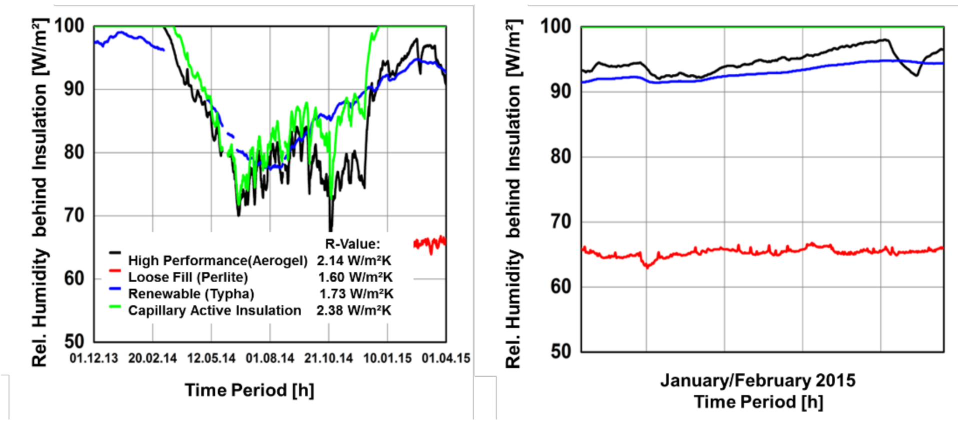

Figure 9. Course of the measured relative humidity behind the insulation for a choice of materials for the whole measured time period (left) and in detail for January/February (right).

Due to their differing material properties, the insulation systems investigated also show different moisture behaviour. Fig. 9 displays the course of the relative humidity behind the insulation for the whole measured period (left) and in detail for January/February (right). The lower relative humidity on the backside of the perlite insulation (start of measurement in Nov. 2014) is obvious. This is on the one hand due to missing built-in moisture (dry construction) and on the other hand because of an inserted vapour retarder. Because of the built-in moisture the measured curves of the aerogel insulation plaster and mineral foam board start at 100 % RH only the Typha (*cattail*) insulation board shows lower values. In the summer period a clear drying of all three systems takes place, so that temporarily the values fall below 80 % RH. The comparably (short-term) constant course of relative humidity below the Typha insulation is noticeable, which is caused by its high moisture buffering ability.

After this drying period in summer, clear wetting during winter (except for the perlite insulation with vapour retarder on the inside) occurs. For the capillary active mineral foam insulation there is a very fast increase up to 100 % RH behind the insulation boards. From the end of December 2014 to April 2015 the measured relative humidity stays at 100 %. This is typical for a capillary-active diffusion permeable insulation system, which depends on the mechanism that condensation water, which appears inside the material is being reverted capillary in order to avoid a continuous wetting. In the same time period the relative humidity for the aerogel and Typha insulation lies respectively between 93 and 97 % (Aerogel), and between 93 and 95 % (Typha). The low short-term variations in time are shown again with Typha insulation.

5. FIRST ASSESSMENT OF THE DIFFERENT INSULATION SYSTEMS

An essential hygric question is the handling of the built-in moisture after the installation, namely the corresponding drying time. Due to different installation times and orientation, this cannot be determined in a proper way by the in-situ measurements at the "Alte Schäfflerei" Benediktbeuern alone. For this reason this assessment is determined by hygrothermal simulations. After implementation of the whole wall construction with a selected insulation system and the corresponding material properties as well as the typical material dependant built-in moisture, the drying of the system can be calculated using equal boundary conditions (orientation, indoor climate, weather, wall-construction, etc.). Fig. 10 presents the results as course of the total water content of the wall for all systems that are fixed directly to the wall (without the infill insulations behind dry wall constructions with vapour retarders).

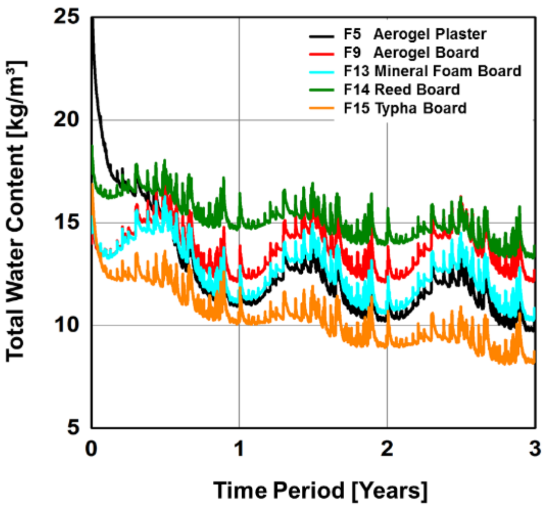

Figure 10. Simulated course of the total water content after the installation of the insulation systems during the first 3 years after installation, taking into account the built-in moisture.

Because of very similar material properties the two aerogel insulation plasters were not treated separately in this simulation. In the beginning every system dries out quickly, except for the aerogel insulation plasters (black curve), which are applied to the interior wall surface with very high starting moisture content. After about 2 months this changes and the total water content of the wall, insulated with aerogel plaster, now falls below the curve of reed (green). After about another half a year the curve also falls below the curve of Aerogel board (red) and Mineral Foam system (blue) as well. All in all the application of reed shows the highest, Typha the lowest water content of all observed systems.

For a comprehensive assessment of the different systems aspects of the energy saving, required energy for production, moisture protection properties, compatibility for the preservation of monuments as well as environmental protection have to be taken into account. Additionally the mechanical properties and expenditures for the application have to be included, but the current results and state of discussion allow only a generalized assessment.

Aerogel plasters and boards show a high potential for use in historic buildings, but still have some limitations in regard to the high price and still open questions in matters of sustainability. Aerogel plasters show very high moisture when being installed that is going down fast. Recently the high costs have decreased strongly and may sink even more in the course of time. Probably every new material has problems in gaining acceptance in the field of heritage protection, but this can be achieved by positive examples of application and long-term experiences with application. Cellulose infill and Typha-insulations show good results in regard to ecological performance. The mineral wool insulation scores with the low price and the installation as a dry construction, but may not be accepted everywhere in historic buildings. The capillary active mineral foam board is already accepted in historic building but because of its low diffusion resistance it shows higher moisture content resulting in a heat conductivity higher than assumed. Although the reed board is a long-established internal insulation system it shows the worst moisture behaviour. The Typha insulation convinces because of its environmental advantages and good mechanical characteristics and stability. Depending on the individual emphasis of separate criteria, different preferences are possible.

In general all examined systems can be used for refurbishment of historic building. All hygrothermal performance aspects have to be weighed against the impact to the cultural heritage building, effort, sustainability and installation costs. All systems investigated have been applicated in a way that a good reversibility should be assumed. The proof of reversibility will be given after the end of the project, when the systems will be partly dismantled.

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Capillary active interior insulation: a discussion

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Abstract – *To thermally upgrade exterior masonry walls, interior insulation is often the only possible retrofitting technique, especially when dealing with historic buildings. In an effort to reduce the risks induced by applying interior insulation, material developers have been looking into potential substitutes for our traditional vapour tight systems. In this respect, nowadays so-called capillary active interior insulation systems are often promoted. This paper includes an overview of the main hygrothermal properties and working principles of these systems. For the different systems on the market, widely varying values for the thermal resistance, the capillary activity and the diffusion resistance are found, which may result in a totally different behaviour as originally intended. The influence of this variation in hygrothermal properties on the working mechanism is demonstrated by experimental and numerical simulations. In this way, this paper aims to clear up a number of misconceptions on so-called capillary active interior insulation systems.*

Keywords – Capillary active interior insulation; hygrothermal performance; wall retrofitting; capillary absorption coefficient; diffusion resistance

1. INTRODUCTION

Climate and environmental changes, rising energy prices and limited energy sources made energy consumption a central concern all over the world. A large potential to reduce our energy use can be found in the building stock. In this respect, historic buildings constitute a huge challenge. And, driven by an increasing adaptive reuse of those historic buildings [1][2][3], this challenge can no longer be evaded. According to the Trias Energetica, a thermal upgrade of the building envelope should be the first step to a better energy efficiency and a higher comfort level. When dealing with exterior building walls of historic buildings, which are mostly monolithic masonry walls, interior insulation remains often the only possible post-insulation technique for a thermal upgrade. Unfortunately, this technique can modify the hygrothermal performance of the masonry wall significantly. Indeed, vapour tight systems result in a potential risk on frost damage, an increased moisture content in the masonry wall and other damage patterns [4], while a traditional vapour open system will induce interstitial condensation [5]. As a reaction to these shortcomings, nowadays so-called capillary active interior insulation systems are often promoted. Capillary active systems allow – due to their vapour open character – a drying out, while their capillary active forces avoid a local increase of moisture due to interstitial condensation. Recently, a range of systems is being sold as novel capillary active insulation system. This paper examines the main systems on the Belgian market, their differences and similarities. Thereto, in a first section, the general working principle of a standard capillary active interior insulation system is described together with its main advantages and disadvantages. The second section introduces some newer systems.

Furthermore, it contains an overview of the thermal resistance, capillary activity and diffusion resistance of the main different systems on the market. The impact of these properties is discussed based on experimental and numerical simulations. In this way, a clearer view on the so-called capillary active interior insulation systems and their working mechanism is pursued. To end, the main conclusions are summarised.

2. THE STANDARD CONCEPT

2.1 The working mechanism

Although nowadays often promoted as an innovative insulation system, capillary active interior insulation has already been applied for many years [6][7]. Traditionally, a capillary active interior insulation system consists of a calcium silicate (CaSi) layer adhered to the masonry wall by a glue mortar. The working mechanism of such a system is shown in Fig. 1. During the heating season, a temperature and vapour gradient induces an outward vapour flow. If the temperature between the glue mortar and the insulation is lower than the dew point, interstitial condensation will occur; though, it can be buffered in the glue mortar and in the insulation material, where it can – due to the capillary active pores of the calcium silicate board – be redistributed toward the room. In this way, a local increase of moisture due to interstitial condensation can be avoided. Additionally, at the interior wall surface evaporation can occur. Important to note is, however, that while the working mechanism is often explained from the perspective of interstitial condensation, the vapour open character allowing a drying out is actually the main reason to choose for a capillary active system.

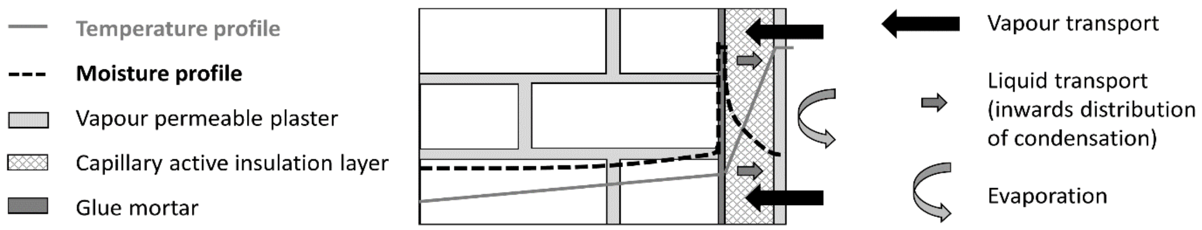

Figure 1. Working mechanism of a standard capillary active insulation system

2.2 Advantages versus disadvantages

The working mechanism as described in section 2.1 can, however, induce a number of side effects [4][5][8]. Indeed, by buffering moisture in the capillary active insulation material, the thermal conductivity will increase, resulting in a lower thermal resistance. Additionally, the evaporation at the interior wall surface may result in too high moisture conditions in the room. Hence, in museums for instance, one has to reckon with a potential extra energy cost to dehumidify. Furthermore, it is important to note that a capillary active system is sensitive to small modifications to, for instance, the finishing layer. When applying a finishing layer or paint that is too vapour tight, drying out to the inside is no longer possible and the moisture will be trapped in the insulation system. Ultimately, it should be noted that the working mechanism as described above is only valid if there is good contact between the glue mortar and the insulation system. An overview of the main ad- and disadvantages of a traditional capillary active interior insulation system is given in Table 1.

Table 1. Main ad- and disadvantages of a traditional capillary active interior insulation system

Advantages	Disadvantages
- *Drying out of the masonry to the inside*	- *Lower thermal conductivity*
- *Buffering of interstitial condensation*	- *Higher indoor surface relative humidity possible*
- *Similar moisture profiles as in the original masonry wall (important if wooden beam ends are present)*	- *Higher indoor relative humidity possible*
	- *Good working principle is sensitive to small modifications (e.g. finishing layer)*

3. VARIATIONS ON CAPILLARY ACTIVE SYSTEMS

3.1 System descriptions

Most studies on capillary active interior insulation focus on calcium silicate systems as described in section 2 [4][6][7][8]. Yet, nowadays different variants on this original system are on the market: e.g. systems in which the calcium silicate board is replaced by a wood fibre board (WFB), aerated concrete (e.g. MULTIPOR®), etc. and systems composed of a combination of materials (see Fig. 2) such as Pavadentro® (WFB with an embedded functional layer), Calsitherm Xtra® (CaSi with PUR, VIP or pyrogenic silicas in it), IQ-Therm® (PUR with small holes filled with a capillary active material).

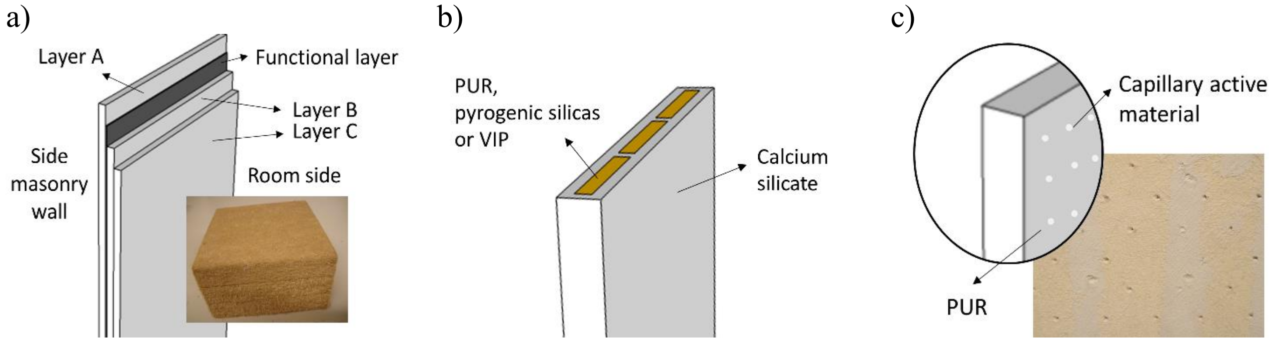

Figure 2. Schematic representation of multi-material insulation systems: (a) Pavatex Pavadentro®, (b) Calsitherm Xtra®, (c) Remmers IQ-Therm®

3.2 Hygrothermal properties and performance

The modifications made to the original capillary active system may influence its hygrothermal performance. To get a view on this, this section gives an overview of the hygrothermal properties of the main variants on the standard capillary active insulation system. As a comparison, the properties of two standard non-capillary active systems (a vapour tight XPS-system and a mineral wool (MW) system with smart vapour retarder) are given. The impact of some of the properties is illustrated by experimental and numerical simulations. An extended discussion of those simulations can be found in [9].

3.2.1 Thermal properties

Calcium silicate has a much higher thermal conductivity compared to traditional insulation materials such as PUR, XPS, MW, etc. For this reason, manufacturers recently came up with insulation boards composed of a capillary active material combined with a more thermal resistant material such as PUR, VIP or pyrogenic silicas. A comparison of the thermal performance of a selection of insulation systems is shown in Fig. 3, and this by indicating the thickness required to achieve a thermal resistance equal to 2,5 m^2K/W. These thicknesses are no commercially available thicknesses, but serve solely to come to a clear comparison. The much higher thickness required when using a traditional capillary active insulation system based on calcium silicate or a system based on aerated concrete (Multipor®) or wood fibre board is clearly visible. Moreover, as the comparison in Fig. 3 is made for dry insulation systems and as moisture stored in a capillary active material can negatively influence the thermal resistance, in practice the capillary active materials can even perform worse. The multi-component systems combining a capillary active material with PUR (IQ-Therm®, Xtra®) show a thermal performance that is more in line with the traditional systems, though that is logically not better than a traditional homogenous PUR system. This makes that, from a thermal point of view, a traditional PUR system is highly preferable.

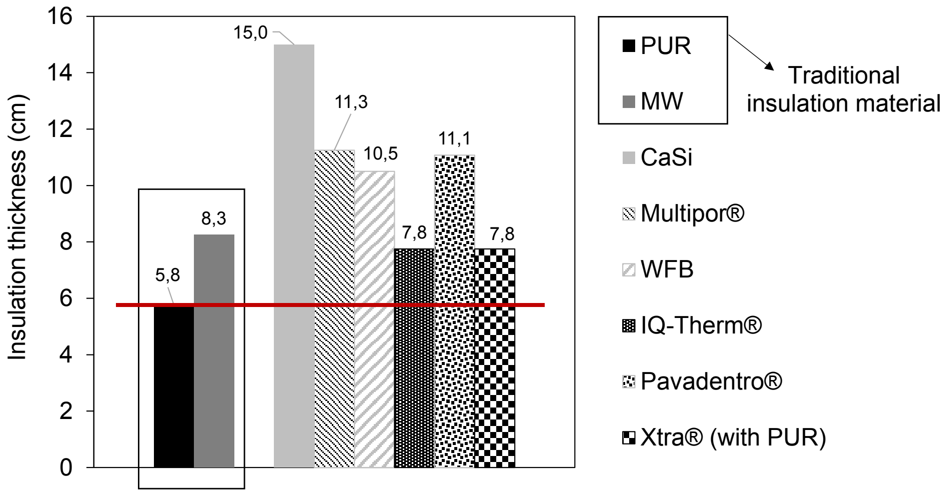

Figure 3. Insulation thickness required to achieve a dry thermal resistance equal to 2,5 m^2K/W.

3.2.2 Capillary activity

Fig. 4a gives an overview of the capillary absorption coefficient of a selection of insulation materials. As clearly visible, calcium silicate has a distinct capillary absorption coefficient. For the other insulation materials, the capillary absorption coefficient is much lower. Some of the insulation materials promoted as capillary active, e.g. IQ-Therm®, Multipor® and layer A of Pavadentro® (the layer at the side of the masonry wall), are actually hardly to call capillary active. The impact of such a lower capillary activity is clearly visible in the moisture profiles and relative humidity courses shown in Fig. 4b, which are obtained in a numerical study of the wall's hygrothermal behaviour for a steady-state winter condition [9]. In case of a Multipor®, due to a lower liquid conductivity and in less extent a slightly lower diffusion resistance factor, more moisture is stored in the glue mortar. Moisture transport toward the room occurs less easily, as seen by the steeper moisture profile at the cold side of the Multipor® insulation material. This less pronounced moisture distribution in Multipor® doesn't has to be a disadvantage however, as the risk on a too high interior surface or indoor relative humidity is less in this way. However, at the warm side of the masonry wall over-hygroscopic moisture can be observed when using Multipor®, while this is not the case for the calcium silicate. Hence, when wooden beam ends are present, a real capillary active insulation system may be preferable.

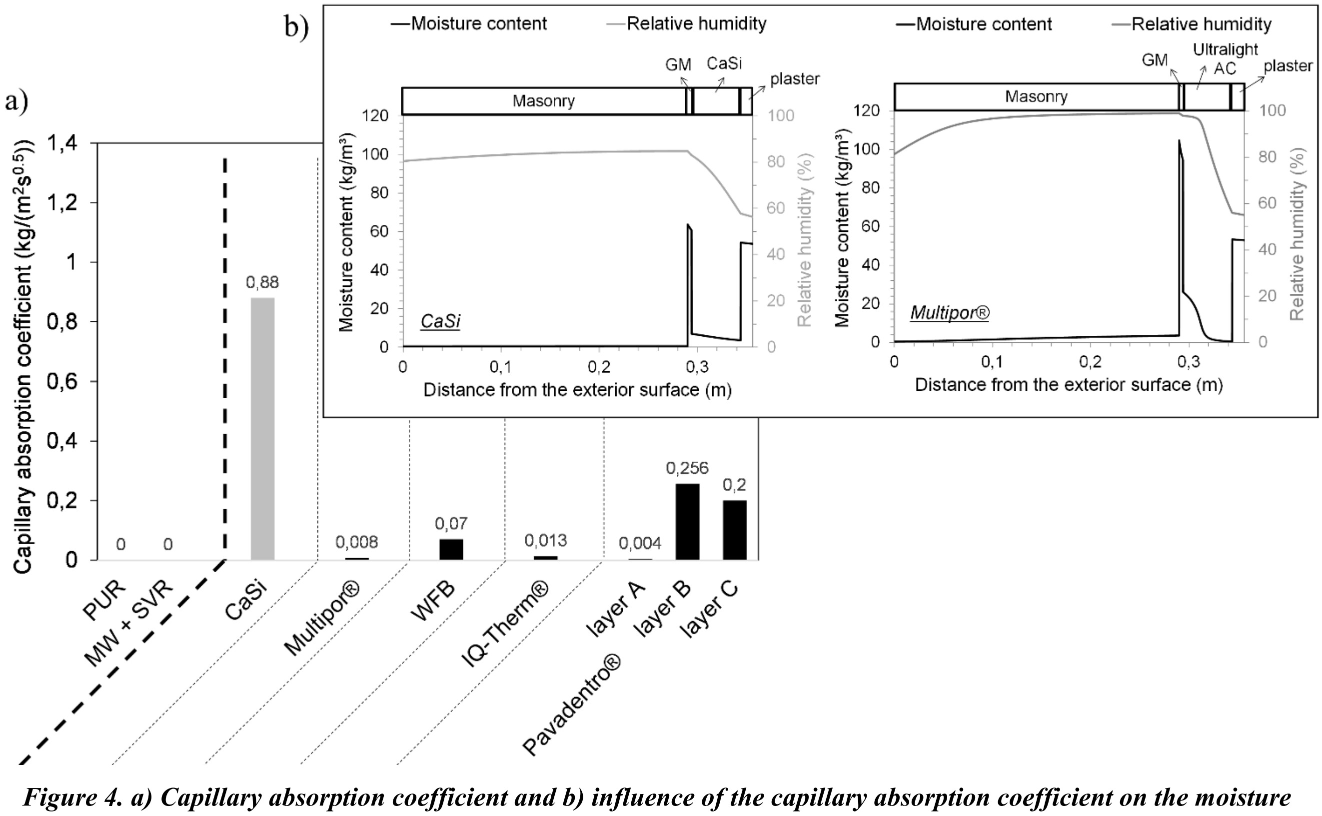

Figure 4. a) Capillary absorption coefficient and b) influence of the capillary absorption coefficient on the moisture distribution during a winter condition (20 °C and 50% RH in the room, 0 °C and 85% RH outside) [9].

3.2.3 Diffusion open character

In Fig. 5a the dry vapour diffusion resistance factor of a selection of insulation systems (with inclusion of glue mortar and finishing layer) is compared for insulation thicknesses resulting in a thermal resistance equal to 2,5 m^{2}K/W. The lower vapour diffusion resistance factor, and thus the higher inward drying potential, of the homogenous 'capillary active' insulation systems is clearly visible. The extra components in the newer systems (IQ-Therm® and Xtra®) added to improve the thermal performance, causes a higher vapour diffusion resistance. Thus, by improving the thermal performance, the drying potential is reduced, while creating a vapour open system was originally the reason to go to capillary active insulation systems. Note also that, as shown in Fig. 5b, a combination of a vapour tight material with a capillary active material can result in a locally higher interior surface relative humidity (see Xtra Position A in Fig. 5b). After all, the lower drying potential due to the vapour tight components results in an increased moisture content in the masonry wall. Hence, more moisture is available to be transported inward by the capillary active parts.

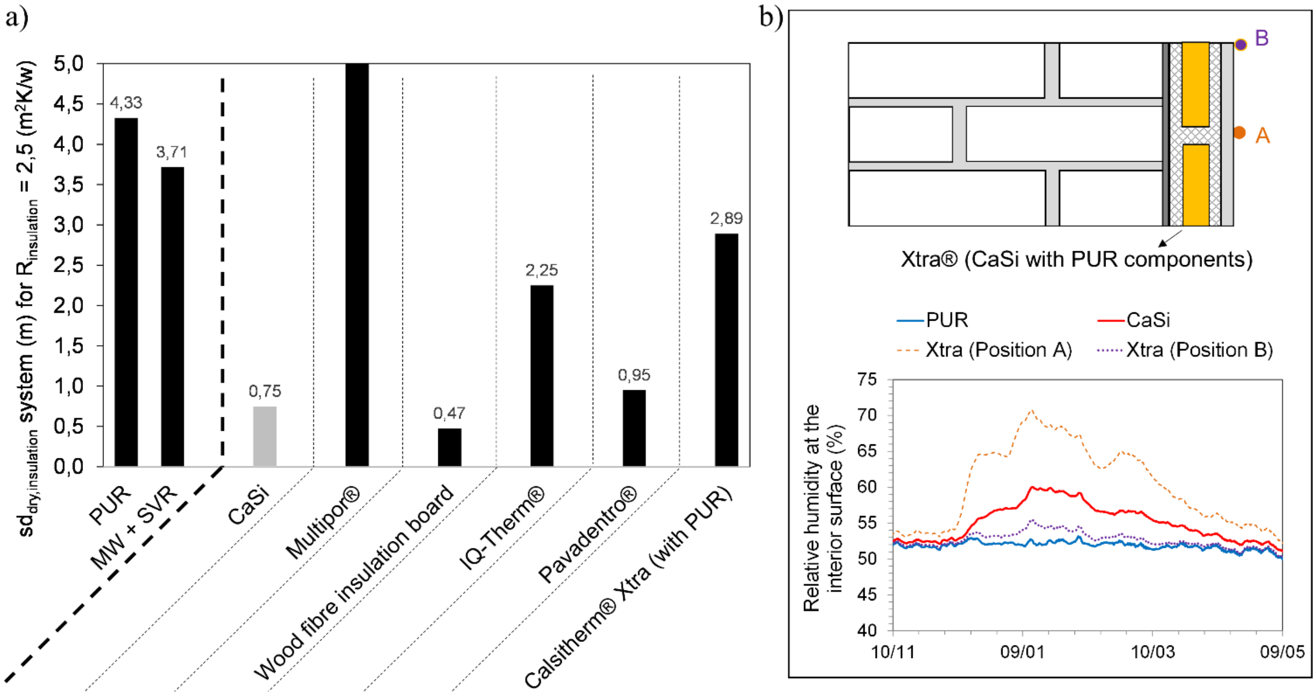

Figure 5. a) Dry vapour diffusion resistance factor (for IQ-Therm® and Calsitherm Xtra® an equivalent one-dimensional value is calculated) and b) impact of a multi-component (vapour tight combined with capillary active) system on the interior surface relative humidity.

4. DISCUSISION AND CONCLUSION

Nowadays, capillary active interior insulation systems are often promoted. As shown in this paper, the so-called capillary active systems currently on the market are, however, characterised by widely varying properties, resulting in a different hygrothermal performance. For instance, some of those systems have such a low capillary absorption coefficient (and thus liquid permeability) that they are hardly to call capillary active. This can result in a higher moisture content at the warm side of the masonry wall and in the glue mortar. On the other hand though, the risk on a too high inward moisture flow – e.g. when the wall is exposed to a high wind-driven rain load – will be lower. Some of the newer systems comprising additional components to improve the thermal performance are, furthermore, found to be less vapour open than the original capillary active systems. The original intention of creating a vapour open system seems to be forgotten during the development of those newer systems. Moreover, these systems could locally result in a higher indoor surface relative humidity than found when applying a homogenous calcium silicate board. This all shows that proper knowledge on the applied interior insulation system is – especially when dealing with historic buildings – of main importance to correctly assess the hygrothermal performance. For the systems currently sold as so-called capillary active, a general analysis for a standard capillary active system does not suffice and could result in unforeseen damage patterns, given the widely varying properties and the deviant behaviour of the newer systems.

5. ACKNOWLEDGEMENTS

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A lime based mortar for thermal insulation of medieval church vaults

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Abstract – *A new mortar for thermal insulation of medieval church vaults was tested in a full scale experiment in Annisse Church, DK. The mortar consists of perlite, a highly porous aggregate, mixed with slaked lime. These materials are compatible with the fired clay bricks and the lime mortar joints. The lambda-value of the insulation mortar is 0.08 W/m K or twice the lambda-value for mineral wool. The water vapour permeability is equal to a medieval clay brick, and it has three times higher capacity for liquid water absorption. The mortar was applied to the top side of the vaults in a thickness of 10 cm, and covered by 10 mm lime plaster, reinforced with cattle hair. This assembly can carry the weight of a person, working with maintenance of the roof. Climate measurements confirmed excellent properties in regards to both moisture transport and thermal insulation. Condensation did not occur at any time, despite a water vapour pressure gradient up to 500 Pa between the nave and attic. There was no reduction in energy consumption the first winter, possibly due to the increased heat loss related to the drying of the mortar.*

Keywords – Church vault; thermal insulation; perlite mortar; vapour permeability

1. INTRODUCTION

1.1 Background

There are 1700 medieval churches in Denmark, and many of these have brick vaults. The thickness of the vaults is usually only 12 – 15 cm, so the heat loss through this building component in winter is significant. The temperature in the attic is close to the outside temperature due to a high infiltration rate. In a permanently heated church the heat transmission through the vaults is half the total heat consumption. There is a large potential for reducing the heat loss through this building component. Computer modelling has indicated a possible saving of 30 – 40 % of the energy consumption.

Thermal insulation has not been permitted until now in respect for the antiquarian value. Modern materials made of mineral fibres or aerated concrete are not appropriate for restoration and repair of medieval masonry. There has also been speculation about the effect on water vapour transport through the vault and the risk of condensation inside the insulation or at the interface. Any thermal insulation should allow both liquid and vapour transport, and membranes should not be implemented. Salt contaminated vaults should not have thermal insulation due to the risk of salt decay. The vaults double curved geometry is also a challenge for thermal insulation. It is difficult to adapt sheets of mineral wool or porous silicate blocks to the surface without air gaps. Granulate insulation cannot adhere to the steep slope and will eventually end up in the vault pockets. To overcome these difficulties it is better to cast the insulation in situ and not use prefabricated materials. The insulation should be stiff enough to resist the weight of a person working with maintenance of the roof. Tests of thermal insulating plasters have been reported by several authors [1, 2] but so far not related to church vaults.

1.2 Annisse Church

A test of vault insulation was performed in Annisse Church, located in northern Zeeland, DK. The nave and chancel date to the 12th century and have lime washed stone walls. The cross arched vaults were constructed around 1400 with fired clay bricks and lime mortar. The tiled roof and the timber construction are from 1967. The total floor area of the nave and chancel is app. 120 m^2 and the volume is app. 500 m^3. The church has electric heating with heating elements mounted in the pews and on the walls

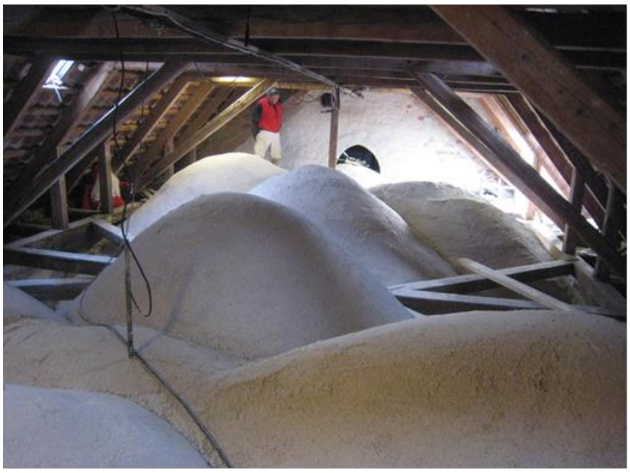

Figure 1. Interior view of the nave and the attic in Annisse Church

2. MATERIALS AND TECHNIQUES

2.1 Perlite Mortar

A new insulation mortar was developed to meet the demands listed above. It is a mixture of slaked lime and perlite grains in the dry volumetric ratio of 1:6. Approximately one part of water is added for workability. Perlite is manufactured by heating volcanic sand to 900 °C, by which the grains expands to a highly porous silicate substance. A grain size of 1 – 6 mm was used for the mortar. The material properties were tested in the laboratory and the most important parameters are listed below. Computer modelling indicated that the mortar would fulfil the requirements mentioned above [3].

Table 1. Material properties

material	properties			
	Density (kg/m³)	*Thermal conductivity λ (W/m K)*	*Capillary suction k (kg/m² √s)*	*Water vapour permeability δ (kg x10⁻¹²/m s Pa)*
Perlite mortar	390	0.08	0.86	35
Brick	1700	0.5	0.3	30

2.2 Application on vault

The materials were prepared on site in a horizontal mixer. The lime was added to the perlite as slurry and blended gently for 30 sec. The top side of the vault had lime slurry applied first to improve the adhesion. The plaster was laid out with a trowel in one layer of 100 mm thickness. A distance of 50 mm was kept to the timber roof construction. After some days of initial setting, 10 mm lime plaster with natural fibre reinforcement was applied. This assembly would improve the load bearing capacity of the mortar. A preliminary test area was prepared in April 2014 in the north web of the second nave vault. The remaining vaults were insulated in September and October 2015.

2.3 Climate monitoring

Climate monitoring was initiated in March 2014. The temperature and relative humidity was measured in the nave and in the attic every hour, using TinyTag2 data loggers with integrated sensors. This device has a capacitive sensor for RH with an accuracy of +/- 3 %RH in the range 0-100 %RH. In august 2014 the monitoring was extended to the vault structure. External sensors for temperature and relative humidity were installed in the insulation mortar, in the vault below the insulation, and in the adjacent vault without insulation. Only climate data for the last year is presented below.

3. RESULTS AND DISCUSSION

3.1 Temperature

The temperature in each monitoring position is given in fig. 3. The temperature in the nave (red) was down to 15 ºC in winter and up to 25 °C in summer. The daily variation of 2-3 °C was mainly due to short heating events in winter and solar gain in summer. The annual temperature variation in the attic was from – 5 °C in winter up to 30 °C in summer. The attic was colder than the nave most of the year, except in summer, where solar radiation heated up the tiled roof. The temperature within the vault structure was always between the inside and outside. The insulated vault (green) was warmer than the vault without insulation (blue) until the beginning of October. After this vault was insulated, the temperature was almost the same in the two vaults for the rest of the period.

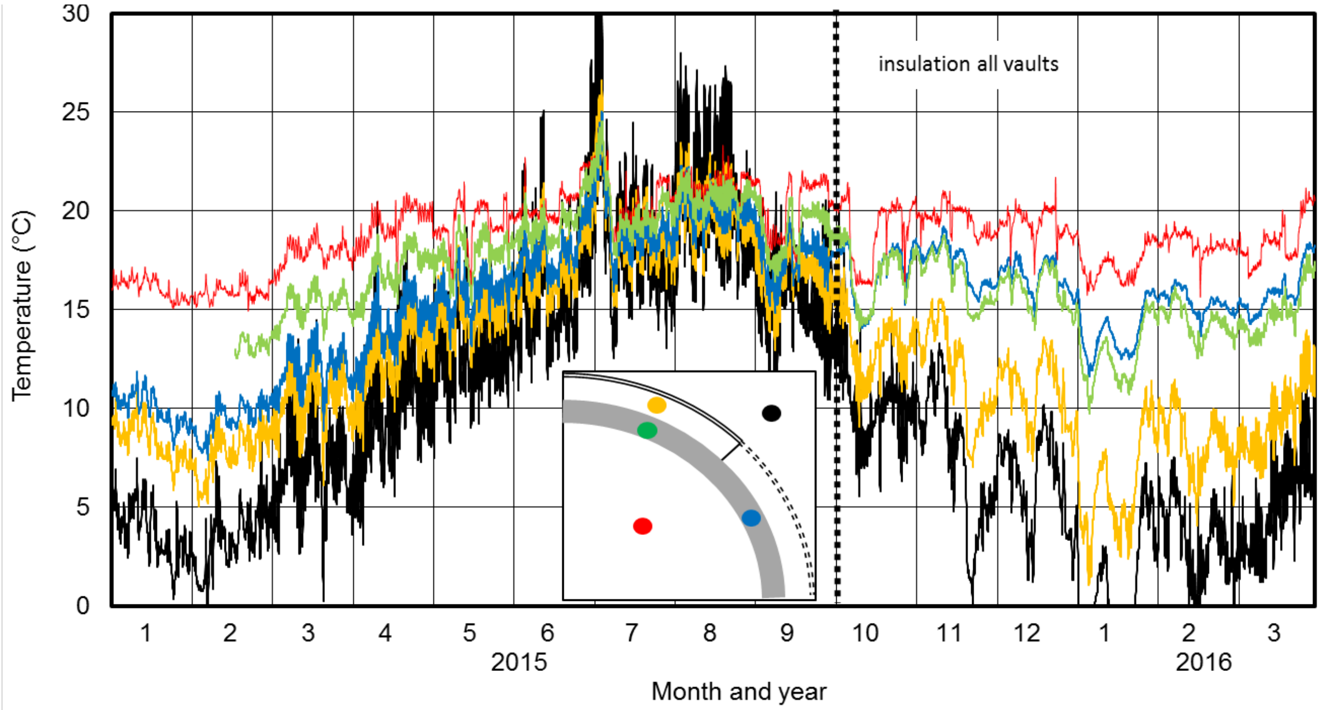

Figure 3. Temperature measurements

3.2 Relative humidity

The relative humidity (RH) in each monitoring position is given in fig. 4. The RH in the attic (black) was higher than the RH in the nave (red) most of the year. Episodes of lower RH in the attic occurred during the spring and in summer. The RH in the vault below the insulation (green) was close to the RH in the nave most of the year. The insulation mortar (yellow) had an RH between the nave and the attic al year, except for a period in September. At this point there was a sudden increase in RH from 70 % to 90 % within 48 hours. The increase in RH coincided with a sudden fall in temperature of 6-8 °C, imposed by a change of the outside temperature. This illustrates that short events of high RH can occur in the insulation mortar. Condensation will only take place if the temperature drop is large enough, but this is quite unusual in Denmark´s mild coastal climate. The RH gradually decreased during the next four weeks and ended at 70 % at the beginning of October. The RH in the vault without insulation was between that in the nave and the attic until October. When insulation mortar was applied to this vault, the RH instantly rose to 100 % and stayed there for the rest of the year. From the beginning of January the RH decreased gradually and reached 80 %RH by the end of March. The RH in the nave was influenced by evaporation from the vaults. This gave an opportunity to test the effect of a large water vapour pressure gradient.

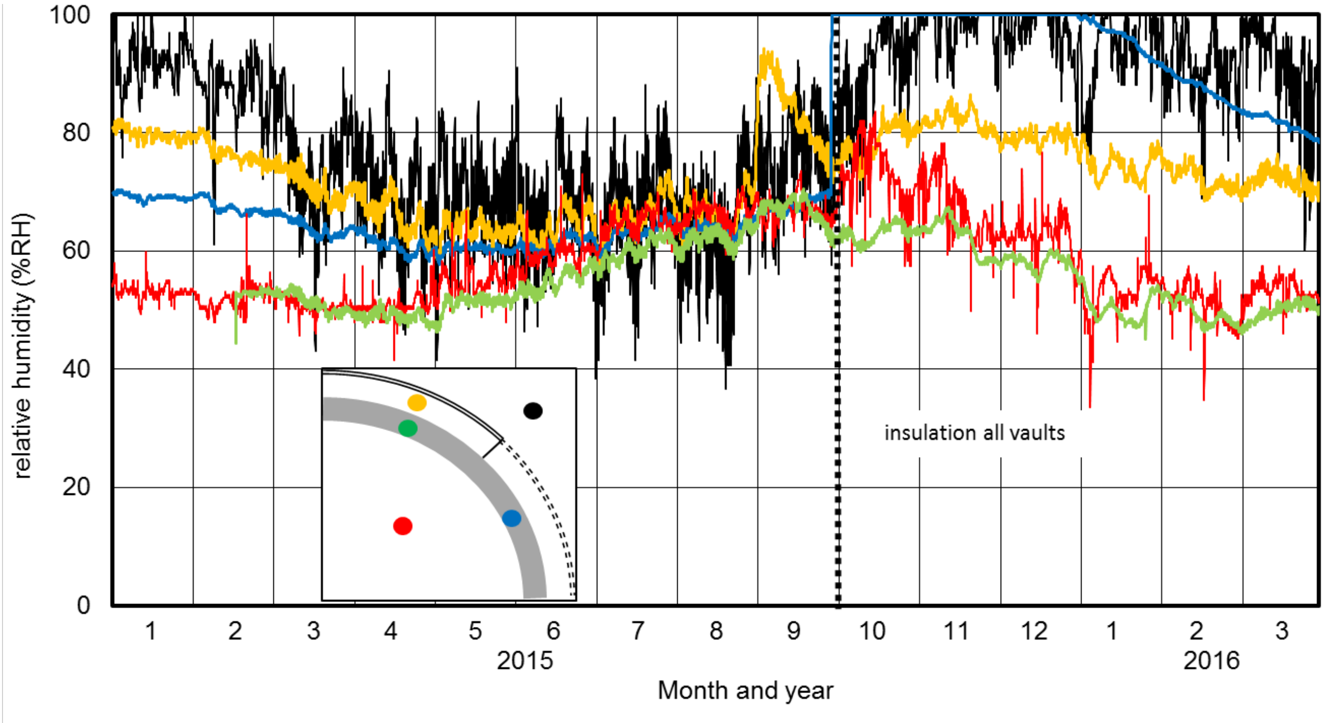

Figure 4. Relative humidity measurements

3.3 Water vapour pressure

The water vapour pressure (VP) in each of the monitoring positions was calculated from the measured data of temperature and RH and given in fig. 5. The diagram shows the moving average over seven days. From January to September the VP was 200 – 300 Pa higher in the nave than in the attic. The VP in the vault and in the insulation mortar was between the nave and the attic for the first months. From April the VP in the vault approached the VP in the attic, and from June and until September there was almost no difference.

From the beginning of October there was an instant increase in VP in the vault, where insulation mortar was applied. The rise in VP was due to the migration of liquid water from the mortar into the vault below. The rise in VP influenced the VP in the nave, so the difference to the attic was up to 500 Pa. There was very little influence on the VP in the test vault, which remained close to the VP in the attic. This shows that the insulation did not reduce the vapour diffusion though the vault significantly. Even such a considerable vapour pressure gradient did not impose condensation in the insulation mortar. The VP in the attic was close to the outside VP, and no condensation was observed in this part of the building, despite of the high RH.

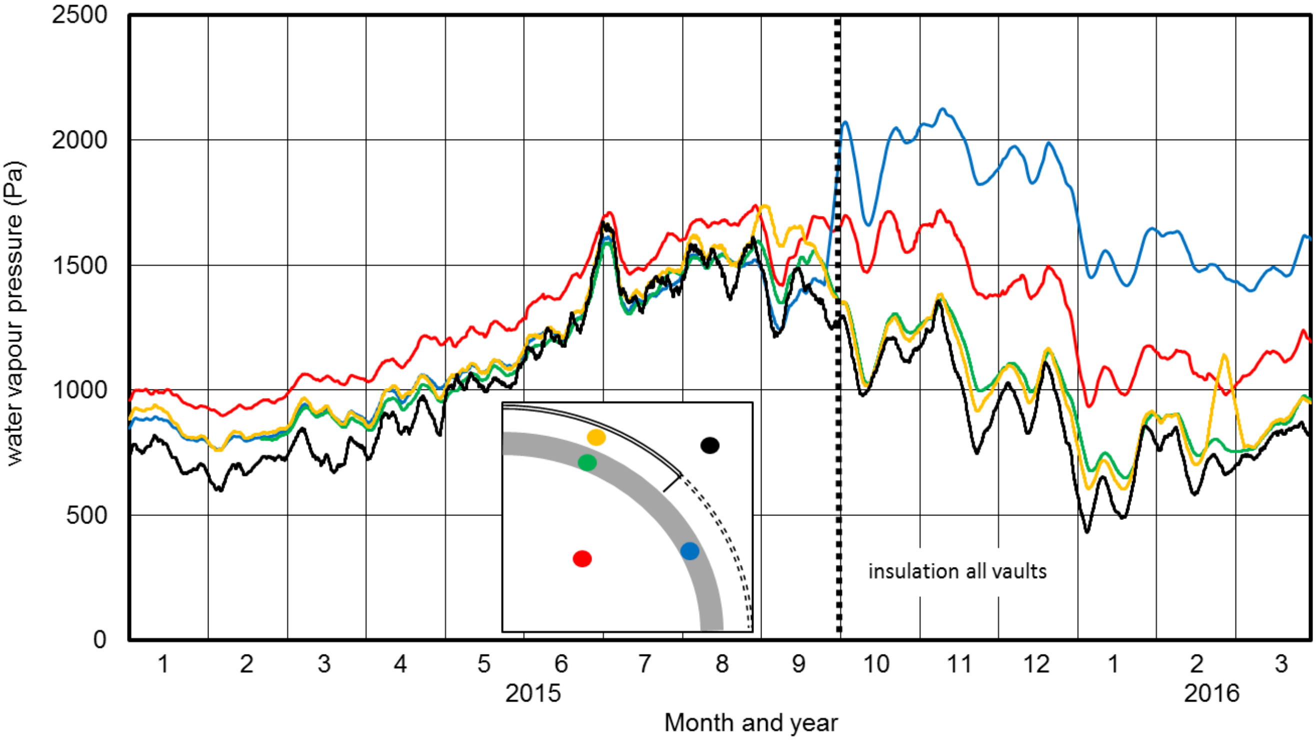

Figure 5. Water vapour pressure calculated from temperature and RH

3.4 Energy

The annual use of electricity is given in table 2. The first column gives the actual consumption and the third column gives the corrected values according to the degree days of the year. The deviation from the corrected five-year average is given in the last column. The use of electricity includes the heating and lighting of the church and a small building for toilets and an office for the church ward. The heating season is from 1 April to 31 March the following year. The energy consumption for the year 2015/2016 was equal to the average of the five previous years. The reason was possibly that the inside temperature was kept 2-5 °C higher than in the previous years in order to dry out the surplus of moisture from the vaults. This would increase the loss by transmission. The heat loss by ventilation was also higher, because the doors were kept open most days for some hours to remove the surplus of humidity. The U-value of the wet perlite mortar would be higher than the dry mortar, which also contributed to an increased heat loss. Further monitoring in the next winter is needed to demonstrate the performance of the vault insulation under dry conditions. For future projects it is advised to apply the mortar in summer and rely on solar heating for drying through the attic.

Table 2. Annual enery consumption

Year	*Actual electricity use (MWh)*	*Degree days correction*	*Corrected electricity use (MWh)*	*Deviation from five years average*
2010/2011	49,6	1.08	45,9	-22 %
2011/2012	46,7	0.83	56,3	-4,3 %
2012/2013	55,4	1.02	54,9	-6,6 %
2013/2014	54,4	0.76	71,8	22 %
2014/2015	50,0	0.81	61,4	4,4 %
2015/2016	55,0	0.92	59,6	1,0 %

4. CONCLUSIONS

A mortar mixed of perlite and slaked lime was applied to the vaults of the medieval church in Annisse, DK. A thickness of 100 mm was laid out with a trowel in one layer. An additional layer of 10 mm lime mortar with cattle hair was applied on top to improve the mechanical resistance. The thermal conductivity of the mortar was 0.08 W/m K, and the water vapour permeability was similar to that of brick. Condensation did not occur at any time, even with a vapour pressure difference of 500 Pa between the nave and the attic. The insulation will not be harmful to a sound vault structure. The energy consumption was not reduced the first year compared to a five years average. This was because the inside temperature was raised and the ventilation was increased to dry out moisture from the vaults. The thermal diffusivity of a wet mortar was also higher than of a dry material. Further monitoring is needed to demonstrate the performance of the vault insulation under dry conditions.

5. ACKNOWLEDMENTS

The application of vault insulation mortar in Annisse church was financed by the congregation. We sincerely acknowledge the support of the church council and in particular the help of the church ward Ivan Strøyer. Master mason Tore Bredtoft and associates did the work on site.

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MONITORING AND FEEDBACK

The role of monitoring and feedback in the refurbishment of traditional buildings: New Court, Trinity College, Cambridge

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Abstract *– This paper describes the monitoring used within New Court to provide information at various stages of refurbishment. In an iterative process, the measurements of numerous conditions are used to establish a picture of the performance of the building. Prior to refurbishment this 'base case' data identified potential areas of risk as well as provided reassurance with regard to some aspects of thermal and moisture performance. Measurements were used to refine design specifications and as input data to calibrate a hygrothermal simulation model (WUFI) to give added confidence to projections. An intermittent round of monitoring was commissioned within a refurbished 'test' room. This data was then fed-back into the design process to further inform specification as well as later, site practices. Post-refurbishment, the project features the long-term installation of multiple monitoring sites throughout the building as part of a mitigation strategy designed to protect the historic fabric.*

Keywords – Monitoring; risk; refurbishment; moisture; U-values

1. INTRODUCTION

Trinity College Cambridge was founded in 1546 by Henry VIII. Its buildings are made up of a number of quadrangular 'courts' of mediaeval, sixteenth and seventeenth origin. New Court was added to the college in the 1820s by the architect William Wilkins. The buildings of the college are listed as grade I and are afforded the highest level of statutory protection within in UK planning law in recognition of their architectural and historic significance.

New Court had been designed and used continuously as college residences. In 2009 the College expressed a desire to continue this use whilst meeting contemporary standards of comfort, utility and energy efficiency. To address the college's requirements a three-stage approach was developed which involved consultation with both Cambridge City Council planning department and English Heritage at each stage. The three stages would; establish a detailed understanding of the building in terms of heritage significance, character and fabric performance, draw up and evaluate a range of possible responses/inventions and from this create an integrated and interdependent package of proposed measures.

The monitoring at New Court was initially undertaken to provide an understanding of the performance of the existing fabric to inform design specifications. As the project evolved the role of monitoring expanded and was used to measure fabric responses from an experimental section of the proposed new wall lining. An intensive programme of post-refurbishment monitoring was then incorporated into the project. This scheme was required as a condition of planning consent along with a 'mitigation strategy' in order to compensate for outstanding uncertainties concerning fabric performance that arose during modelled assessments of the refurbishment design.

The methods and techniques used in monitoring at New Court have developed along with the requirements of the project. It is therefore appropriate to discuss the methods and findings of the work in a series of stages, as each stage informed the work of the following stage.

2. PRE-REFURBISHMENT MONITORING

2.1 Methodologies

The first phase of monitoring involved the measurement of thermal transmissivity and hygrothermal responses of eight walls selected to represent the variety of thicknesses, aspects and finishes present within New Court. The walls are of solid brick construction, some with historic lath and plaster internal linings set off from the wall on battens. *In situ* U-value measurements were undertaken following the methodology set out in ISO EN BS 9869 (1994) [1]. This uses the mean values of heat flow, from a heat flux plate attached to the interior wall surface, in combination with internal and external surface temperature measurements taken over a period of days, the minimum being 14, to establish a quasi-steady state U-value.

Archimetrics have innovated the methodology, instrumentation and analysis for Interstitial Hygrothermal Gradient Monitoring (IHGM) across building fabric to answer, specifically, moisture transfer questions. This bespoke approach; developing electronics, code, instrumentation and analysis techniques provides a high degree of control and accuracy to monitoring research processes. Measurements of temperature (± 0.4˚C) and RH (± 3%) are made through a wall section. Four measurement sites, or nodes, are established by core drilling to specified depths, the measurement zone is fully isolated and a bespoke probe located at the measurement site. The probe samples the small air void at the point of interest. Measurements of RH act as a proxy reflection of moisture conditions rather than being a direct measure of moisture content and benefit from avoiding the uncertainty caused by the presence of salts. A sampling interval of 5 minutes ensures a high level of detail which further aids understanding. Additional measurements of temperature and RH are made both internally and externally on the surfaces and in the air in proximity to the installation.

In addition to these measurements the first phase of monitoring also recorded ambient conditions (temperature and RH) within the wall sample rooms. These conditions were also measured within the floor voids along with the moisture content of timber joist ends and masonry measured using electrical resistivity probes embedded 30 mm into fabric. The location of the monitored rooms are shown in Figure 1.

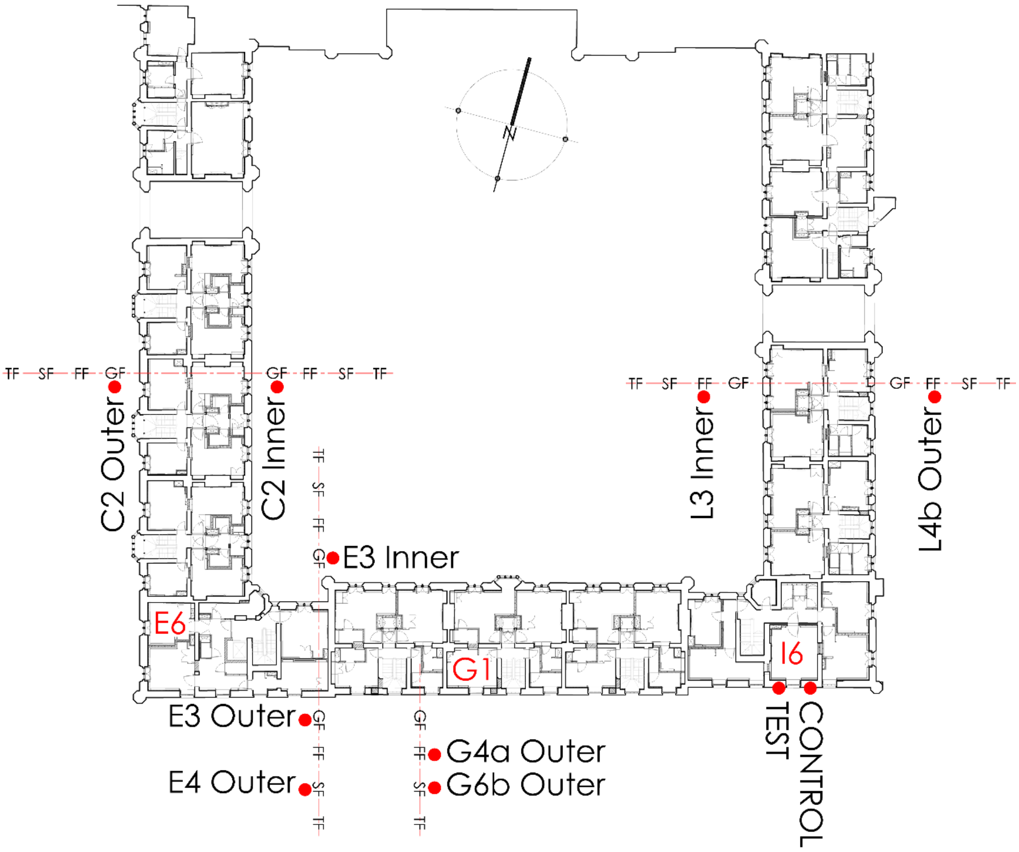

Figure 1. Plan of New Court, Trinity College, Cambridge showing location of monitoring rooms.

2.2 Results

2.2.1 U-values

The results of the *in situ* U-value measurements found U-values for the eight sample walls ranging from 0.59 – 0.78 W/m^{2}K for walls that varied in thickness from between 600 – 690 mm. The average U-value for these walls was 0.69 W/m^{2}K (Table 1). This average was compared with a standard calculated U-value for the wall (following ISO 6946 [2]) of 0.94 W/m^{2}K, a 25% difference, equivalent to 15mm of the woodfibre insulation that was being considered as a possible insulation material at that time.

Table 1. In situ U-value Results, New Court.

Location	Wall Thickness mm	Construction Details *(internal – external)*	U-value $W/m^2 K$	W/m^2K Error %
C2a Inner	600	Lime plaster - Brick – Render	0.68	6.90
C2a Outer	640	Lime plaster - Brick - Limestone ashlar block	0.77	5.36
E3 Inner	675	Lath & plaster lining – Void - Brick – Render	0.59	5.91
E3 Outer	600	Lime plaster - Brick	0.78	6.67
E4 Outer	690	Lath & plaster lining - Void - Brick	0.70	5.90
G4a Outer	600	Lime plaster - Brick	0.64	6.45
L3 Inner	640	Lath & plaster lining – Void - Brick - Render	0.61	6.14
L4b Outer	600	Lime plaster - Brick – Render	0.71	6.61
Averages	**631**		**0.69**	**6.24**

The measurement of eight U-values for the traditionally-built walls at New Court provided confidence regarding the actual heat loss of these elements. This was significant in relation to New Court as it was during this time (2011) that evidence was emerging of the over-estimation of heat loss by the standard U-value calculating methodology for the walls of older buildings [3, 4]. If standard or default U-values are used when planning energy efficiency improvements for solid walls these can suggest poor thermal performance. There is, therefore, a danger that large amounts of insulation may be used when trying to achieve lower performance targets, 0.3 W/m^2K being a commonly used objective [5]. For solid walls which incorporate internal wall insulation (IWI) there is a danger that excessive quantities of insulation could result in the over-cooling of wall fabric. In certain solid walls, particularly those subject to driving rain, a proportion of heat transfer through the wall is required to avoid a build-up of moisture within the fabric. The *in situ* U-value measurements at New Court allowed for a more accurate definition of the likely heat losses of the highly protected walls and thus more precise specification of the quantities of insulation material needed to reduce this heat loss without accidental excess fabric cooling. In addition, the more exact measurements also allowed for more realistic predictions of future performance targets.

2.2.2 Interstitial hygrothermal behaviour

The findings from the interstitial hygrothermal gradient monitoring were also able to provide some confidence with regard to the condition of the existing walls. Measurements of temperature and RH made over a twenty-four day period, over winter, were used to create ‘hygrothermal sections’; averaged quantities from each sensor plotted to create a mean temperature and dewpoint temperature gradient through each measured wall section. The difference between these two gradients was then factored in terms of ˚C to create a ‘saturation margin’ (Table 2).

Table 2. Interstitial Hygrothermal Gradient Monitoring Results

	Average values over monitoring period					
Location	**Internal Surface Temp °C**	**External Surface Temp °C**	**Internal Dew Point Temp °C**	**External Dew Point Temp °C**	**All 4 Nodes Margin °C**	**Outer Node Saturation Margin °C**
C2a Outer	22.7	7.2	7.7	3.7	8.2	3.1
E3 Inner	21.3	7.6	5.5	4.8	5.3	1.1
E3 Outer	20.4	8.4	5.4	4.5	8.8	3.7
E4 Outer	22.9	7.3	4.5	4.5	8.3	2.8
E6 Inner	20.9	7.6	6.3	4.9	9.0	3.7
G1 Outer	18.3	8.0	6.9	4.5	8.0	2.3
G6b Outer	18.2	8.4	6.1	4.5	9.0	4.0
L3 Inner	22.6	7.5	5.2	5.8	8.2	2.5
Averages	20.9	7.7	6.0	4.6	8.1	2.9

The saturation margin represents an indication of risk. Over the relatively short monitoring period there were no instances of 0˚C saturation margins which might have suggested the presence of liquid water or the potential for the formation of interstitial condensation at any of the monitoring locations. Within the limits of the exercise, it was thought that this implied that there were no underlying moisture problems in the walls under examination which suggested that the construction could tolerate the judicious application of internal wall insulation. However, it was noted that this 'safe' performance with regards to moisture was probably influenced by the building's heating regime which resulted in high internal temperatures for most of the rooms. The refurbishment proposals for New Court included the provision of under-floor heating and individual room heating controls which would inevitably result in lower internal temperatures for the building. For these and other reasons it was decided that hygrothermal simulation modelling be undertaken to assess the impact that these lower temperatures might have on moisture behaviour within the internally insulated wall fabric.

The hygrothermal simulation modelling was carried out by Max Fordham Engineers using WUFI Pro 5.0. The measured temperature and RH data from the winter monitoring was provided along with site-specific material properties for a variety of the wall materials found at New Court. This information, along with observations made from the core drilling of walls with regard to density, moisture content and the presence of air layers behind historic linings and mortar type, allowed Max Fordham to refine and 'calibrate' the WUFI model. Simulation outputs were compared with those recorded during the monitoring period and adjustments made to the model to provide a better 'fit' with monitored data, (Fig. 2). More detail concerning this work is provided in section 3.2 of the companion paper 'Retrofit Internal Insulation at New Court, Trinity College, Cambridge: Options, Issues and Resolution Through Material Sampling and Modelling'.

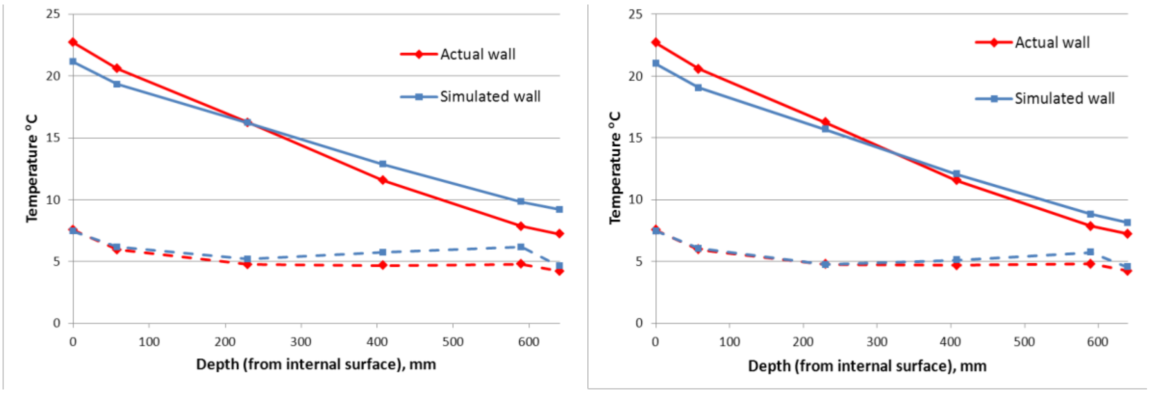

Figure 2. Comparison of monitored and modeled outputs for New Court walls before (left) and after (right) refinement of WUFI inputs. Max Fordham Engineers.

In its report on this work, Max Fordham concluded that the large range of properties measured for the wall material samples did not result in significant variations in simulations of the uninsulated wall over the short period for which monitoring data was available. However, this changed when insulation was added to the modelled wall [6]. The variability of construction materials and the subsequent uncertainty in performance led to a recommendation that *in situ* monitoring of interstitial conditions be installed at New Court following the insulation of the walls.

3. TEST WALL MONITORING

As part of the informed specification process it was decided to install and monitor an experimental section of the internal wall insulation alongside an original 'control' wall in the same room, over a full year. A room, on the Garrett Hostel Lane elevation, I6, was found for this purpose (Fig. 1.). It was this south-facing elevation, thinner than other external walls with a bare brick external finish that had been found to be most vulnerable with regards to insulation in various modelled scenarios.

3.1 Methodologies

A similar set of measurements to that of the original monitoring programme were undertaken in I6, comprising of U-values, IHGM and room condition monitoring. Two sets of measurements were made of the walls either side of a window; one side consisting of the original wall structure and the other having been insulated with 72 mm of woodfibre insulation (Pavadry) and finished with a 13 mm gypsum fibreboard (Fermacell). In addition to these % moisture content measurements were made in the timber and masonry of the cornice on the refurbished wall and a series of temperature measurements at a depth of 30 mm at 50 mm intervals was measured along a partition wall return with the insulated external wall.

3.2 Results

The monitoring in I6 took place over a period of one year allowing the performance of both the insulated and original walls to be assessed through an annual range of seasonal conditions.

3.2.1 U-values

The insulated wall measured an *in situ* U-value of 0.28 W/m^2K in comparison with 0.58 W/m^2K, the U-value measured from the uninsulated wall. The application of 72 mm Pavadry insulation was found to have more than halved the heat loss of the wall.

3.2.2 Interstitial hygrothermal behaviour

The interstitial moisture responses of the refurbished wall were of primary interest as it was here that uncertainty of modelled outcomes was felt to be greatest. On this occasion the analysis included plots over time of the RH measurements made by each sensor embedded within and on either side of the wall (Figs 2 and 3). At the beginning of the monitoring period this showed a divergent and unusual pattern for the Test wall when RH measurements made at the interface between the brick and insulation (node 2) were higher than those measured elsewhere within the wall. It is normally the case that over the winter %RH values are highest in proximity to external conditions (at node 4). This is due to a decreasing temperature gradient through the wall section as a result of a warm, centrally heated interior and colder exterior temperatures, as well as the potential presence of wet material often as a result of wind-driven rain. Indeed, an examination of the analysis for the uninsulated Control wall in I6 shows just this pattern (Fig. 2). Over time, it can be seen that %RH values at the masonry/insulation interface (node 2) of the refurbished Test wall reduce and resume a more usual position around the middle of the year. The %RH behaviour seen at node 2 is a response to the drying of construction moisture as a result of the application of a wet lime plaster parge coat used to seal and level the wall prior to the application of the woodfibre board. The extended length of time required for wet materials to 'dry' was noted and used to directly influence site practice; the contractor was required to leave the wet plaster for a specific period of time depending on the thickness of the levelling coat before proceeding with the installation of the IWI.

The plaster and IWI on the Test wall can also be seen to have a further and perhaps unanticipated benefit. The RH responses recorded in Figure 4 have a smoother signature than those found for the uninsulated Control wall and indicate a reduction in the quantity of air moving through the wall structure. The presence of the parge and IWI has, in effect, moderated the air movement both through, and in and out of, the wall thereby reducing the amount of air moving through the structure and further benefitting the thermal performance of the upgraded wall fabric.

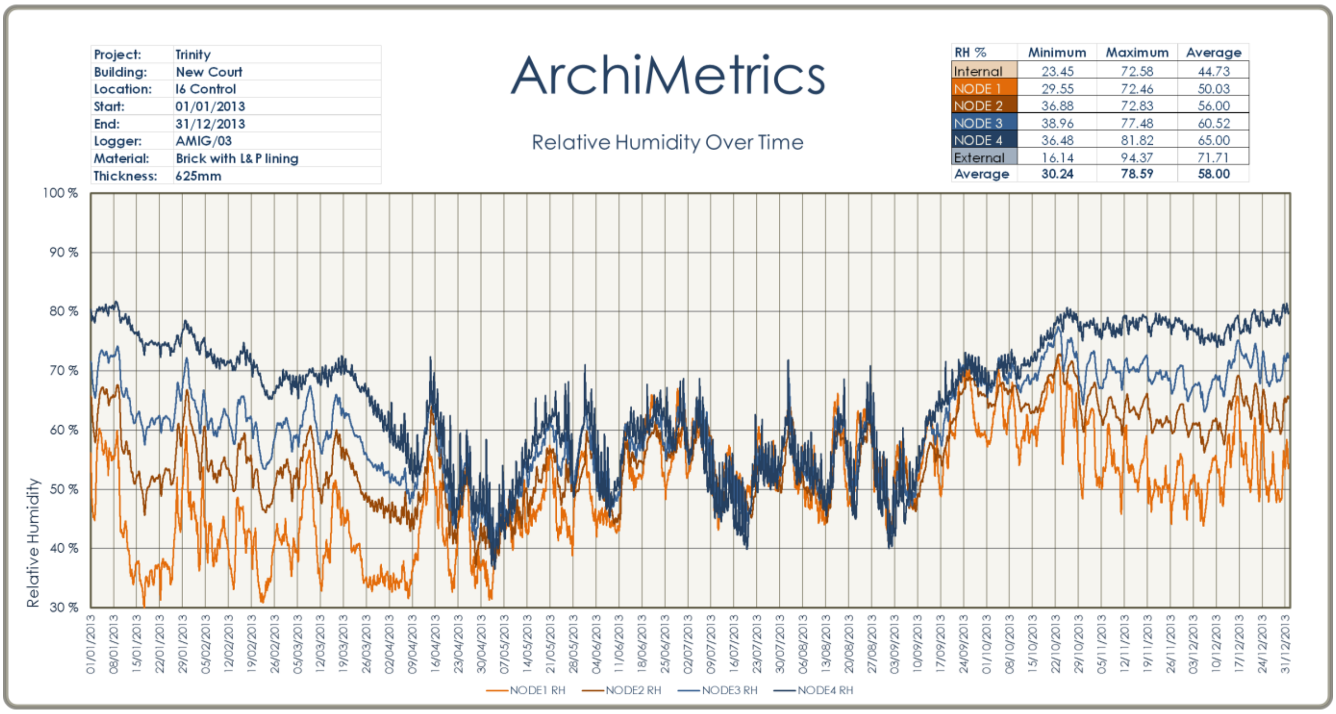

Figure 3. Relative humidity over time, control wall, I6, New Court.

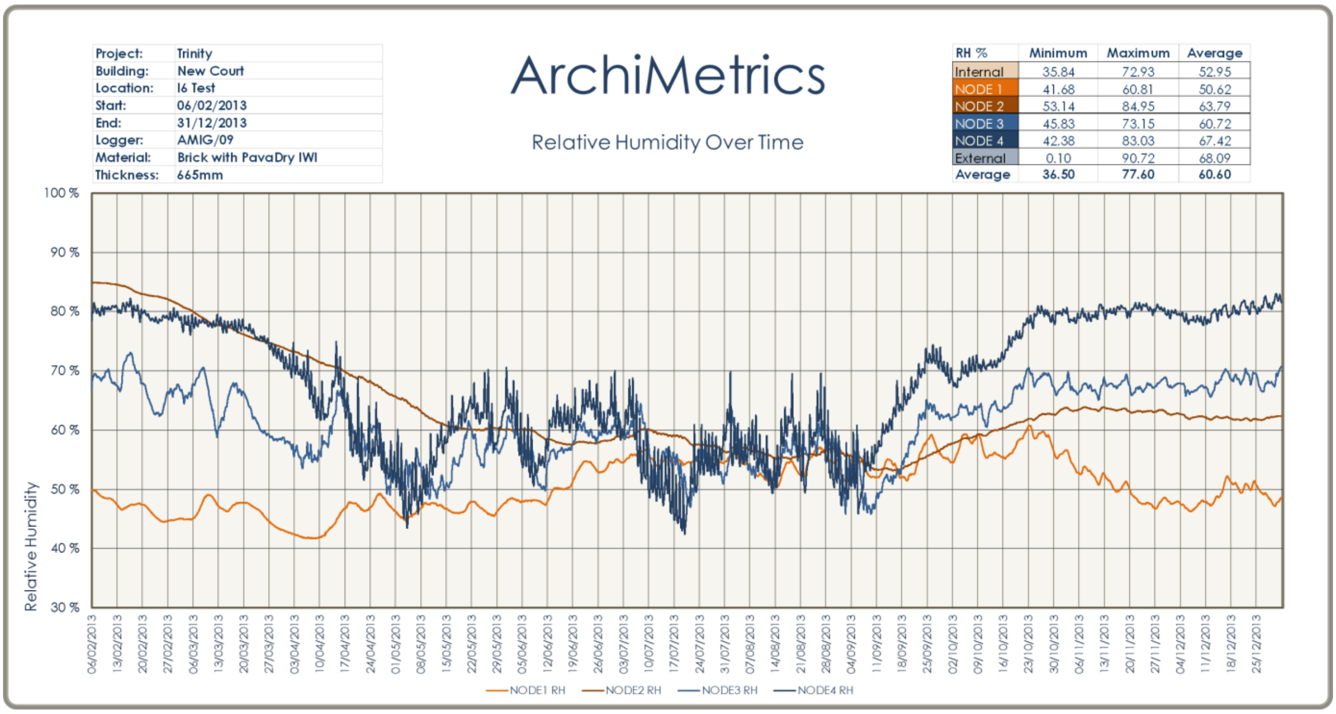

Figure 4. Relative humidity over time, test wall, I6, New Court.

With regards to saturations margins, these are analysed on a monthly and annual basis and no instances of 0˚C margins are found for either the Control or Test walls indicating little risk. The narrowest margin for the potentially vulnerable insulated Test wall, 2.46˚C, was found during February 2013 at node 2, as a result of construction moisture introduced at this point. As has been previously discussed this part of the wall is seen to 'dry' during the year and by the following winter, at the end of the monitoring period, has an increased 'safer' margin of 3.25˚C. The findings for the Test wall gave confidence to the modelled predictions for the insulated walls previously provided by Max Fordham, which had similarly found no instances of moisture build up or interstitial condensation.

4. POST REFURBISHMENT MONITORING

The granting of planning permission for the refurbishment of New Court was conditional upon the development of a post-refurbishment monitoring scheme, operational for at least seven years, along with a 'mitigation strategy' [7]. This strategy identified the steps that should be taken to ameliorate or alter conditions if states that may suggest harm to the protected historic fabric or put inhabitants at risk were reported from the monitoring.

4.1 Methodology

The post-refurbishment monitoring measures thermal performance, hygrothermal conditions and material moisture content of walls in a variety of accommodation and service rooms. It also measures Indoor Air Quality, IAQ (CO_2) and hygrothermal conditions within the rooms as a watch on the Mechanical Ventilation and Heat Recovery system, MVHR incorporated within the refurbished rooms. The scheme is designed as three ground-floor to roof 'sections', one in each of the three court quadrants undergoing renovation. Whilst comprehensive coverage of all building fabric is not feasible it is hoped that the system captures both vulnerable elements, such as wet rooms (showers, bathrooms, kitchens), roof and floor timbers, as well as conditions generally and thereby can be taken as reasonably representative of the fabric as a whole

The primary risk to fabric as a result of the refurbishment was considered to be higher material moisture levels, perhaps as a result of lower room temperatures and cooler insulated fabric. The greatest risk was felt to be vulnerable materials such as built-in timber elements; lintels, bearers, grounds and joist ends, where high humidity or moisture could be the potential starting point for decay. This concern was addressed within all the monitored rooms via a network of resistivity probes installed in these timbers which were exposed during the refurbishment process.

Installed alongside the IHGM monitoring, in parallel with the temperature and RH sensors, is a set of bespoke gypsum-based moisture sensors set within a core through the wall and fully bonded to the wall substrate measuring moisture content via electrical resistivity. This additional array means that moisture behaviour within the wall is observed via two different methods, through two different proxies, air in the case of RH as well as a directly coupled and isolated mineral material. It is hoped that this will allow for a more thorough view through the wall section capturing the impact of moisture in two different states, in the air and as a liquid. As well as facilitating a more comprehensive analysis of interstitial moisture behaviour, this installation will allow a comparison between the two different methods of moisture measurement.

4.2 Results

The refurbishment building work has been undertaken in two phases and at the time of writing equipment has been operating for three months in the completed first phase. Thus far three *in situ* U-values have been measured from three walls in K staircase; 0.34, 0.32 and 0.45 W/m^{2}K, the higher value perhaps a reflection of the thinner width of the wall higher up at second storey height, which is 590 mm as opposed to 700 mm. All three U-values are slightly greater than that measured previously for the Test wall of 0.28 W/m^{2}K, the reasons for this require further analysis and may be a reflection of the new heating regime and wetter wall materials. A further point of interest has been RH measurements in one of the rooms, K7. Initially, monitoring at the interface between the new insulation and brick wall showed the expected trend of decreasing RH as was observed for the Test wall installation, however in mid-January RH began to rise at this location. Once again, at this time it is difficult to be definitive about the causes of this change although it is hoped that further analysis in the coming months will provide an explanation.

5. CONCLUSIONS

Monitoring has been used in a variety of ways to identify and ameliorate risk in the refurbishment of New Court, Trinity College. Monitoring was originally envisaged as a means by which the performance of existing fabric could be assessed in order to improve and reduce the risks inherent with the application of internal wall insulation to a solid wall building. However, as the project developed, in the absence of certainty from building simulation models, monitoring was also used to test the proposed measures with regards to thermal performance and fabric moisture risk. Ultimately, outstanding, long-term, performance questions have been, in part, contained by the inclusion of a continuous monitoring scheme for New Court. The monitoring has been used to provide accurate specification of materials (and realistic calculation of performance targets) calibrate building simulation models, test the suitability of proposed measures, confirm and reinforce modelled findings and inform site practices. The on-going post-refurbishment monitoring keeps a watch on the performance of building fabric, including the most vulnerable elements, as a means by which to check and manage remaining or previously unidentified risks. In this way monitoring can provide improved confidence for the practices of refurbishment, essential if we are to strive towards improving the energy efficiency of even our most precious and protected buildings.

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Building Performance Evaluation – a design approach for refurbishment of a small traditional building in Scotland

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Abstract – *The drive for carbon dioxide (CO_2) emission reductions has, in recent years, seen thermal improvements being made to the fabric of historic buildings. This paper discusses, through a case study, the use of Building Performance Evaluation (BPE) to inform refurbishment design of the community owned Land Sea and Islands Centre, located in Arisaig, Scottish Highlands. This is a 19th century stone building with high heat losses, inefficient heating and lighting systems, resulting in occupant discomfort and high running costs. Funding was awarded in 2014 to improve its energy performance. Pre-refurbishment BPE results identified areas of significant heat loss, low internal surface temperatures, discrepancies between predicted and measured U-values, thermal bridges and excessive air infiltration. Refurbishment was completed in June 2015 and post-refurbishment BPE utilised to quantify improvements in building fabric, energy consumption and comfort levels, advocating pre-refurbishment BPE as a beneficial tool for informing traditional building refurbishment.*

Keywords – Refurbishment; building performance evaluation; energy; air permeability; Indoor Air Quality

1. INTRODUCTION

Understanding our historic building stock is essential to allow sympathetic refurbishments to be made to support the Scottish 42% emission reduction by 2020 and 80% by 2050 [1]-[2]. The drive for these reductions has shifted to include the refurbishment of existing and historic building stock with upgrades to building fabric and heating systems becoming common [3]. In most cases there is a greater challenge involved in adapting historic buildings for energy efficiency [4] as their retrofit requires a different pallet of materials and construction techniques than most new builds [5]. If not adopted, damage can occur to the original building fabric, with performance and character being compromised [6]. If undertaken correctly retrofit works can upskill the workforce [7], which is particularly important for energy efficiency measures applied to non-listed buildings that contribute to cultural heritage.

Building Performance Evaluation (BPE) on historic buildings is not common practice, but when BPE is undertaken it is more routinely conducted post-construction to review performance of new buildings. The resultant findings are typically disseminated to the client group and designers to facilitate improvements in their design practices. This paper focuses on a case study of an existing 19th Century building where BPE was used to inform its refurbishment. The Land Sea and Islands Centre (LSIC) (Fig.

1), is a 79m^2 former blacksmiths located in the centre of Arisaig, a rural coastal village in the north west of Scotland. In 1999 the building underwent major renovation including replacement windows, insulation to ceilings and selected external walls, the construction of three extensions and application of cement render to the external walls. Subsequently the building was used to house artefacts and documents promoting the local heritage and operated as a visitor centre. In 2012 Arisaig Community Trust (ACT) took ownership of LSIC, however, the LSIC remained closed throughout the winter as ACT experienced difficulty in heating the building above 16°C and the lighting was expensive to run. In 2014 ACT were awarded a Climate Challenge Fund (CCF) grant for the energy efficient refurbishment, with projected energy improvements of 75%.

Figure 1. View of LSIC building, north facing entrance and reception and north gable wall of exhibition area.

Sam Foster Architects (SFA) were appointed and developed design proposals using materials compatible with the existing historic building. These measures were applied to the 'Exhibition Room' and 'Room with a View' (RWV); they have not been applied to the shop area, which is planned to be replaced with a larger, energy efficient extension. To accurately identify areas of high heat loss and assess the internal thermal environment SFA approached Mackintosh Environmental Architectural Research Unit (MEARU) to assist, jointly applying for grant funding from the Scottish Funding Council (SFC) for pre-refurbishment (PR1) BPE. The outputs provided a 'PR1' benchmark against which a subsequent 'post-refurbishment' (PR2) BPE could be compared. The six-month refurbishment commenced in January 2015 and further funding was sought through Zero Waste Scotland (ZWS) to conduct PR2 BPE.

2. METHODOLOGY

PR1 BPE was conducted throughout December 2014 and the study was repeated in December 2015, post-refurbishment. To assess the thermal performance of the building quantitative and qualitative testing was undertaken. The qualitative assessment comprised a semi-structured questionnaire completed by those employed or volunteering at LSIC and included comfort polling and assessment of the user understanding for building operation. The quantitative element consisted of building fabric testing, environmental assessment and energy consumption monitoring. The building fabric testing included air permeability testing with thermography and in-situ U-value measurements. Air permeability testing was undertaken in accordance with the Air Tightness Testing and Measurement Association (ATTMA) guidelines [8]. Thermography, conducted during the Air Permeability Testing, was used as a tool to detect air movement patterns beneath the finished surfaces. U-value measurements were taken on four building elements: a ceiling element, insulated external wall (two separate locations), and an uninsulated external stone wall with rubble core. The methodology for measurement and subsequent analysis followed the procedures set out in ISO9869:1994 [9]. Due to the orientation of the building it was not possible for all measurements to be on north facing elements, therefore apparatus was installed to east facing ceilings, two insulated walls and one north facing stone gable.

Internal environmental monitoring was undertaken in three rooms using data loggers recording internal temperature (°C) and relative humidity (RH), and separate but adjacent data loggers for carbon dioxide concentration (CO_2) monitoring. External °C and RH measurements were recorded at the gable wall located on the north and north-east of the building. These instruments were set to simultaneously log at five minute intervals through the assessment period.

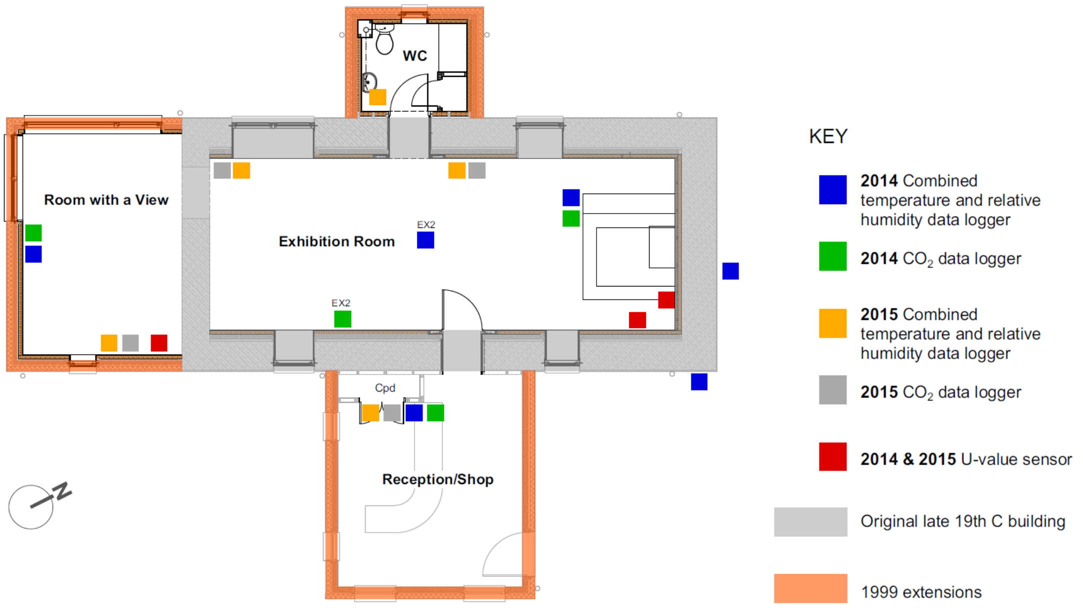

Figure 2. Plan view of LSIC building, indicating the historic core, 1999 extensions and location of monitoring apparatus for pre and post-refurbishment BPE.

During the PR1 study LSIC maintained a manual log of meter readings for the two electricity meters serving space heating and mains consumption. The metering arrangement was altered during refurbishment works and PR2 monitoring used ACT's energy monitor for space heating consumption. This monitor was display only and did not record, so manual recordings were taken from this by the LSIC staff twice per day. A meter was used on the lighting circuit, recording directly to a web application and the building's mains consumption was manually recorded.

3. RESULTS

The PR1 air permeability testing revealed the building experienced excessive infiltration (Table 1). While the building was held under negative pressure air pathways were traced using smoke pencil and thermography tests. This confirmed locations where infiltration was most severe, most notably in areas where the three 1999 extensions joined the existing building, at the ceiling, joist ends, mains electricity cable point of entry and around the soil vent pipe located behind the WC. In contrast, the PR2 testing indicated an 85% reduction in air infiltration rates. However, infiltration rates remained significant in the shop area, which was not subject to the same level of refurbishment as the rest of the building.

Table 1. Air Permeability measurements pre and post refurbishment

Test	**Air Permeability Measurements ($m^3/h.m^2$ @ 50Pa)**		
	Negative	*Positive*	*Mean*
Pre-Refurbishment	16.76	19.32	18.04
Post-Refurbishment	2.61	2.79	2.70

The thermography, performed together with the airtightness testing, visually identified these infiltration pathways. In the pre-refurbishment state areas of missing insulation and air passages behind plasterboard and timber linings were identified. Figures 3 and 4 illustrate the contrast between the before and after refurbishment thermography of the North West area of the exhibition room. PR1 thermograms were taken during December 2014 and PR2 thermography in February 2016. These were undertaken to indicate air movement patterns present behind the finished surfaces.

The results in Table 2 illustrate that the pre-refurbishment measurements did not meet the building regulation requirements at the time of installation. Manual steady-state calculations, based on the 1999 'as built' drawings, using thermal properties of materials obtained from best practice guidance, indicate inaccurate assumptions were available for the U-values during the design process. In contrast the post-refurbishment measurements confirm a 63%, 45%, 16% and 57% improvement in U-Value in building elements A, B, C and D respectively.

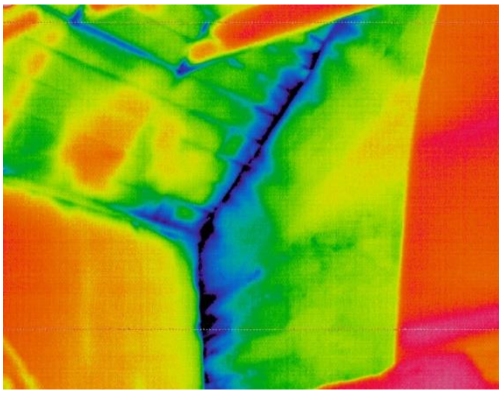

Figure 3. Thermogram of where the uninsulated north gable joins with insulated west wall and ceiling, indicating significant air leakage at joist ends, cool spots behind timber ceiling and air ingress at the corner.

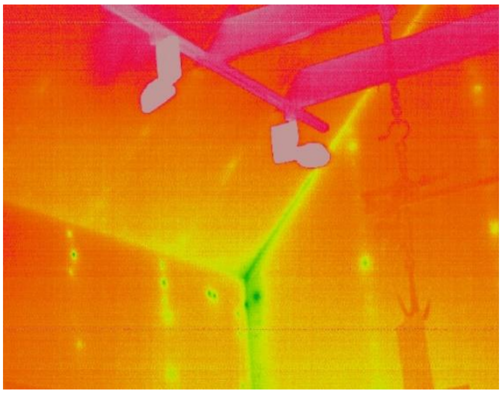

Figure 4. Thermogram of where the newly insulated and lined north gable joins with re-insulated west wall and ceiling, indicating slightly cooler area at the corner and no cooler area at joist ends.

Table 2. Comparison of predicted U-Value with pre and post refurbishment measured U-Values W/m²K

Surface	Room	Building Element	Orientation	1999 Elemental U-Values	SFA Manual U-Value	In-Situ U-Value Pre Refurbishment	In-Situ U-Value Post Refurbishment
A	RWV	Ceiling	East	0.20	0.43	0.72	0.26
B	RWV	Lined wall	East	0.30	0.49	0.40	0.22
C	Exhibition	Lined wall	East	0.30	0.49	0.25	0.21
D	Exhibition	Stone wall	North	n/a	1.64	0.93	0.40

The temperature comparison in Figure 5 indicates that both of the minimum and mean internal temperatures have improved from 8°C and 13°C respectively by 4°C compared to the PR2 monitoring. The PR2 temperatures provide a more comfortable internal environment with less of a temperature swing. The indoor maximum RH for December 2014 and 2015, shown in Figure 6, indicates a 10% reduction in the two rooms that underwent major refurbishment. Although the reception RH has reduced, the maximum RH remains close to 70% RH which can negatively affect the building fabric and artefacts within this area.

The electrical consumption relied primarily on manual data collection, during the second tranche of monitoring a power cut reset the data collection device, negating daily comparisons. Using meter readings made at the start and end of each monitoring period a 57% reduction in energy consumption was achieved compared to the December of the previous year.

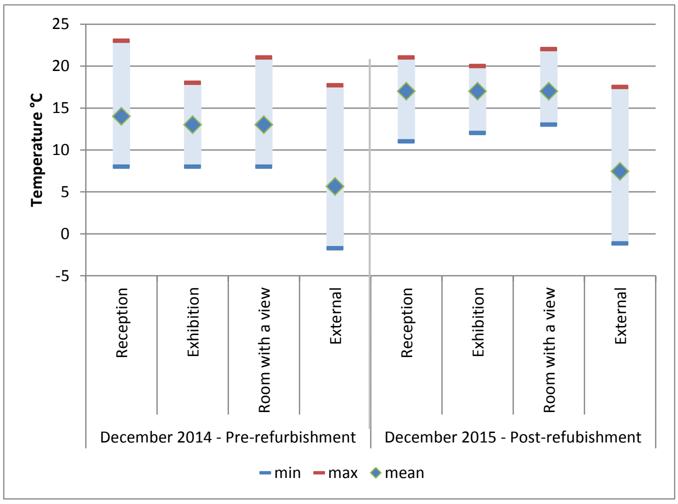

Figure 5. Minimum, maximum and mean temperature comparison, 2014 and 2015 monitoring.

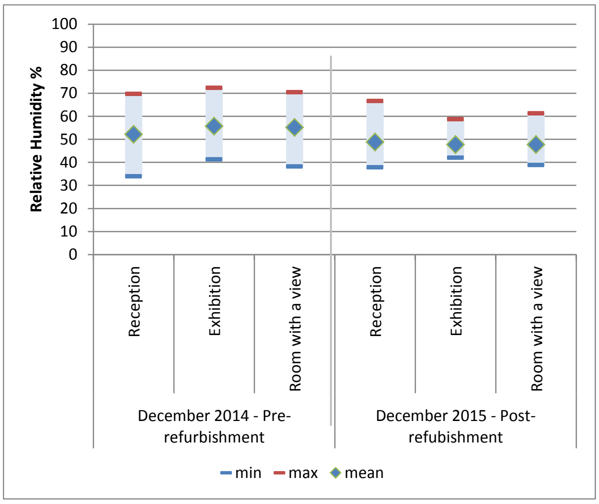

Figure 6. Minimum, maximum and mean relative humidity comparison, 2014 and 2015 monitoring.

4. DISCUSSION

There are a number of justifications for refurbishing existing listed and unlisted traditional buildings, including sustainability and the conservation of cultural heritage. Many of these buildings, particularly in smaller settlements with fewer buildings, are cultural landmarks with which residents and visitors have some form of attachment. Increasing support from EU, central and local government is resulting in local community groups undertaking ownership and maintenance of small traditional buildings in their towns and villages. With the Land Reform (Scotland) Act 2003 [10] and the Community Empowerment (Scotland) Act 2015 [11] this trend is likely to continue and the work carried out by communities will become more common as community groups seek to minimise their running costs. In Scotland 20% of the building stock was constructed pre-1919 [6][12], therefore a large number of people and communities are affected by the need to refurbish appropriately. Case studies of sensitive and appropriate refurbishment of small traditional buildings have the potential to provide clear, relevant information to homeowners who are considering improving the energy efficiency of their homes.

The improvements to thermal performance and comfort post-refurbishment highlight the positive impact BPE has made to the upgrading of the LSIC building. While the architect had planned for improved airtightness and insulation measures to be applied to the building, using natural vapour open building materials, the initial BPE results vindicated the architects design intent and highlighted the areas where particular attention was required. For example, the in-situ U-value testing indicated the heat transmission through the stone walls was less than expected allowing proposed insulation thickness to be reduced. This provided a cost saving which allowed an offset against additional insulation measures to the buildings ceiling that had exhibited poorer thermal characteristics than anticipated through using steady state manual calculations. As the measurement of U-values may not be practical in every situation, the inconsistent results provided by the steady state calculations indicate thermal property assumptions for building materials in best practice guidance documents is perhaps outdated and requires updating, to allow for more accurate predictions of U-values in existing buildings.

The use of vapour open building materials and finishes such as lime plaster, wood fibre and sheeps wool insulation and natural paint finishes could, according to manufacturer's literature, benefit the hygrothermal performance of the building. The initial results indicate improved hygrothermal performance in the exhibition room and room with a view where hygroscopic building materials were applied. However the aim of the monitoring was not to undertake assessment of hygrothermal performance and further research would be required to evaluate this. It would be advantageous to monitor hygrothermal conditions before and after the planned removal of the external cement render during the next phase of refurbishment.

The predicted energy reductions originally were set to achieve a 75% reduction in CO_2 emissions from the building have not been reached, however, the 57% energy reduction is a significant improvement, which will improve as the users become accustomed to optimising building use. The overarching result is that ACT are now able to heat LSIC to a comfortable temperature, permitting regular opening hours during the winter months and increased demand for the building's use during evenings for local community events. The extended use and opening hours may have impacted on the additional energy consumption but the refurbishment has delivered positivity in the village. Moreover the control over the internal environment has provided a reduced and more stable RH protecting the condition of the artefacts on display within the building and safeguarding the local heritage. The sympathetic refurbishment and comfortable environment has prompted the local community to refurbish homes of similar construction to improve energy efficiency within the village, some using airtightness permeability testing prior to refurbishment to indicate where works need to be undertaken.

5. CONCLUSION

This paper presents a case study of a historic building that used BPE as part of the design process. The PR1 indicated that the earlier retrofit in 1999 did not meet the building regulations at the time, which, combined with the excessive infiltration, meant that the building was underheated (even with the heating at maximum output) and unused during the winter months as the occupants found it too uncomfortable. Although the refurbishment included natural building materials compatible with historic buildings, the CCF refurbishment grant funding did not cover the removal of cement render applied in 1999, which impacts on historic building thermal and hygroscopic performance [6]. LSIC are planning to remove the cement render in the future.

Improvements to the building have not only improved the energy efficiency but created a more comfortable and useable space that has greatly impacted on the users and wider community. It is also worth noting that although the original CCF grant required 75% carbon reductions, no measures were built into the framework to check whether these savings were achieved. It is recommended that further research be undertaken into building performance gap closure in relation to grant funding for energy efficient refurbishments, as well of the impact of these on the building fabric as a whole.

The BPE project provided tangible results for the sympathetic refurbishment of a historic building, which can be replicated in similar traditional properties in the area. However, owners (individual and community groups) of non-listed traditional buildings require better access to support and information that can help with improving energy efficiency of their homes. More research is required into undertaking pre- and post-refurbishment BPE and the accessibility of these tools and information for the general public.

6. ACKNOWLEDGEMENTS

Scottish Funding Council for funding the pre-refurbishment BPE and to Zero Waste Scotland for funding post-refurbishment BPE. Without the funding input from both organisations the study would not have been possible. The Land Sea and Islands Centre staff and volunteers played an instrumental role in the BPE and having endured monitoring equipment in the building during the busy Christmas holiday period for two consecutive years.

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Understanding Our Heritage: Monitoring of energy and environmental performance of traditional terraced houses of Northern England.

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Abstract – *Existing buildings play a key role in the achievement of the ambitious energy saving and greenhouse gas reduction targets that Europe has fixed for 2020 and 2050. Research has demonstrated that the impact in terms of decrease of energy use and CO2 will be strong, considering that, in Europe, 80% of the 2030 building stock already exists and 30% are historical buildings. To achieve these goals, reliable data about energy consumption, building components and systems performance of the existing building stock is needed to implement adequate strategies.*

United Kingdom (UK) is one of the most advanced European countries in regards to the implementation of regulations and programs to measure and assess the real performance of its old buildings. One of these programs is the Green Deal Go Early Project (GDGE) that the University of Salford has conducted for the UK Government during 2015 and which first discussions are presented in this paper. The values obtained from the monitoring of 16 solid-wall pre-1919 Victorian terraced houses in Greater Manchester are in accordance to those extracted from the BRE report on "In-situ measurements of Wall U-values in English Housing", what validates the methodology followed to approach the monitoring of these case study houses as well as the preliminary results. This alignment provides a closer definition of the real U-value of solid wall housing typology confronted with those currently provided by the Standard Assessment Procedure (SAP) and Reduced Data Standard Assessment Procedure (RdSAP), leading the way to a better understanding of the performance of historic buildings and hence an improvement in the retrofitting strategies.

Keywords – Traditional Housing; monitoring; energy performance; Northern England; terraced houses

1. INTRODUCTION

The urban fabric of European cities is largely shaped by old and inefficient residential buildings whose energy demand can exceed 200kWh/m² per year [1]. More than 40% of our European residential buildings have been constructed before the 1960s when energy building regulations were very limited [2]. As a matter of fact, the energy used in domestic buildings contribute a large percentage of the world's carbon emissions [3]: while modern building techniques are able to produce dwellings with a low in-use energy requirement, a greater impact can be made by improving the existing, poorly performing housing stock [4].

Additionally, architectural heritage deserves very particular attention within a sustainable architectural approach, with regard to sustainable energy development and historic buildings protection [5]. Preservation of the architectural heritage is considered a fundamental issue in the life of modern societies [6] contributing significantly to the value of the city by branding the city´s character. The need of preserving historical constructions is thus not only a cultural requirement, but also an economical and developmental demand [7].

In United Kingdom (UK), the number of new buildings contributes at the most 1% per year to building stock [8] whilst the other 99% are already built buildings. In fact, UK is one of the countries in Europe with the largest components of older buildings [9]: 21% of UK housing were built before 1919 and the advent of cavity walls [10]. Terraced houses account for 6.788.000 [11] what supposes a 29.9% of the total building stock [12]. Moreover, from the 3.076.000 dwellings in North West England (where Greater Manchester is sited), 35.5% are terraced houses [12]. The retrofitting of this residential stock could so provide considerable potential in energy conservation and sustainability benefits [13]. However, the achievement of the benefits reaped from the retrofitting could be jeopardised by the scarcity of knowledge about the behaviour of historic buildings and its consumption patterns, what supposes a major obstacle to take right decisions over a specific building stock.

This research seeks to address the following two questions: first, the need to establish an efficient monitoring system assuring good data availability and data quality; and second, the need to develop a systematic understanding, methodology and analysis when approaching these buildings which incorporates the many interactions both within specific elements and at a whole house level including technical factors and user behaviour [14]. It reviews the research conducted on 16 Victorian terraced houses sited in the area of Great Manchester and it is the result of a two-year monitoring of pre and post-retrofitted housing developed under the Green Deal Go Early (GDGE) project run by the University of Salford for the UK Government. Whether some air test results and Energy Performance Certificates (EPC) energy use calculations are provided, this paper does not present results but preliminary descriptions and discussions. Therefore, no results chapter has been provided.

2. STUDIED SAMPLE: TERRACED HOUSES OF NORTHERN ENGLAND

Our targeted building stock is described by English Heritage as “a property built prior to 1919 with solid walls constructed of moisture-permeable materials” [14]. This stock is defined by a solid two layers of brick non-insulated envelope. The insulation of solid wall housing is indeed one of the greatest challenges for energy efficiency policy, but it also potentially offers some of the most significant savings [15].

The Building Research Establishment (BRE) [16] defines two types of housing among this stock: Standard and Non-Standard. Standard buildings are those with less than 330mm wall thickness while Non-Standard are those beyond. Only two of our examples are Non-Standard houses with a triple brick solid wall dated before 1800. They have been considered as part of the sample because the time period, wall structure and material use.

As aforementioned, all buildings improved in this study had solid walls with no cavity. Insulation was placed on the inside or outside face of the buildings during the retrofitting respecting the original fabric and the authenticity of the historic values of the buildings. In most cases, the insulation was placed on the outside of the buildings around the rear and sides, and the façade was preserved by installing insulation on the inside across the front elevation although internal insulation caused much more disruption to the occupants, removing some of the living space. The insulation layers also needed to 'overlap' somewhat to prevent the brickwork becoming a cold bridge. On a couple of the buildings, thin tiles that resemble the original brickwork where placed over the insulation to mimic the original appearance.

Table 1. Housing samples definition and identification

ID	Archetype	Standard/Non-Standard
C1 - C18	Semi-detached Pre1800 brick.	Non-Standard
C8 - C9 - C10 - C12 - C14 - C15, S2	Semi-detached pre 1919 solid wall.	Standard
C6-C17	Mid terraced pre 1919 solid wall.	Standard
S3 - V1 - V3 - V4	End terraced pre 1919 solid wall.	Standard
V2	Terraced pre 1919 solid wall.	Standard

3. METHODOLOGY

The methodology followed in the project focuses on gathering and storing data from buildings that could be analysed in the future. The relevant steps for this paper are building selection and data collection, which correspond respectively to the processes to *identify and select buildings to monitor* and the *collection of quantitative and qualitative data* from the selected buildings.

3.1 Building selection

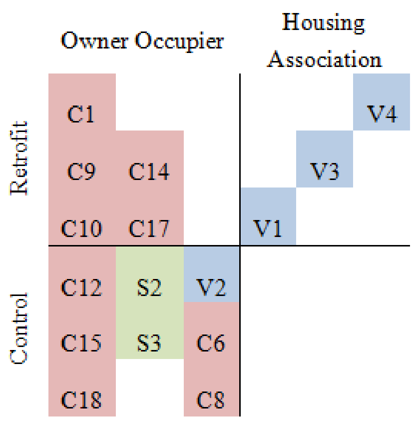
The eligible dwellings are a sub-set of those that forms the GDGE monitoring project. Started in 2012, this project included in-use performance monitoring and fabric testing of domestic properties across greater Manchester with the aim of investigating the effectiveness of the UK government's Green Deal (GD) program. This report concerns itself with the terraced archetype. Sixteen properties have been classified by experimental group: either 'Control' (unaltered, no retrofit measures) or 'Retrofit' (significant energy efficiency measures applied), and by ownership status: 'Owner Occupied' (owned by the occupant) or Housing Association (owned by a third body, responsible for the retrofit measures, and rented to the occupant). Figure 1 shows how the sample properties are distributed regarding to these indicators:

Carbon Coop: Properties recruited through a cooperative community benefit society formed by householders from Greater Manchester. The houses included are mid- and end-terraced houses.

Control Group: Unimproved end terraced houses.

Housing association: recruited from a housing association in Greater Manchester, the retrofit houses are all end terraces.

Figure 1. Classification of sample properties



3.2 Data collection

The goal of this task is to collect dwelling quantitative and qualitative data as follows: quantitative data about the house as a whole is collected by direct *monitoring* with sensors and by the *availability of EPCs*; quantitative data of the building fabric is collected using both testing methods (*U-value* and *air tightness*) and *thermography;* and finally, qualitative data about user satisfaction with the retrofitting is gathered with a survey.

3.2.1 Whole House Methods

Monitoring: The monitoring period, between 2013 and 2015, comprised the adoption of retrofit strategies in some of the housing examples what provides pre and post retrofitting measures to the study. The monitoring equipment included small, battery powered sensors that communicated wirelessly with a central 'hub' that periodically stored/updated data into a central server. Data includes information of primary energy consumption (gas and electricity), internal conditions (temperature, relative humidity and CO2 emissions) and external temperature.

Energy Performance Certificates (EPC) In many cases, EPCs where available for retrofit houses in their pre-retrofit state, allowing a before and after comparison. In the UK, EPCs are generated using a reduced version of the Standard Assessment Procedure and presented as a band A to G (A is higher efficiency) and a score 1 to 100(100 is higher efficiency) [12].

3.2.2 Building Fabric Methods

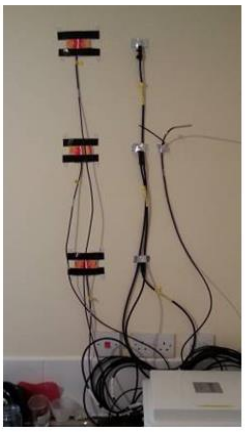


Figure 3: U value measurement

Figure 4: Air tightness test

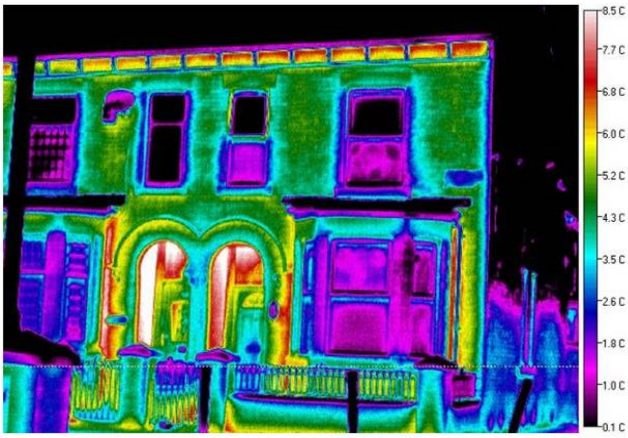


Figure 5: Thermographic image

U- value testing: The U values of several of the houses where measured according to ISO 9869-1:2014 [17] (Figure 3, above). U values were also calculated using BS EN ISO 6946:2007 methodology [18].

Air tightness testing: Air tightness tests using the 'blower door' method (Figure 4, above) were carried out to determine the rate of air infiltration. The test gives a result as a q50 value, being the volume of air (m3) infiltrating the building envelope (m2) per hour (hr) at a pressure difference of 50 Pascals (50pa). The tests conformed to BS EN 13829:2001 methodology [17].

Thermography: For maximum accuracy, and in conformity with the BS EN 13187:1999 methodology [18] (Figure 5), the surveys where carried out in the evening at least 2 hours after sunset when the internal temperatures of the building where a minimum of 10°C higher than external air temperature.

3.2.3 User Methods

User Survey: The households filled in a personal survey conducted by the expert before and after the retrofitting. This survey gives a qualitative approach to the measures. The preliminary findings of the project indicate that it is very difficult to disaggregate the effects of fabric improvement from the occupant's behaviour.

4. FIRST OUTCOMES AND DISCUSSION

This paper presents the preliminary outcomes of the monitoring of 16 terraced dwellings as well as the methodology followed. The obtained data is being processed using a bottom-up and top-down approach:

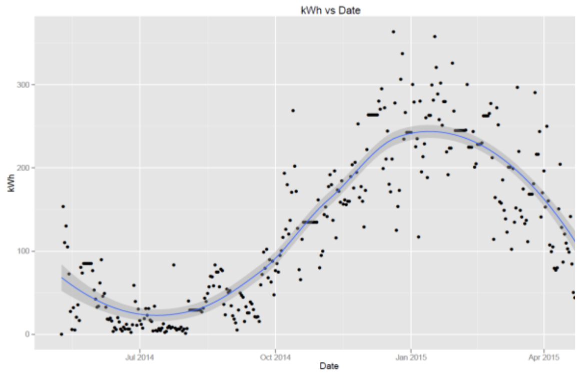


Figure 6: kWh gas use by date (example)

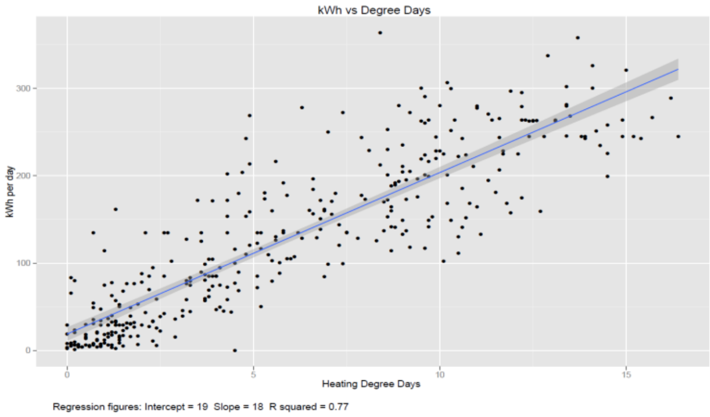


Figure 7: Degree day regression on same data

Bottom-Up: Energy consumption is a key indicator to evaluate the improvement of a retrofit strategy. Gas and electricity consumption has been measured in all the selected houses. A first problem encountered was that primary energy use data cannot be compared between houses directly as the monitoring interval was not identical. As an assumption, degree day regression was used to normalize the energy use against external temperature. Graphics comparing the consumption and the degree day regression assumption has been developed for all the houses what allows direct comparison of energy data from multiple houses over different time periods (see Figure 6 and 7). The distribution of the values in figure 7 display a strong positive correlation, with an r^2 value of 0.77. This is at the high end of the range of r^2 values indicating that the energy use in this house is particularly responsive to changes in temperature, suggesting an effective use of heating controls.

In 2014, BRE published their report about in-situ measurements of wall U-values in English Housing [16]. This report concludes that the averages of the measures values for solid un-insulated walls are below the standard values used in the RdSAP methodology and below the mean of the theoretical calculated U-value regarding to the wall typology. Table 2 shows the comparison of those results with the ones measured in the monitored housing. The U-values of the 'as built' pre retrofit properties fall within an acceptable margin of the BRE report. Differences could be due to the number of examples used for the different studies - 300 in the case of BRE - that provides them with more accurate averages. The improved properties with 'external wall insulation' show a sizable improvement when compared to the same archetypes in the BRE report. The U-value measured from the End terraced pre 1919 solid wall (* above) is particularly high, possibly due to the deterioration of the building fabric due to damp.

However, the figure is within the 99% confidence interval of the BRE report sample (assuming normal distribution, within three standard deviations from the mean), suggesting that although unusually high, the value is not necessarily in error.

Table 2. Summary of results compared with those of the BRE report [13]

Retrofit improvements	Archetype	U-Value Measured_Mean (W/m²K)	Measured U-Values BRE_Mean (W/m²K)	Percentage difference
As built	Semi-detached Pre1800 brick.	1.6	1.28	25%
	Semi-detached pre 1919 solid wall.	1.3	1.57	-17%
	End terraced pre 1919 solid wall.	2.38*	1.57	-50%
External wall insulation	Semi-detached Pre1800 brick.	0.4	1.28	69%
	Semi-detached pre 1919 solid wall.	0.29	1.57	82%
	Mid terraced pre 1919 solid wall.	0.32	1.57	80%

Top-Down: the GDGE project has provided data of pre and post retrofit measures. Among the 16 sample cases, half of them were retrofitted. Figures 8 and 9 show the impact of retrofitting strategies on air infiltration (q50) and primary energy consumption calculated from the EPC [16]. Regarding to EPC rating, important improvements could be appreciated in the semi-detached solid wall typology. During the measurements, it was noted that unimproved properties can be more airtight than expected due to regular maintenance; the attitude of the occupants towards draught proofing has a large effect on the q50 value. Conversely, the disruption to the building fabric caused by the retrofit measures, particularly the installation of internal or external insulation, can potentially cause disturbances to the fabric that lead to an increase in the infiltration rate.

The results presented in this paper are just a preliminary overlook of the datasets collected during the last two years. A methodology has been established to approach a unified understanding of the outcomes that could be compared through all the housing examples. Some assumptions have been made in the adoption of this methodology that need refining in the ongoing analysis.

Currently, the data has been processed in the micro-scale by looking to individual measures separately by individual housing. Some clues of a wider look have already been introduced in the discussion but more work has to be done in proposing global reliable values that define the whole building stock.

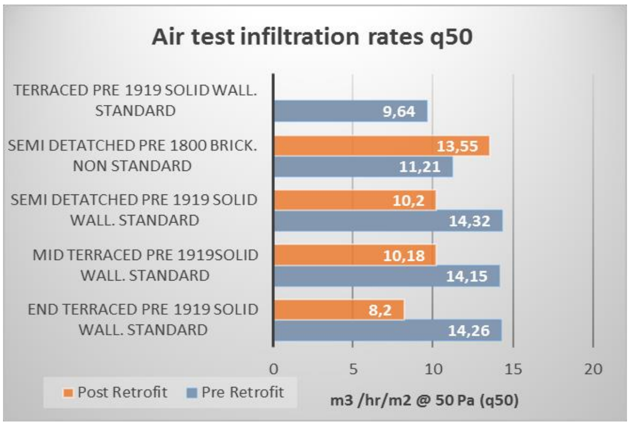


Figure 8: Air infiltration rates pre and post retrofit

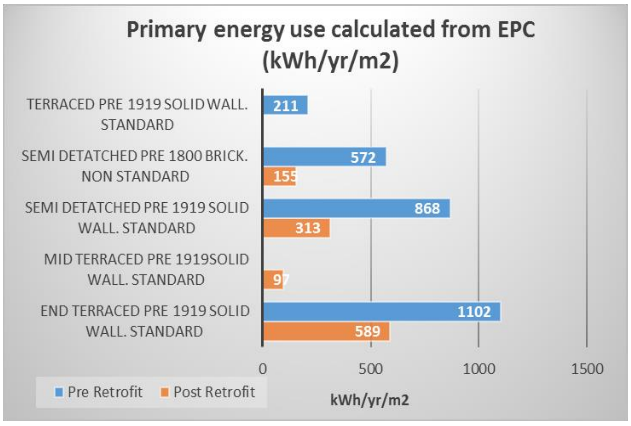


Figure 9: Primary energy use pre and post retrofit (Figures from EPC)

5. CONCLUSION

The approach to traditional buildings needs a systematic understanding, methodology and analysis. This paper presents the results of a two years monitoring of pre and post retrofitted examples of solid wall terraced buildings in the area of Greater Manchester. The outcomes of this study serve as base to a better understanding of the performance of these buildings. The results included in this paper suggest consistent improvement in air infiltration rates, U-Values and EPC calculated energy use estimates. As the analysis progresses more detail into the effectiveness of the retrofit measures will emerge, which will contribute to further programs of retrofit measures promising reductions in energy consumption and CO^2 emissions in the whole building stock.

The green deal, now defunct, relied on a "golden rule": that the occupants will always be paying less for their heating even with the additional surcharge added to their bills to pay for the improvements. The preliminary findings of the project indicate that it is very difficult to disaggregate the effects of fabric improvement from the occupant's behaviour, for example, comfort taking, ventilation practices, secondary heating. Therefore, a simple calculation based on estimated energy saving will be insufficient. For future government initiatives for retrofit, a different finance mechanism should be considered.

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On-site assessment of hygrothermal performance of historic wall before and after retrofitting with insulation

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Abstract – *The impact of thermal insulation scenarios on the hygrothermal balance of traditional walls has been investigated. In three pre-World war II houses subject to a global thermal retrofit, instrumentation devices were used on-site to monitor the interior and exterior climates, and the temperature and humidity at different points inside the walls. These measurements were made before and after the retrofitting. Then a comparison was done between the hygrothermal behaviour of the old wall and the insulated wall. Based on the measures, dynamic hygrothermal simulation has been performed with a commercial tool (Wufi 2D) to anticipate the evolution of moisture inside the insulated walls over ten years. The cases analysed are a brick house retrofitted with exterior insulation and two half timbering houses retrofitted with interior insulation, i.e. cellulose wadding and moisture control barrier and wood fibre insulation board respectively.*

Keywords – Hygrothermal performance; on-site assessment; thermal insulation; historic wall retrofitting

1. INTRODUCTION

The need to save energy and master greenhouse gas emissions leads the actors of the building sector to intervene on the existing stock. This is partly reflected by the need to thermally insulate buildings. The family of "pre-world war 2" buildings represents more than 30% of the French building sector and is a real stake for energy savings and comfort improving. The retrofitting process has to take into account the heritage considerations and the different risks for the building and the occupants. In the global process of retrofitting, the presented study will focus on the walls and the humidity issue as excessive level of moisture in building leads to construction disorders [1]. The increasing number of thermal retrofits concerns buildings with common and vernacular material with sensibility to humidity. The idea of sustainable development involves guaranteeing the durability of the technical solutions applied to the walls to improve their thermal behaviour and in a larger spectrum, to decrease the energy need of the building. In [2], the main hypothesis is that instead of aiming at saving the most energy, solutions that pay regards to finding a balance between energy savings and the durability in terms of reduced moisture risk need to be put forward.

1.1 Overview of the hygrothermal performance of insulated heritage walls

Depending on the architectural particularities and the heritage conservation issues of historical buildings, the insulation process could take place from inside or from outside. The latter technique is the most efficient, when it is possible. Applying interior insulation will modify the hygrothermal behaviour of the wall and may induce a risk on interstitial condensation, frost damage or mould growth.

In [3] the interior insulation of a historical building was instrumented for 4 years, it consists of a hydrophilic mineral wool without vapour barrier on a heritage brick wall in Prague. A lime-cement basis was applied between the insulation and the brick. The conclusion is that the system performs well and no internal condensation had occurred in the studied period. In [4] and [5], conclusions gave the benefits and disadvantages of two families of interior insulation process on historical walls after experimental analysis in laboratory and a large number of simulation with a dynamic tool. The first insulation process represents the family of vapour tight interior insulation (XPS panels or mineral wool with traditional vapour barrier) and the second one represents the capillary active insulation systems (calcium silicate boards). Results show that a vapour tight system is preferable to capillary active system from the point of view of interstitial condensation. On the other hand, the vapour tight system has a larger risk of frost damage and additionally such system would be more risky for wood beam ends, allowing an elevated moisture retention in the masonry. Concerning new insulation techniques such as vacuum insulation panels, the hygrothermal behaviour of a heritage brick wall renovated with them was investigated in [6]. The conclusions are that it provides a great thermal behaviour but ther exists risks of moisture damages such as frost in the exterior part of the brick, especially in Bergen climate, and risk for wood beam ends inside the wall. Finally, an important question is raised in [7]. It is the evolution of the properties of the materials through years. In this article, it is shown that the properties of mineral wool in a building has been largely modified after 25 years of services. For instance, the degradation of the polymeric binder had caused the decrease of the hydrophobicity of the material with a greater water sorption.

1.2 Objectives

The literature review warned us on the specific risks associated with each solutions. In France but also elsewhere in Europe, solutions with hydrophilic materials are more and more promoted as systems that diminish the moisture storage in the wall structure by still allowing an inward drying. Such system are in the centre of the work presented in this article. The focus is put on three walls from three heritage buildings with projects of insulation with cellulose wadding or wood fibre insulation board. The impacts of the retrofitting scenarios on the hygrothermal balance of the traditional walls have been investigated. Measurements after and before the retrofit have been performed and completed with simulations to check the projected behaviour for ten years and compare the chosen solutions to other ones.

The building A is a brick house from the beginning of the 20th century, typical of the suburbs of Colmar region in Alsace. The retrofit consist in exterior insulation with cellulose wadding and wood fibre board for the walls, the installation of a single-flow mechanical ventilation system and the insulation of the roof. The building B is an half timbering house with a project of interior insulation with cellulose wadding and moisture control smart barrier for the walls, insulation of the roof and the installation of a single-flow mechanical ventilation system. The building C is another half timbering house with a project of interior insulation with wood fiber board for the wall and the roof. All three houses are in Alsace, in the east of France with a continental climate.

2. METHOD

2.1 In-situ measurements

The three houses were monitored during a year before the retrofitting process and at least a year after. The local climate was assessed with a weather station (air temperature, relative humidity, wind direction and speed, rain, horizontal global solar radiation), the indoor climate in the different rooms of the houses were recorded hourly with data-loggers (air temperature and relative humidity). Finally, two walls in each houses were specifically monitored with temperatures and relative humidity probes inside the walls at three different places (four for the house A). These relative humidity measurements need special care during the installation of the sensors but it has already been successfully used in [8]. Figure 1 presents the scheme used for the house B.

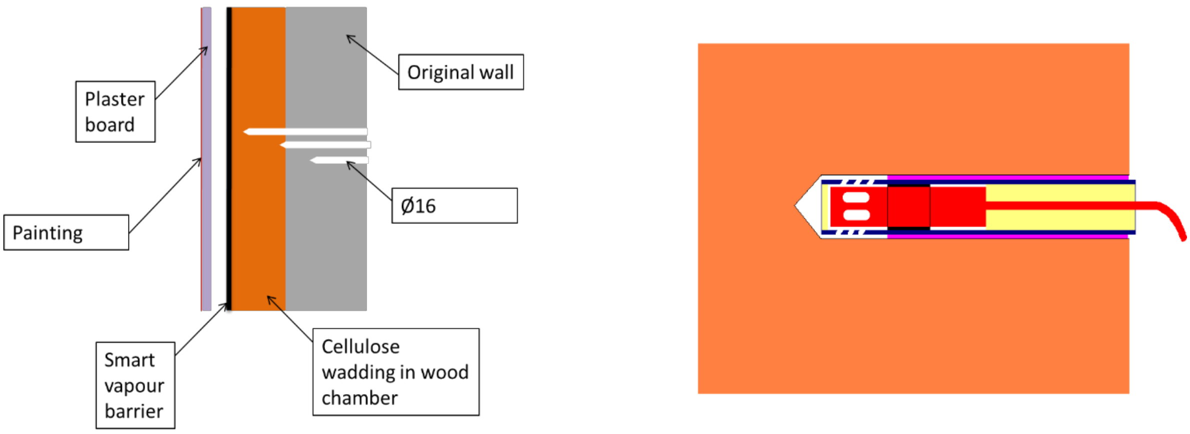

Figure 1. Temperature and relative humidity sensors in the walls of the house B

To complete the set of data, thermocouples were used to assess the different surfaces temperatures. The full diagnosis of the houses before and after the retrofitting were performed, including infrared analysis, air permeability measurement and control of the ventilation system. In the 3 cases, the air permeability has been strongly improved with the retrofitting to reach the low consumption in retrofitting French label. The relative humidity measurements in the small cavity in the material are supposed to be in balance with the water content of the material around it, considering the water sorption function for the material. These materials properties have been measured in laboratory in another part of the general project (“Humibatex” from the French National Research Agency). The Figure 2 presents the configuration of the monitored wall of the houses A and C, for house B it is in Figure 1. The letters represent the position of temperature and relative humidity sensors.

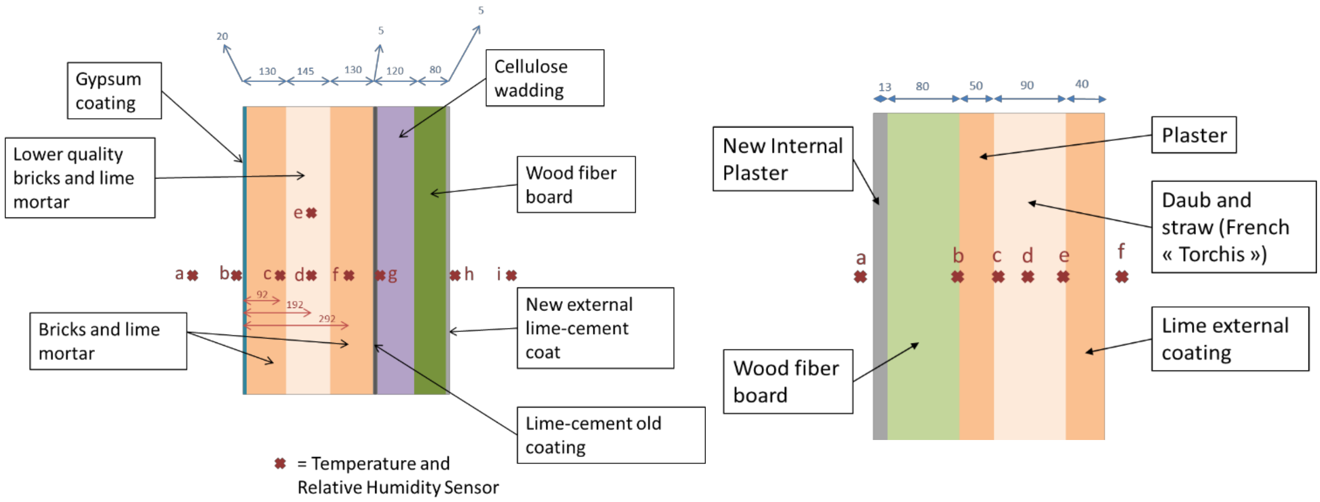

Figure 2. Monitoring and configuration of the wall east of the house A (left) and the wall south of the house C (right). (dimensions in mm)

2.2 Hygrothermal dynamic simulation

The Figure 3 illustrates the water content in the middle of the brick section of the eastern wall of the house A after the retrofitting.

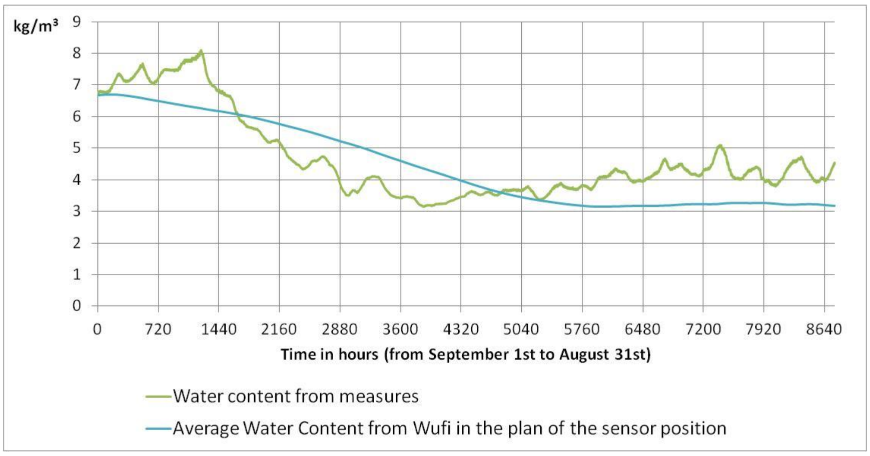

Figure 3. Water content in the middle of the brick section of the eastern wall of house A during the first year after the insulation

The measurement campaign only allows to draw conclusions on one year whereas the risks involving humidity could be on the long terms. The simulation tool Wufi from the Fraunhofer Institute, based on the work of Künzel [9] was used to simulate ten years. A comparisons between the simulation and the year of experimental data was performed for all buildings. It shows a satisfying convergence on the northern and eastern walls. On the western or southern walls, the rain and the solar radiation add complexity to the confrontation and the comparison is more difficult. The initial data needed for the simulation have been set up with the measurements. The simulations and the measures do not perfectly fit but it was considered enough given the objectives of the study. Explanations for the differences could be mostly differences between the properties of the materials in the model and the real ones. The boundary conditions of the 2D models are the measured climates for the exterior and the interior. The other boundaries have been considered adiabatic.

3. RESULTS AND DISCUSSIONS

3.1 Exterior thermal insulation

3.1.1 Durability of the solutions

The simulation results presented on Figure 4 illustrate the comparison between the hydrophilic, capillarity active and vapour open solution chosen in the house A and a solution with expanded polystyrene for the same thermal resistance. The average water content in the old masonry is in both cases far lower after the exterior insulation and is lower with the chosen solution than the EPS in winter and spring.

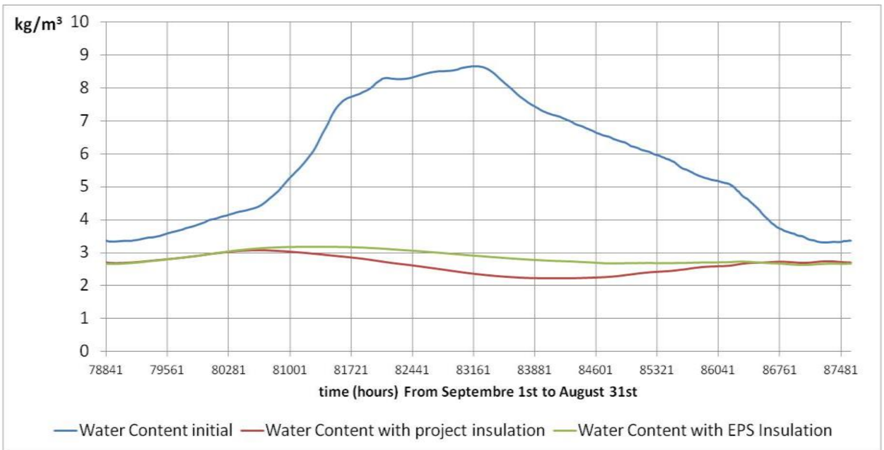

Figure 4. Comparison of the average water content in the brick of the house A on last year of simulation b -

The maximum water content ratio in the cellulose wadding is 4.8% in mass of water by dry mass. The notice criteria for this material to avoid moisture risk is 15%. The interface between the insulation material and the old masonry wall have been checked and the water content there is higher with the cellulose wadding than with the EPS solution but in both cases, no interstitial condensation have been noticed. The level of moisture in all material is steady over the simulations years.

3.2 Interior thermal insulation

3.2.1 Ventilation consideration

The air change rate inside the building is strongly affected by the low air permeability of the building envelope after the retrofitting process. The installation of a ventilation system is strongly recommended to keep a reasonable level of air change rate. In the example of the house A, the indoor relative humidity was at an average of 69 % before the retrofit and at an average of 59 % after it with the services of a mechanical ventilation system (single flow).

3.2.2 Durability of the solutions

The measurements during a year before and after the insulation of the walls for the house C show that the water contents inside the original parts of the walls are higher after the retrofitting project but this higher level is still largely acceptable for such construction materials. No interstitial condensation was noticed. No risk with the wood fibre board in the "dry rooms" but in the "services room" with a higher humidity rate, a smart vapour barrier is needed to avoid interstitial condensation. The Figure 5 presents a confrontation between measurements and simulation results. The differences could be explained by materials properties as "daub and straw" is difficult to characterise and by the southern wall boundary condition which is affected by direct radiations and rain.

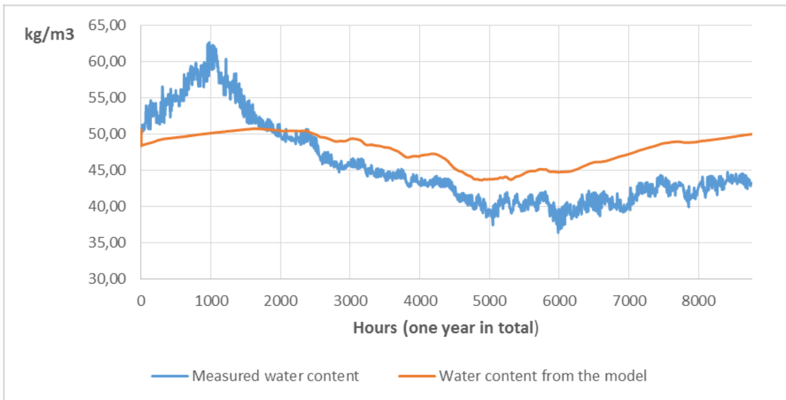

Figure 5. Confrontation of the model and the measurements in the daub and straw of the southern wall of the house C: Water content in the first year after the retrofit

On the house B, simulations considering mineral wool, wood fibre board or expanded polystyrene in place of cellulose wadding have been performed and the result validate the choice of the architect. It is with the cellulose wadding and the smart vapour barrier that the original walls (bricks, lime mortar and wood) has the lowest water content in the simulation results. These simulations have been performed with a source terms in the model to represent flaws in the continuity of the barrier. The hypotheses for these sources can be found in [10]. It represents a hole of 0.26 cm²/m² of vapour barrier. A warning can be issued for house B because of a freezing risk on the external coating: a temperature of 0°C on this coating was recorded.

4. CONCLUSION

In this study, three houses have been monitored to assess the durability of the associated retrofitting projects. The interior or exterior insulation with hydrophilic, capillarity active and vapour opened material has been investigated. With the studied cases and with the considered indoor and outdoor climate, no hygrothermal risk could be revealed but a list of warnings need to be highlighted. The freezing risk is always present with interior insulation and the external coating have to be well preserved and replaced or repaired when needed. The simulation considering flaw in the smart vapour barrier has shown a good resilience of the hydrophilic solutions even with accidental situations such as holes in the barrier. The investigations have to be continued with other realistic parameters such as rising damp to assess the limit of the use of the different insulation materials.

5. ACKNOWLEDGEMENT

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Thermal behaviour and comfort of a building pre- and post-intervention: the case of the Engineering School of Bejàr

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Abstract – *Historic buildings are responsible for a large amount of energy consumption and CO2 emissions, besides presenting comfort condition problems. There is a strong need to bridge the gap between conservation of historic buildings and users comfort, through a comprehensive method for diagnosis and monitoring. This paper deals with this diagnostic method applied to one case studies of the FP7 EU project 3ENCULT. Techniques integration in a scientific based diagnosis and evaluation tool can benefit the whole process, leading to energy efficiency and users comfort improvement. The methodology proposed covers three main phases of interventions: comprehensive diagnosis pre-intervention, evaluation of retrofitting strategies and assessment of the interventions, based on targets in the fields of historical value conservation, energy balance and comfort improvement. Building energy performance simulation tools are combined with non-destructive tests, such as IR thermography, blower door test, and wired and wireless monitoring. Example results will be shown with trend and values.*

Keywords – Monitoring; NDT; comfort

1. INTRODUCTION AND AIMS

Historic buildings are responsible for a large amount of energy consumption and CO2 emissions, besides presenting comfort condition problems, due to, among others, pathologies derived from their constructive conditions. There is a strong need to bridge the gap between conservation of historic buildings and comfort of users, through a comprehensive method for diagnosis and monitoring. This paper deals with this diagnostic method applied to one of the case studies of the FP7 EU funded project "Efficient Energy for EU Cultural Heritage" (3ENCULT) where the specific techniques integrating the diagnosis procedure are depicted, concluding how the development of this scientific based diagnosis and evaluation tool can benefit the whole process, leading to an improvement of the energy efficiency and comfort of users. The methodology proposed covers three main phases to drive these interventions: comprehensive diagnosis pre-intervention, evaluation of retrofitting strategies and assessment of the interventions after their implementation, based on a set of targets in the fields of historical value conservation, energy balance and comfort conditions improvement. The diagnostic phase, through a scientific procedure, is based on the utilization of building energy performance simulation tools combined with non-destructive tests, such as the IR thermography, blower door test, and wired and wireless monitoring, used to set up the baseline of the current conditions. The control strategy carried out in some representative rooms of the building lead to comfort improvement and energy savings (i.e. reducing electricity consumption). Results will be shown with trend and values of energy consumptions and their improvements.

2. DIAGNOSIS TOOLS

Diagnosis is a fundamental step for assessing the current health-state conditions of the buildings as well as their energy performances and comfort conditions. Non-destructive tests (NDT) or minor invasive testing techniques should be preferred for the diagnosis of historic buildings due to conservation and preservation requirements. Among the available non-destructive techniques, blower door test and IR thermography have proved reliable for the diagnosis of energy-related problems [1, 2]. The blower door test is a non-destructive, standardized method used to determine the air-tightness of the building envelope. It is based in the imposition of a difference pressure between inside and outside by means of a dedicated fan mounted on a window/door frame. The resulting rate of air exchange is used as input value in energy performance simulations and allowed discovering air loss of building envelope. IR thermography, instead, is an electromagnetic contactless technique that measures the radiant heat flow from the surface. The results, in terms of bi-dimensional temperature distribution maps allow detecting thermal bridges, air leakages as well as structural characteristics, defects and moisture. The combined use of these two methods allows on the one side, the detection of thermal losses of the building and on the other side, the determination of the potential energy savings achievable with insulation systems, thus helping in selecting proper intervention strategies [1].

3. CASE STUDY: ENGINEERING SCHOOL OF BÉJAR

The Engineering School of Béjar, located in Spain (Figure 1) is one of the case studies of the 3EnCult project. It was built between 1968 and 1972, following the design project of the architect Manual Blanc Díaz. The formal definition of the building, characteristic of the Modern Movement, supposed a rupture with traditional architecture of the region in that period. However, it takes some minor formal aspects from the regional architecture, as the big lattice which reinterprets the façades of the traditional houses of Béjar, that were made with roof tiling for protecting the most exposed façades from strong winds and rain. The building has a net built area of 13,624.85 m^2 and a net usable area of 9,467.10 m^2 distributed on two basements, one ground floor and four floors above ground. The structure is made of reinforced concrete pillars and slabs, which are the cantilevers in the east façade. The pillars and slab fronts, without thermal insulation, embedded on the walls and independents from the brick surfaces, cause important pathologies (thermal bridges, lines of infiltrations, etc.). The building envelope is made of two faces, where the outdoor face is made of concrete blocks and the indoor face is a double hollow bricked wall with interior plaster. The walls have not insulation material but between the two faces there is a non-ventilated air camera, of 5 cm. The transmittance of these elements is U=1.50 $W/m^2 \cdot K$. The original windows were replaced in a recent refurbishment with aluminium windows with thermal bridge rupture and double glazing (4+6+4). Now their transmittance is U=3.45 $W/m^2 \cdot K$, and the g-Value is 0.76.

Figure 1. Main façade of the building (left), longitudinal section (right)

3.1 Building diagnosis

3.1.1 Energy performance simulation

Two energy performance simulation tools have been used in order to simulate the thermal behaviour of the building and the annual heating and cooling demand: PHPP and TRNSYS. PHPP, developed by the Passive House Institute, is a static simulation tool, where the climate data uses average monthly values, which causes some uncertainty. On the other hand, TRNSYS uses a dynamic calculation engine, where the simulation is developed hourly, which results in more precise results. Annual heating demand is quite similar (Table 1), although in disaggregated losses and gains there are substantial differences: transmittance losses (a 30% less in PHPP) and ventilation losses (a 30% less in PHPP), while solar gains are reduced in an 81% and internal heat gains in a 40% in PHPP compared with TRNSYS. In this sense, could be said that PHPP penalizes the calculations both in summer and winter, and this tool could not be useful for certain buildings (e.g. in buildings with low insulation level). The main difference probably lies on the considerations used by PHPP regarding climate data, where the use of average monthly data is not precise enough. Thus, while PHPP considers the ventilation air in a constant temperature throughout each month, TRNSYS considers its variation. Similarly, these considerations affect the transmittance, the systems efficiency, and, above all the solar gains, where the difference between annual average values used by PHPP and those used in TRNSYS is very different. It has been verified that using the data provided by TRNSYS in PHPP, the solar heat gains determined by both tools resemble much more.

3.1.2 Lighting simulation

Lighting discomfort was detected in the building together with an oversized lighting system. Therefore, an additional diagnosis tool for that purpose was used. In this case, a Dialux simulation was rendered. The main issue in this case is the distribution of the luminaires because they are perpendicular to the windows, thus there is not an effective use of the daylight; this distribution might provoke low performances both at comfort and energy levels. The simulation demonstrates that the comfort levels are not achieved by using less luminaries (50% in Figure 2 centre), neither having all the lighting sources on (Figure 2 left).

Table 1. Energy performance results

Heating energy balance	PHPP (kWh/m^2a)	TRNSYS (kWh/m^2a)
Ventilation	17.90	25.70
Transmittance losses	94.70	154.89
Windows	*34.60*	
Floor/slab basement	*13.20*	
Roof	*11.90*	
Ext. wall (ground)	*2.30*	
Ext. wall (ambient)	*32.70*	
Solar gains	11.60	62.72
Internal heat gains	13.00	22.23
Convection		*12.26*
Radiation		*9.97*
Annual heating demand	88.00	95.64

3.1.3 Monitoring sensor network

Monitoring is a powerful tool for the building diagnosis as it has a twofold objective: the generation of a baseline of energy performance indicators (like comfort parameters or energy measures) that can be compared with the monitoring results after the interventions, and its integration in the control strategies for the optimization of the energy systems. For the analysis of the building status, two test rooms have been selected in which the comfort conditions and the performance of the energy systems have been evaluated. The criteria for selecting these rooms are based in the existing energy systems and the replicability of the intervention strategies in the whole building and for other structures. Thus, it was selected the library as it is the only room in the building with both heating and cooling systems, used also during the summer and that presents serious comfort problems. Regarding the classrooms and laboratories, the effects on the comfort conditions (temperature, humidity and illuminance in this case) due to the different characteristics of the east and west façades, affecting also the thermal distribution system, can be analysed in the laboratory of physics, which has a configuration with windows in both façades that makes this space optimum for this kind of evaluation (Figure 2 right). In these spaces, temperature, humidity and illuminance level sensors have been installed together with occupancy sensors, in order to analyse the occupancy patterns and establish the most adequate control strategies. Apart from these comfort sensors, also electrical and thermal energy meters have been installed for analysing the energy performance of the building before and after the implementation of the efficiency strategies.

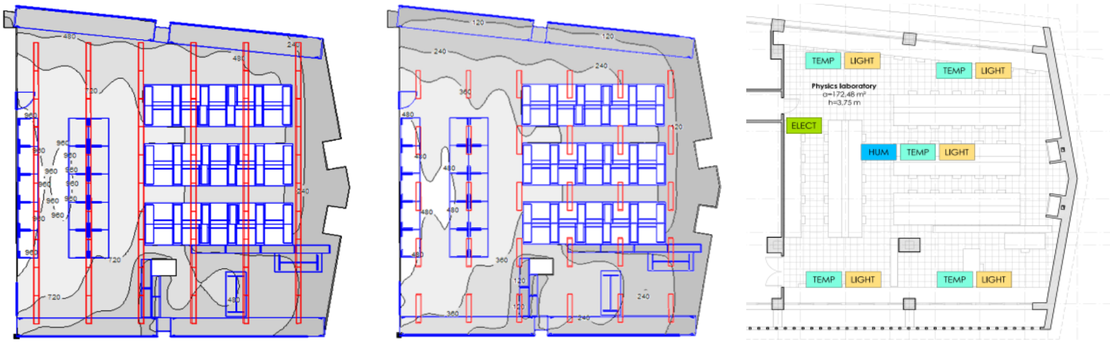

Figure 2. Lighting simulation results with all lights on (left) or half of the lights on (centre); deployment of monitoring network in the physics laboratory (right)

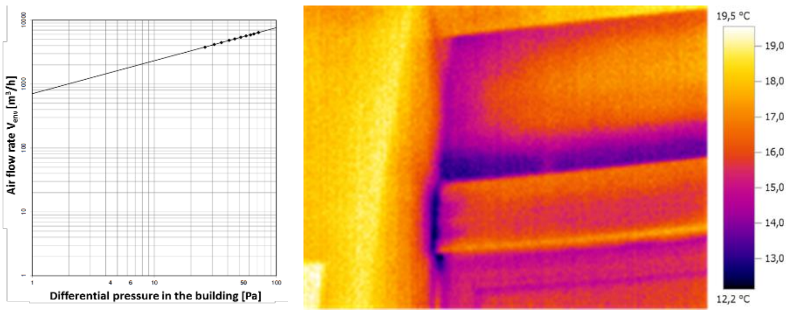

Figure 3. Blower door test results and example of IR thermography results

3.1.4 Blower door test and thermography

In all building energy performance simulation it is necessary to quantify the medium annual rate of airtightness, which normally is very different from the estimated values used in the first steps of the calculations, which are almost always optimistic. The process for determining the air permeability of the building is described in the norm ISO 9972:1996, modified, where it is explained the pressurization method with ventilator. For that the Blower Door appliance in the access door of the room and a pressurization/depressurization rate is imposed in the indoor space: the relationship among the circulating flow and some fixed pressure thresholds allows the calculation of the air changes rate per hour, with a pressure reference of 50 Pa (Figure 3 left) [3]. Complementarily, IR thermography allows the detection of air leakages (Figure 3 right). The tests results show how the building envelope presents a very low level of airtightness ($q_{50} \approx 10.0$ m^3/m2·h), due to three main points of air entrance: in the external walls, the different rigidity of the structural elements made of reinforced concrete (pillars and slabs) and the brick walls without anchoring elements, caused longitudinal cracking in the joints; the joints of the windows and blinds boxes with the walls are not sealed: in this kind of historic buildings this is due to the degradation of the sealing material but, as in this building windows were replaced recently, it makes sense to think that it is due to a construction deficiency; there is a circulating air coming from adjacent locals through the camera above the ceiling..

4. INTERVENTIONS AND RESULTS

According to the pathologies of the building, from the results of the diagnosis phase, several retrofitting strategies and solutions were proposed. Among these possibilities mainly aimed at improving the comfort of the users while reducing the electricity consumptions, owing to restrictions from the owner, two interventions were selected and carried out in two representative rooms of the building: the physics laboratory and the library. First of all, in the physics laboratory, the luminaires' circuits were re-distributed to favour the daylight taking into account the positions of the workbenches for the students. Moreover, it was installed an automatic control system for turning on and off the lights based on the luminance levels and occupancy of the room. The new redistribution, as represented in Figure 4 left, allows reaching the comfort levels by only switching on half the luminaries in the room, thus ensuring energy savings. On the other hand, the strategy for improving the comfort conditions in the library was the automation of the cooling system control. This caused comfort problems as temperature was out of the comfort range during large time periods, and increased the energy consumptions since the cooling systems, if left on, were working even when the room was unoccupied. In that sense, the new controller sets the on/off of the three fan-coils in function of the temperature the control of the velocity as well as the occupancy of the room. The control pattern for turning on/off the fan-coils activates the heating mode when the temperature is below 22ºC and the cooling mode when temperature is above 25ºC and the intermediate slot is the dead band where the fan-coil is stopped (comfort levels reached).

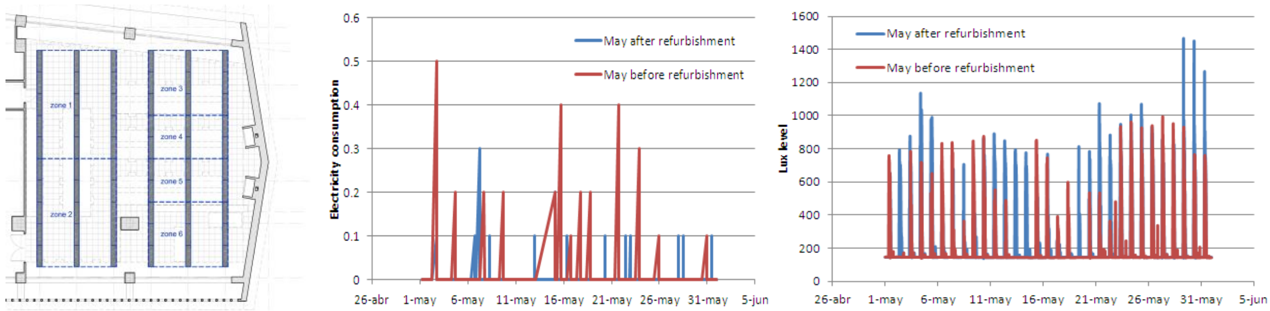

Figure 4. Physics laboratory: new distribution of luminaries (left), comparison of electricity consumptions (center) and lighting levels (right) before and after retrofitting

4.1.1 Energy and comfort improvements results

The results of the deployed solutions in terms of energy savings and comfort improvements are reported for the two test rooms. Firstly, in the physics laboratory, with the new distribution of luminaires and control based on occupancy patters, the energy consumption decreases from 15 kWh to 8.60 kWh. For example, in May, the electricity consumption is widely reduced in comparison with the non-retrofitted status (Figure 4 center). Besides, the comfort levels are also increased, reaching the minimum of 500 lux for these spaces (Figure 4 right). Secondly, in the library, both energy performance and comfort levels were improved. Figure 5 illustrates the energy consumption in kWh for one of the fan-coils per month and the temperature trends monitored in May, before and after refurbishment. As it is shown, the energy consumption is reduced from a cumulated energy of 50.90 kWh before intervention to a value of 48.80 kWh after intervention. With respect to the comfort levels, the curve after refurbishment plots temperatures lower than previously which reduces the overheating in the room. It is important to remark that there are some days where the temperature is lower than 22ºC, but it is due to un-occupancy of the room.

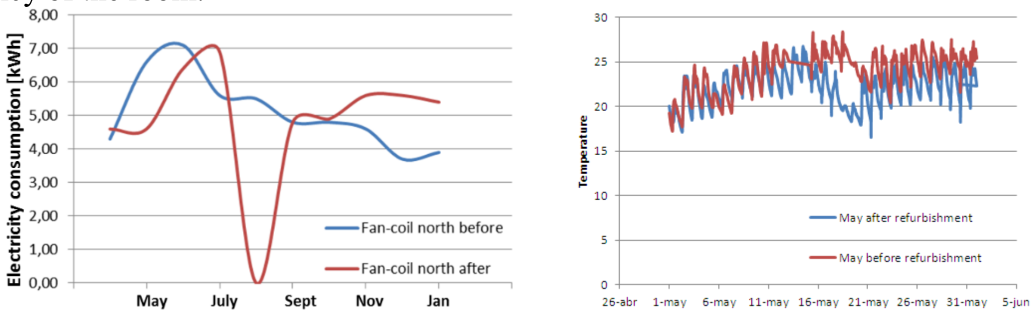

Figure 5. Post-intervention evaluation of the library: comparison of electricity consumptions of a fan-coil (left); comparison of monitored temperature trends in May (right)

5. CONCLUSIONS

In this paper the scientific based diagnostic methodology employed at the case of Engineering School of Bejàr is presented. The diagnosis has foreseen the combined application of energy simulation tools, monitoring systems and NDT to evaluate the status of the building pre-intervention, to propose specific retrofitting solutions aimed at improving energy efficiency and users comfort and to evaluate the performances of the deployed solutions after their implementation. The selected solutions based on redistribution of luminaires and automation of control systems in two rooms are low-cost and highly replicable and allowed enhancing the users comfort while reducing the energy consumptions.

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GOVERNANCE

GBC Historic Building®: a new certification tool for orienting and assessing environmental sustainability and energy efficiency of historic buildings

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Abstract – *Environmental certification represents a key issue for improving energy efficiency, environmental quality, rational use of resources, and design innovation, allowing greater transparency on energy uses and environmental management in buildings. The paper presents the new rating system GBC Historic Building®, derived from the most diffused environmental sustainability assessment method worldwide (i.e. Leadership in Energy and Environmental Design (LEED®) and developed by an interdisciplinary working group, in order to evaluate the sustainability level of restoration, refurbishment, and integration in pre-industrial buildings. The protocol is structured in the already existing categories within the LEED® rating system, to which a brand new one has been added, i.e. "Historic Value", introduced to improve the knowledge on the historic building construction and a sustainable approach throughout the restoration process.*

Keywords – Deep Renovation; historic value; energy retrofit; indoor environmental quality; rating system.

1. INTRODUCTION

In the recent years, the European Commission has decided to set up a specific legislative framework to cut the CO_2 emissions, increase the share of renewable sources, and enhance the energy and the environmental performances. As underlined in the last European Directive [1], it is very important to find effective policies not only for the construction of new energy efficient buildings, but also for existing buildings' refurbishment, also considering traditional and heritage buildings. The improvement of energy performances of architectures pertaining to the cultural heritage entails a balance between different requirements related to energy efficiency, environmental sustainability, indoor comfort, and historic values. Considering energy efficiency as an effective mean rather than an added restriction for protecting the cultural heritage [2] can lead to a conjunction between the culture of environmental sustainability and the wealth of knowledge of the restoration world [3]. In this context, environmental certification is a key issue for improving energy efficiency, environmental quality, rational use of resources, and design innovation, allowing greater transparency during all the process' phases and on environmental management in buildings, while preserving their cultural identity.

2. HERITAGE VALUE AND ENVIRONMENTAL SUSTAINABILITY: A NEW TOOL

2.1 Development process

Since the multiple factors and stakeholders involved within a conservation process, the understanding and delivery of cultural values represent and important asset for decision-making about what and how to conserve, and what are the priorities and potential threads [4]. To this regard, environmental sustainability assessment methods offer an effective model and structure in terms of reliability and transparency to be adopted to the heritage field. This understanding, together with the great potential regarding the historic building stock to be renovated at a national and European level [5], has led the Green Building Council of Italy to develop a new rating system called GBC Historic Building®, a voluntary and third-party certification tool for orienting and assessing the sustainability level of restoration, refurbishment, and integration processes in pre-industrial buildings. The tool is based on a local version of the LEED® rating system for New Construction and Major Renovation, named LEED® Italia, which, although applicable for existing buildings' deep renovation, it does not include specific requirements oriented towards to the historical and cultural values enhancement.

2.2 Field of application

GBC Historic Building® is applicable to the building stock constructed before 1945, the year that saw the beginning of the post-war reconstruction activity and the rise of the industrialization of the building process in Europe. Being "material testimony having the force of civilization" [6], this part of the stock is characterised by pre-industrial building process (in terms of phases, tasks and operators), pre-industrial materials and construction techniques (spontaneous and local), and technical elements made through pre-industrial processes. The existing building undergoing the assessment must have been built before 1945 (or after 1945 if pre-industrial features are recognised) for at least 50% of the existing technical elements measured in square meters of the front surface calculated without considering voids (windows and doors). In case the building was built before 1945 for a portion of less than 50% of the existing technical elements, the project can be assessed through the already existing rating systems pertaining to the LEED® or GBC® family. In addition, it is to be noticed that the protocol can be used for projects seeking restoration, rehabilitation or recovery/integration processes, which must entail a major renovation, defined as action which involves significant elements of HVAC systems and the renewal or functional reorganization of interior spaces, evaluating the possibility of a building envelope performance improvement consistent with the preservation of the cultural, architectural, and construction features.

2.3 Structure of GBC Historic Building®

In GBC Historic Building® a new topic called "Historic Value" has been introduced beside the already existing LEED® thematic areas to make the rating system bespoke the historic context. Therefore, the protocol is structured in the following categories:

- “Historic Value - HV” (20 points): it pays close attention to the principles and different stages of the restoration process, while improving the overall environmental performances;
- “Sustainable Sites” (13 points): it encourages strategies for regenerating damaged areas, minimizing retrofit and building impacts, and promoting alternative transportation;
- “Water Efficiency - WE” (8 points): it stimulates a smarter use of water and its conservation holistically, considering indoor, outdoor, and specialised uses, as well as promoting metering;
- “Energy and Atmosphere - EA” (29 points): it approaches energy performance improvement from a holistic perspective, considering energy efficiency as a protection tool;
- “Materials and Resources - MR” (14 points): it minimises impacts associated with the extraction, processing, transport, maintenance, and disposal of materials, as well as the embodied energy;
- “Indoor Environmental Quality - IEQ” (16 points): it aims to achieve high standards of indoor air quality and thermal comfort for the occupants;
- “Innovation in Design - ID” (6 points): it rewards design solutions that are distinguished by the characteristics of innovation and high environment performance within the conservation process;
- “Regional Priority - PR” (4 points): it encourages design teams to focus on the environmental characteristics that are unique and specific to the region in which the building is situated.

All topic areas are made by prerequisite(s), which are mandatory, and credits, which are voluntary and rewarded with points. The distribution of scores, like other LEED® protocols, is focused on the effects of each credit on environment and human health, compared to a set of “impact categories”. The sum of the achieved points defines the level of certification attainable by the project, i.e.: i) “Certified”, from 40 to 49 points; ii) “Silver”, from 50 to 59 points; iii) “Gold”, from 60 to 79 points; iv) “Platinum”, from 80 to 110 points.

3. RECOGNITION OF HISTORIC VALUE AS A SUSTAINABILITY PARAMETER

In terms of sustainability, it is necessary to design intervention on historical buildings closely to the monumental heritage they carry and without compromising the real and potential wealth in the context in which we are asked to get involved. If sustainable development is the “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [7], this ‘potential’ has to be kept in order to make future generations benefit from it. This process depends on multiple interdependent dimensions: environmental, economic (long term), social and, above all, cultural. Therefore, restoration, as the “methodological moment in which a work of art is appreciated in its material form and its historical and aesthetic duality for its transmission to the future” [8], becomes a sustainable ‘action’ itself, thus assessable through tools and methods pertaining to the sustainability context. Humanity has always dealt with the issue of maintaining, repairing, restoring effectively and/or adapting to new functions related to the continuously changing needs [9]. In the past few decades, technological-related literature has highlighted with a certain insistence that the behaviour of pre-industrial humanity could be called ‘sustainable’ as it was particularly focused to the consumption of raw materials and energy. It is often noted that regaining such behaviour could represent today a step towards a sustainable approach to development. Actually, it is incorrect to speak about the sustainability of pre-industrial humanity, because the use of techniques which allow an effective economy of resources is not motivated by the attribution of value to the resources themselves, but by their mere economic determination as a 'scarce' resource. We can speak of sustainability in the modern sense only when the sustainable action has the goal of preserving the resource whose value is recognised in view of its preservation for future generations. These are two very distant goals: in the past, preservation of resources stemmed out from their shortage at the time and because of a recognised short-term economic potential within them; on the contrary, today, resources preservation is the result of their foreseeable shortage in the future, although their preservation in the present may turn out to be economically unfavourable. Therefore, the concept of 'environmental sustainability' qualifies maintenance (intended as preservation) with respect to an already existing potential (i.e. an equilibrium between already existing potentials) whose environmental value is recognised. The concept of 'cultural sustainability' qualifies maintenance (intended as preservation) with respect to a pre-existing structure (i.e. an equilibrium between pre-existing structures) whose cultural value is recognised. It is then possible to assert that restoration, in the modern sense, identifies a sustainable action, from a cultural point of view, with respect to pre-existing monumental heritage, whose cultural value is recognised. To this regard, GBC Historic Building® is an innovative tool that, in addition to answering the needs of the market to meet high levels of well-being for users, sees restoration as the first sustainable action that concerns the pre-existing structure whose cultural value is recognised. It is precisely the holistic approach that characterises the LEED®/GBC® tools that the new rating system seeks to achieve, maintaining and transmitting the building in both its physical form and cultural values it represents to future generations. The choice of restorative actions is founded on a series of principles developed from the late 19th century up to the latter half of the 20th century. In the new topic area "Historical Value", the operational principles largely shared in the realm of restoration (such as minimal intervention, distinguishability, reversibility and compatibility) were expressly integrated for giving the designer a useful guide for intervention on pre-industrial constructions.

For a wider sustainability and for not compromising the authenticity of the subject (in material, structural and figurative terms), the intervention must be carried out through the "minimum intervention" to preserve the material, restore the image, and functionally renovate the asset. Even the structural improvements or integrations must be designed under this perspective, without introducing elements that are not strictly necessary. This principle is the basis of the preliminary analysis (HV prerequisite 1) and advanced analyses (HV credits 1.1, 1.2, and 1.3). Related to the previous one is the principle of "reversibility" of the project's works. The purpose is to allow future generations, who may potentially avail of different and more advanced technologies than our own, to get involved with a greater degree of conservation and in a more respectful manner than the current approach. To this regard, HV credit 2 should be read in favour of either traditional or contemporary techniques to ensure both authenticity and aesthetics. The principle of "compatibility", which concerns the durability of the work for posterity, can be applied to various elements that range from the ways in which the asset can be used (HV credit 3.1), to the materials used for the restoration of architectural surfaces (HV credit 3.2), and for structural consolidation (HV credit 3.3). The attention given to the "durability" of the restoration is also confirmed by the importance given to the scheduled maintenance plan (HV credit 5). To make it consistent with the asset's requirements (both environmental and conservative), the preliminary compilation of a specific risk assessment sheet has to be provided. Not at least, the elements related to the sustainability of the restoration site (HV credit 4), which is identified as the third and final stage of the process, with important and significant repercussions in terms of environment, economics and culture.

4. THE CHALLENGE OF HISTORIC BUILDINGS' ENERGY RETROFIT

The approach has a strongly interdisciplinary nature, starting from the analysis of different thematic areas related to restoration, energy efficiency, and human comfort. Similarly to other LEED® protocols, the energy and environmental retrofit is focused on building level, considering also the main effects on district level. The "energy issue" is directly and indirectly addressed in different areas.

4.1 Topic "historic value"

Understanding the environmental behavior of a historical building is essential to identify possible modifications or operational solutions for improving its performance. Particularly, energy and environmental evaluation allows to optimize the energy efficiency level and to foster environmental sustainability, preserving and enhancing the positive qualities of a pre-industrial building. An accurate energy audit is the first step to identify the suitable energy retrofit intervention. It is «[…] a systematic procedure to obtain adequate knowledge of the existing energy consumption profile of a building […], identify and quantify cost-effective energy savings opportunities and report the findings» [10]. As stated by literature [11] and American standards [12], the protocol asks for different types of energy audit according to the analytical level to be obtained: i) "walk-through audit", for assessing the general energy quality and individualizing the inefficiencies; ii) "standard audit", for quantifying the energy loses linked to a specific issue; and iii) "simulation audit" that provides a dynamic simulation of the energy performance of the building. The "walk-through audit" is mandatory to understand the energy behavior of the building. The scheme includes also on-site measurements and None Destructive Testing to quantify energy use and performances. The IR-Thermography is suggested to reveal the most important thermal anomalies on building envelope and systems and it is useful to detect the presence of thermal bridges, non-homogeneity (different thicknesses, traces of arcs or other components, low performances, missing of insulation, different materials, etc.), damage (decay, cracking of plaster, moisture, water percolation, air leakages from windows and cracks, and losses) or malfunctioning of installations and plants (missing of insulation on boilers, high consumptions, malfunctioning, etc.). In parallel, the heat flow-meter measurement permits to determine the thermal transmission properties (C-value and U-value) on a representative part of the building envelope. Then, the criteria of reversibility and compatibility should guide the choice of the energy and environmental retrofit. Similarly, the implementation of a planned conservation plan is considered as a tool for guaranteeing the maintenance of the building, also looking at energy efficiency (HV credit 5).

4.2 Area "sustainable sites"

The fundamental aspects responsible for the improvement of the liveability and the quality of the urban environment that have an impact on the energy issue are related to: i) the enhancement of public and alternative transport; ii) the recovery of high-permeability open spaces; iii) the reduction of the "urban heat island effect" phenomena, by using passive techniques with low aesthetic impact; iv) the rationalization of the illumination system, reducing the intensity of light pollution.

4.3 Area "energy and atmosphere"

Energy efficiency and retrofit process represent a practice for guaranteeing the building protection, not necessarily a "change" in the original material consistency. The possible design and management strategies in the topic are related to:

- energy commissioning of systems (fundamental in prerequisite 1 and enhanced in credit 3), moving also towards the envelope's commissioning as a technique for improving the knowledge and respect for the building;
- improvement and optimization of building energy performances (minimum in prerequisite 2 and optimised in credit 1) compared to a "reference case" defined in the historical context and considering all forms of energy consumption, rather than upgrading to a minimum standard energy performance. This approach is based on the consideration that each improvement on the historic building, although modest, is considered an important step for increasing the occupants' comfort, reducing the energy consumption, and cutting the greenhouse gas emissions. The evaluation can be conducted either by using static methodologies (obtaining at least an improvement of 5% of the initial energy consumption basing on the national standard) or dynamic methodologies (obtaining at least an improvement of 3% basing on the ASHRAE American standard [12]);
- integration of renewable energy sources (credit 2) produced on-site or resulting from certified off-site green energy production;
- refrigerant management (minimum in prerequisite 3 and enhanced in credit 4);
- measurements and verification of the consumption in operation (credit 5).

4.4 Area "indoor environmental quality"

The achievement of high standards for thermal comfort and air quality for occupants in historic buildings has to balance the requirements for the protection and enhancement of cultural heritage. Moreover, the high artistic and cultural value does not often allow the inclusion of plant terminal units or substantial intervention on the technical elements. For this reason, this topic is structured in two parts, respectively related to the conservation and preservation of historic architecture, and respect of thermal comfort and indoor air quality for the occupants. This dual approach allows the user to respect the historic environment for the protection of surfaces and high-quality materials and, at the same time, to achieve the highest levels of comfort and indoor air quality exploiting the potential offered by the boundary conditions. The possible design and management strategies in the area are related to: i) the improvement of the internal air quality; ii) the indoor pollution control; iii) the hazardous materials reduction; and iv) the control of indoor air quality for the occupants.

5. CONCLUSION

In front of the increasingly urgent need to adapt historic buildings to new uses by upgrading their overall performances, the transparent process of the third-party certification could represent a valuable mean for orienting the building sector towards a sustainable market transformation. GBC Historic Building® is a new Italian rating system born to tackle the issues connected to the integration of environmental, energy efficiency and indoor environmental quality objectives within the restoration process. The tool's aim is to support stakeholders to plan all building process phases in an effective and holistic manner, pursuing a conscious and sustainable preservation process which will allow the historic building to remain a source of cultural identity while meeting today's needs. The protocol has been released in 2015 and it is currently undergoing a pilot period for its validation through the application to real case studies in Italy, which will contribute to the tool's implementation for the local market.

6. ACKNOWLEDGMENT

Paragraph 2 and 5 are authored by Paola Boarin. Paragraph 3 is authored by Marco Zuppiroli. Paragraph 4 is authored by Elena Lucchi. Paragraph 1 authored by all the authors.

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The impact of the energy efficiency regulation on residential built heritage – the case of Gros District in the city of San Sebastian -2010/2015

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Abstract – *Since the first European regulation on the energy performance of buildings was adopted in 2002, it has been a priority for the EU to improve the energy efficiency of the building stock of European cities. Part of these cities is made up of historical districts, and we can find that many of the buildings of these districts represent the residential built heritage. In Spain, the European regulation started to be applied some years later, in 2010. After five years, it may be time to analyse the impact of applying these laws on the historical city, as in this study of Gros District of San Sebastian. In this evaluation, the results of applying the regulation in existing buildings have been taken into account, as well as the energy gains achieved, and the impact on the architectural composition of this residential built heritage.*

Keywords – Residential; built; heritage; energy; regulation

1. INTRODUCTION

One of the main problems that humanity faces in the early twenty-first century is the excessive energy consumption and the consequences that may result from it on the environment. One of the first sectors to have an impact on it is the construction sector. As a consequence, the European Union has recently approved some new regulations to reduce the growing energy consumption in buildings. Taking into account all the building stock, the majority are existing residential buildings, and a large part represents the residential built heritage. Some of these buildings are protected by current laws, whilst others are not yet. To achieve the energy gains established by the EU, a holistic energy intervention must be done in those buildings. The application of this energy policy could have a deep impact on residential built heritage. For this reason, and because this intervention has already started, this study focuses on the application of the energy efficiency regulations adopted in Spain in recent years regarding the residential built heritage. It has been eight years since the first regulation concerning energy efficiency in buildings was approved. Furthermore, in the case of the city of San Sebastian, in the Basque Country, another local energy regulation was approved in 2009. In this law the requirements of reducing energy consumption on buildings was increased with respect to the Spanish one. This study and the results achieved until now in Gros District of San Sebastian may represent what will become the future of a part of European cities.

2. BUILT HERITAGE AND ENERGY REGULATION

Since the EU acquired the commitments in the Kyoto Protocol in 1997, one of its priorities has been to reduce energy consumption in buildings. In this regard, the first regulation of reference on energy efficiency in buildings was approved in 2002, namely Directive 2002/91/CE [1]. For the first time, this Directive addressed the need to improve energy efficiency in newly constructed buildings and in existing buildings if they had a surface area of more than 1000 m^2. Buildings that had some kind of official protection were excluded from this requisite. This Directive was transposed to Spain through two regulations, RD 314/2006 [2], which approved the Technical Building Code (CTE), and RD 47/2007 [3] which regulated the need to certify the energy efficiency of buildings. Later on, the second European regulation related to energy efficiency of buildings, Directive 2010/31/EU [4], was approved. In this Directive, the parameters of the previous Directive were reviewed, and the energy saving requirements demanded for buildings were increased. With regards to existing buildings, it no longer depended on the surface area of the building, and any intervention on any element of the building envelope sufficed to be obliged to improve its energy efficiency. In Spain, this resulted in the creation of two new regulations, the review of the CTE via Order FOM 1635/2013 [5] and RD 235/2013 [6] relating to the certification of energy efficiency of buildings. Both of these included the decisions of the European Directive with respect to the need for energy improvement in any intervention carried out on the envelope, providing this was technically and economically feasible. Finally, in 2012, European Directive 2012/27/EU [7] was approved, which laid the bases to foster the energy retrofit of building stock. A result of the transposition of this Directive was the approval of Law 8/2013 in Spain on Urban Rehabilitation, Regeneration and Renovation [8]. Finally, San Sebastian City Council approved an energy regulation in 2009, which required buildings, in addition to having an energy certificate, to have a minimum Energy Qualification [9]. In all these cases, despite the increasing promotion of energy intervention in existing buildings, officially protected buildings, or in other words, the built heritage, were excluded from compliance with these laws. On the other hand, buildings that are excluded from this official protection are directly linked to energy improvement, whenever any type of intervention is carried out on its envelope, and without taking into account the result of it on its architecture.

3. GROS DISTRICT OF SAN SEBASTIAN

The Gros District of San Sebastian has been selected to conduct this study, because, despite it is not the old town of the city, it does form part of the development of the historical centre. This part of the city is less known than the Ensanche Cortazar [10], developed in the 19th century, but it is as well a consolidated district developed in the late 19th century and the early 20th century. Despite the fact that not all the complex has official protection, it does have some characteristics that mean it should be considered as part of the consolidated historical city. The most important characteristic is the large amount of protected residential built heritage that it contains.

From an urban development viewpoint, Gros District is similar to many "ensanches" or new suburbs of other European cities carried out throughout the 19th and 20th centuries. This district gradually went from being an industrial suburb to become a residential area of the city centre. The existence of a previous industrial settlement, made the district urban development progressive, resulting in different residential building styles. Its morphology is made up of a series of enclosed blocks with an inner courtyard. Practically the entire urban complex is for residential use, and only some tertiary buildings complete the district. The building typology is comprised of the different construction types that were developed during the end of the 19th century and the end of the 20th century. These characteristics confer great wealth on building architecture and construction systems. As a result, a great number of these residential buildings are protected by current laws from a heritage viewpoint. Among these buildings, the most noteworthy from a residential built heritage viewpoint, are those developed during the end of the 19th century and the first half of the 20th century. Thus, we can find nineteenth-century style buildings as well as buildings from the first Rationalist movement. These are the constructions that are mainly protected by the local legislation. However, buildings from later periods, such as the Post-War or Policy of Development of the 60s, also have architectonic features that have a special interest. These buildings, however, are not protected. The legislation that covers the protection of this heritage is the Special Protection Plan of Constructed Urban Heritage of San Sebastian – PEPPUC [11]. The buildings that are protected by this PEPPUC represent more than half the existing buildings in Gros (55%). The type of protection in these buildings is in most of the cases the conservation of the main facade, leaving the possibility to act in the rest of construction elements. On the other hand, and from an energy viewpoint, it has the quality of a compact city, where the percentage of surface area of each building envelope is much less than that of isolated buildings of a dispersed city.

Figure 1. Residential built heritage in Gros. Source: Author

4. THE IMPACT OF ENERGY REHABILITATION ON GROS DISTRICT

If we analyse what has happened over the last few years in the case of Gros District, insofar as the approval of the energy regulation and its application in existing buildings and residential built heritage, it could give us an idea of what may await us in the future. Thus, it is important to analyse the results from three viewpoints: how the approved regulation has been applied; which energy achievements have been applied during the period analysed; and finally, observe if this energy intervention has had an impact on the residential built heritage. The time interval, 2010 to 2015, has been selected for this study, analysing the files of licenses granted by San Sebastian City Council for the rehabilitation of facades in Gros District. Hence, we can see the number of licenses that have been processed, how many have been solely for the rehabilitation of pathologies, and how many have addressed energy rehabilitation. On the other hand, we can count how many of these energy interventions have been carried out on protected buildings and what have been the consequences of these rehabilitations.

4.1 Analysis and results - 2010/2015

To obtain these data, 112 files of licenses to intervene on facades during the period 2010-2015 by San Sebastian City Council have been analysed. If we bear in mind that Gros District is comprised of 404 residential buildings, and if 112 types of licenses have been processed for interventions or rehabilitations on facades, the result is that over this 6-year period, more than 25% of the residential building stock of Gros have been intervened in some way. If we analyse the types of intervention carried out, we can see that only 22 of the 112 files refer to energy rehabilitation, and all of them were carried out from 2012 onwards, mainly in 2014 and 2015. The rest of the interventions were only rehabilitations to repair pathologies. With respect to the impact of these interventions on the residential built heritage, only three have been required to obtain the rehabilitation license and only two of them carried out to date. These, like the interventions carried out on non-protected buildings, have been granted over the last two years.

Figure 2. Residential built heritage in Gros and rehabilitation on protected and non-protected buildings, 2010/2015. Source: Author

Table 1. Energy rehabilitation in residential built heritage in Gros District.

Year	Files	Energy Rehabilitation	Energy Rehabilitation in Built Heritage
2010	21	0	0
2011	19	0	0
2012	19	3	0
2013	15	2	0
2014	21	10	2
2015	17	7	1

4.2 Energy rehabilitation cases

The three licenses requested for the energy rehabilitation in built heritage are located in Usandizaga 3, Paseo Colon 17 and Avda. Zurriola 22. The first two licenses were asked in 2014, while the third was asked in 2015. The request of the rehabilitation license for Zurriola 22 was refused because the solution that it proposed was based on the insulation of the main facade with a SATE (Exterior Thermal Insulation System). This means that even if the facade was protected by the PEPPUC, the original facade turned out covered. In the other two cases, Usandizaga 3 and Colon 17, both protected in its main facade by the PEPPUC, the energy rehabilitation solution not impinged on the protected elements. What was proposed for both cases was to isolate the unprotected rear facade with the same constructive solution, a SATE system. Once they granted the rehabilitation license, the works were carried out. Energy improvement achieved by this energy rehabilitation was partially achieved in both cases, Colon 17 and Usandizaga 3.

Figure 3. Buildings of built heritage of Gros District that requested license for energy rehabilitation. Zurriola 22, Colon 17 y Usandizaga 3. Source: Author.

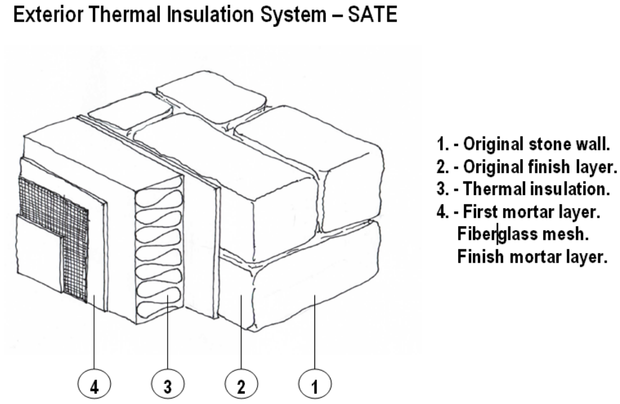

Figure 4 and 5. Rear facade of a building in Gros District and the construction detail of a SATE system (Exterior Thermal Insulation System). Source: Author.

5. CONCLUSIONS

First, we can say that even if the energy regulations in Spain are being applied since 2010, as far as Gros District is concerned, the legislation has not started to be entirely applied until 2014. This means that there are very few energy achievements to date and no conclusions can be drawn. We must wait for a few more years to be able to observe the consequences of applying the energy regulation on residential built heritage

Regarding the energy improvement achieved in Gros district during the period 2010/2015 we can say that despite having acted in 112 buildings, no more than 25 of them have been rehabilitated from an energy point of view. That means only 7.5 % of total building stock of Gros District. What refers built heritage, energy achievements are even lower. Actually only in 2 cases there was energy rehabilitation, and in those cases the intervention was made only partially. Regarding energy achievement it is therefore, a poor background.

Regarding the impact on the residential built heritage, energy rehabilitation has only been carried on a few protected buildings. To date, there are more interventions on built heritage to repair damages (51 from the 112 licenses) than to improve energy performances (3 cases). From these 3 licenses requested, only 2 granted the rehabilitation license, and in these cases, the energy rehabilitation was carried out partially. The elements protected by the current law, as the main facades, are exempt from the energy rehabilitation. As a result, energy rehabilitations on built heritage carried out in Gros are partial interventions that conserve the built heritage but that achieve medium energy performances.

Finally we can conclude that despite being yet soon for drawing conclusions, we can foresee what the trend may be. In fact, energy rehabilitation only impinges on unprotected elements of the buildings, leaving untouched the protected elements. This means that the current energy regulation will be implemented; built heritage will be practically conserved as we know it today, but energy improvement will be partially achieved. It seems that something more can be done about improving energy achievement and conserving built heritage as current regulation requires to date.

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Energy performance certificates and historic buildings: a method to encourage user participation and sustainability in the refurbishment process

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Abstract – *By correlating findings from research projects LEAF and CulClim, this paper aims to present and discuss a method to include owners and users in the post-EPC refurbishment process of historic buildings. Case studies from Norway and Sweden, with conceptually contrasting energy performance certificate (EPC) systems, are used. Identified advantages and shortcomings concerning both systems are discussed. In Sweden, the restrained recommendation of measures can lead to national mitigation targets not being realised. In Norway, excessive and unqualified recommendations risk reducing the cultural heritage values of the existing building stock as well as having negative environmental impact on greenhouse gas emissions. A bottom-up approach incorporating the resident's objectives is presented and discussed. Results suggest a broadened procedural method can support the post-EPC decision making process of carefully refurbishing historic buildings on short and long term without altering the historic character.*

Keywords – Apartment blocks; historic buildings; EPC; decision support; resident involvement

1. INTRODUCTION

Improving energy performance in buildings is needed to reduce energy dependency and greenhouse gas emissions. The European Energy Performance of Buildings Directive (EPBD) [1] promotes this matter by driving member states to establish necessary energy requirements. In addition to national energy requirements, energy efficiency measures are promoted by Energy Performance Certificate (EPC) systems. These are designed to provide the owner, the prospective buyer or tenant of a building or apartment correct information about the energy performance of the building and practical cost-effective advice on improving its performance. Improving the energy performance of historic buildings in particular is a balancing act between heritage significance and energy efficiency measures. This aspect distinguishes working with such buildings from working with the building stock in general.

The aim of this paper is to shed light on the problematic relation between EPCs, historic apartment blocks and the implementation of energy efficiency measures. It also aims to present and discuss a bottom-up method that can be used as support in the decision making process of carefully refurbishing historic apartment blocks. The structure of the method is proposed on the basis of findings from two research projects on one hand, and the drafted procedural guidelines for improving the energy performance of historic buildings [2] on the other.

The paper draws on findings from two research projects. The ambition of Norwegian project Cultural Valuable Buildings and Climate Change Responses in a User Perspective (CulClim) is to elucidate user relevant knowledge on the topic of climate change, energy efficiency and historic buildings. The investigation of how users can implement non-intrusive energy efficiency measures in historic buildings is in particular focus. A historic apartment block in a conservation area of Oslo is used as a case study for both technical surveys and interviews with owners and residents. The apartment block consists of two buildings. Low Energy Apartment Futures (LEAF) is a European-wide project aiming to improve the energy efficiency of apartment blocks. The project is funded by the EU's Intelligent Energy Europe programme and local organisations in each country. LEAF aims to overcome a number of key barriers to retrofitting such as the limitations of Energy Performance Certificates (EPCs) and difficulties associated with buildings under multiple ownerships. The project has developed a toolkit that provides a step-by-step approach to retrofitting apartment blocks. In Sweden four case studies on apartment blocks in Visby have been carried out, piloting the toolkits. The buildings are all located in the UNESCO World Heritage Site and therefore restrictions apply due to cultural values.

1.1 Case studies

The case study buildings in both countries were constructed between mid-19th century and early 20th century. They are brick buildings or a combination of brick and timber. The case study buildings are all situated in conservation areas, where restrictions for cultural heritage preservation apply. The restrictions prevent significant exterior alterations and some internal. In Sweden the four case study buildings are smaller apartment blocks (9–16 apartments) owned by cooperatives, each resident owns a share in the cooperative and thereby the right to live in the apartment. The residents pay a monthly fee to the cooperative, which covers the costs of the centralised heating and hot water, interests and instalments on the cooperative's loans, maintenance and taxes, among other things. The fee is normally determined by the apartment size, and usually set year by year depending on the cooperative's budget. In Norway the two case study buildings consist of 16 apartments. Any issues concerning the centralised hot water system and façades, roofs, windows and entrances, courtyard, stair cases and cellars are managed by a board of representatives. All apartments are owned individually as properties. The heating is decentralised and most commonly direct electric heating. Each apartment unit covers its own heating fees.

It is well known that apartment buildings, where more stakeholders are involved in the decision making, are generally more challenging with respect to the energy efficiency process [3]. Adding to this is a common lack of knowledge on potential savings and benefits, environmental impact, payback expectations and existing regulatory and planning issues [4]. In order to reach energy targets through building refurbishment, incitements, policy instruments and objectives must be entrenched among the owners. When there are cultural heritage aspects to be included, the process is even more complex. To overcome these and other barriers in retrofitting historic buildings, the value of user engagement and raised awareness has been underlined [5, 6] but the lack of empiric findings calls for intensified research activities.

2. ENERGY PERFORMANCE CERTIFICATE SYSTEMS

2.1 EPC in Sweden

The Swedish EPCs are conducted by certified private energy consultants and paid for by the house owners. In the EPCs the measured energy data provides the basis for all calculations, with very few exceptions. If measured energy data is unavailable the experts can calculate the energy performance according to their best knowledge. It is also up to each certified consultant to decide on conversion factors, division of energy use and standardised values. The climate data, for comparing the energy use with the climatically normal year, is provided by the responsible authorities. Since 2014 the Energy Rating is shown with the letters A-G on a multi-coloured scale, which is very common in Europe. The rating in Sweden is based on how the building performs compared to the demands on new buildings. New buildings performing according to the legislation, or a little better, will get a C, many older buildings will normally receive an E or an F.

Recommendations on how to improve the energy performance of the buildings are provided by the energy consultant if she/he can find any. It is not allowed to recommend measures that are not cost effective, and measures that might compromise the character of protected historic buildings are also prohibited. The cost effectiveness, a way to measure the profitability, is calculated by the consultant and is based on several different factors, such as interest and discount rates, energy price trend, economical life span of the measure, investment and maintenance costs, it is presented as "cost per kWh". So far around 580 000 EPCs have been conducted in Sweden. This includes dwellings (apartment blocks and single-family houses) and public and commercial buildings with other purposes. There is no system for controlling the outcome of the EPC in terms of suggested measures being implemented.

2.2 EPC in Norway

Conversely, the Norwegian implementation of the EPBD provides a service on different levels of detail developed specifically to make homeowners conduct the EPC themselves. The two main methods "simple EPC" and "detailed EPC" are both provided as online free-of-charge systems. Instead of using measured data, the user provides basic building or apartment information, e.g. size, age, heating system etc. This input is in turn linked to a reference dataset with predefined information about U-values, coefficient of performance etc., and used to estimate the energy performance of the dwelling. A third chargeable option is called "Expert EPC". Expert EPCs are conducted by certified private energy consultants and generally provide a higher level of accuracy. Yet statistics show it is nowhere near the impact of the two simpler methods. The energy rating is, similar to the Swedish system, shown with the letters A-G scale which is determined by defined intervals between 80 kWh/m2/a and upwards. A building constructed in accordance with modern energy requirements would normally acquire a C. It is also illustrated how much of the heating is estimated to come from non-renewable sources.

Recommendations on how to improve the energy performance of the buildings or apartments are automatically provided on the basis of the user input. Recommendations are general rather than specific and do not consider cost-effectiveness, technical compatibility or historic character. Instead they address any point of refurbishment potential. The user is for instance always advised to install new windows if their performance does not reach modern minimum requirements. To support increased use of "energy efficient" building components, Enova, a public enterprise owned by the Ministry of Petroleum and Energy, offers financial support to households that implement some of the recommended measures. Information on how many EPC recommendations that have been followed-up is not known, but the figures can be seen in light of how ca. 40 000 apartment-specific EPCs were conducted in 2015 [7]. Approximately 300 000 single family dwellings and 250 000 apartments (of a total of 2.5 million households) have had EPCs carried out since the system was first introduced in late 2009.

2.3 Discussion: risks and benefits with current systems

The system can be considered efficient in terms of reaching out, in both countries as many buildings have had the EPC made. The Swedish system has been criticised for generating few energy saving recommendations, which are often general and do not save much energy [8]. The consequences of the Norwegian system, where many recommendations are irrelevant, could lead to unsuitable measures being implemented. But it seems more like both system have the opposite effect; few measures are being implemented [7], especially in historic buildings. It may be that too few recommendations lead to an idea that "nothing can be done" and too many might lead to a difficulty to see what is actually feasible. This is a risk especially when it comes to apartment blocks with these types of ownership models, and particularly when the buildings have some sort of heritage designation. The cooperative owner (i.e. Sweden) or the board of members handling the common interests of the building (i.e. Norway) normally do not have the knowledge needed to bring forward retrofit work. This indicates there is a need for procedural information and guidance, as well as methods to reel in the needs of the residents.

3. CASE STUDIES

3.1 Method and approach

The case study buildings were chosen because of how they are representative regarding their age, size, ownership model and how none were in impending need of refurbishment. They also had similar restrictions regarding the preservation of exterior elements. Parallel to conducting a technical survey of the buildings, a questionnaire was distributed to the residents in order to establish baseline before a potential energy refurbishment process. This gave the residents the opportunity to, in an early stage of process, be involved in the investigation of identifying needs, priorities and general objectives. Questions (both yes/no, multiple choice and scaled questions) circled the following subjects:

- Perceived IEQ conditions during the last winter/summer
- General knowledge about the purpose of EPCs
- Maintaining a building's historic character

- Priorities when implementing energy efficiency measures: improving IEQ, reducing costs for heating, improving energy behaviour, preserving historic character, etc.

3.2 Main perceived barriers to carrying out energy efficiency measures

3.2.1 EPCs in the case studies

In the Oslo-case, a simple and thus the most common form of EPC was conducted for one apartment. It was assumed the results would be similar for the other apartments since heating system and building construction are the same. Results showed poor energy performance equivalent to F and ca. 500 kWh/m^2/yr. Recommended measures included added insulation to thermal envelope, new windows and doors, a heat recovering ventilation system, new kitchen appliances and programmable radiators. In the Swedish case studies all buildings were rated F in the EPC. This means the energy performance is between 181 and 235 % above the demand on energy performance of a new building, in these cases varying between 115 and 195 kWh/m^2/yr. Recommended measures included loft insulation, new heat circulation pump, hydronic balancing and new thermostats.

3.2.2 Results from questionnaire

The structure was divided in two parts regarding the building and the apartment respectively. In Norway the questionnaires had 16 respondents from all 16 apartments. Identified concerns regarded draughty windows and doors (69 %) and difficulties to control the indoor temperature during heating season (40 %). Meanwhile, main priorities were the lowering of heating costs (81 %) and dealing with humidity problems in the cellar (75 %). When asked about barriers for realising upgrade projects, the majority meant there was a lack of knowledge regarding possible measures and energy savings (87 %), as well as challenges to agreeing on common goals and decisions (75 %). 75 % did not know whether the building or their apartment had a valid EPC. 75 % found it moderately or very important to respect the historic character of the building. Residents in the Norwegian case study pay their own heating bills and hardly face any short- or mid-term economic profit from installing a centralised heating system. In order to reduce the heating demand, measures should instead address simpler measures such as draught proofing of windows and doors. However, this is not information that is brought forward in the EPC recommendations. It instead suggests the installation of new windows, which not only is a measure that does not necessarily pay off, but in turn will risk being incompatible with the historic character. To know what is needed, a building specific investigation is required.

In Sweden the questionnaires had 31 respondents out of 47 apartments. The main problems were draughty windows and uneven temperatures during heating season (52%). Their priorities were generally energy saving and improved comfort. The main barriers identified by the residents for implementing energy efficiency improvements were lack of financial means and lack of information on technical solutions and energy saving potential. Very few residents in the case study buildings had seen the EPC and expressed their opinion on it, only one or two in each building. Comments on the EPC showed a lack of understanding towards its two most important features; the energy rating and the recommended energy saving measures. Also, recommended measures were generally considered "slightly useful" or "not useful". There was a clear demand for further information on investment costs of the recommended measures. Residents in the Swedish case studies pay a monthly fee that covers heating, hot water and all other expenses the cooperative has. The cost for heating and hot water is not specified in the bill and saving on it will not make a difference in the fee. An extensive renovation or retrofit would rather increase the monthly fee, since the cooperative would need to pay for the works. In the long run the cooperative will benefit from it, but this will probably not mean the monthly fee will decrease, but rather not be raised for a few years (when the immediate costs have been paid). Of course it is in all members' interest to keep the building in good shape for the sake of marketability of apartments. However, what the residents notice immediately is improved indoor comfort and that is what motivates the implementation of energy efficiency measures according to findings in this study.

4. DISCUSSION

While the Swedish EPC shows only cost effective recommendations, findings from the case studies indicate that economic saving is not necessarily the only important parameter in the case of cooperatively owned historic apartment blocks. Pay-back time will obviously play a significant role in the decision-making process, but to encourage stakeholders to implement the recommended measures, it is suggested that the EPCs supplement cost-effective measures with information on other benefits related to the measures. Furthermore, with the current mandatory information on recommended measures being a ticked box with the name of the measure, calculation on energy saving (kWh), cost per saved kWh and a description (which can be more or less extensive depending on the consultant) , one can argue that it does not live up to the purpose of providing practical information[8]. The reason is that the cost per saved kWh is based on calculations on investment and maintenance costs, current and future energy price, interest rates, life-span of the measure and other factors. The consultant however, rarely present the numbers used in the calculation. According to the LEAF and CulClim findings, residents and owners ask for explicit information on energy savings, investment costs and running costs since this will help them compare the calculation in the EPC with real tenders when the renovation process is started. Considering this, the two systems can most certainly make use of solutions from each other's systems. The Norwegian system for instance, contrary to the Swedish, does provide general information about several possible measures while specific cost- or kWh-related benefits remain unknown. Yet if the automatically recommended energy efficiency measures are implemented, there are no guarantees that actual environmental savings are reached or that the cultural heritage values of the building are respected.

In all, the findings underline that there are significant barriers and challenges to implementing sustainable energy efficiency measures in historic apartment blocks. This calls for further research, but

[8] Information on calculated energy saving (kWh) and cost per saved kWh is not included in *simple* or *detailed* Norwegian EPCs.

it also indicates a general need for improved decision support. As a way forward, we suggest making the EPC systems more informative and proactive with emphasis on raising user-awareness as this can help clarify objectives and incitements. However, to facilitate such a bottom-up approach, day-to-day users of the building need to become an integral stakeholder throughout the energy refurbishment process. It is, as stated in the drafted CEN guidelines for improving the energy performance of historic buildings, important that the energy refurbishment process is initiated with a clear indication from the owner or user of the building outlining the general objectives and needs. At this stage residents have imperative part of bringing about the grounds for future decision making. A dialog with the residents should be held continuously throughout the decision making process.

When the energy refurbishment process has been initiated a building survey and assessment will provide the rest of the necessary information for making an informed decision. The survey should include information on heritage significance, conservation restrictions, construction, technical condition and energy performance, i.e. the EPC. Having identified the objectives for technical, energy and indoor environment quality improvements, long-term ambitions for the management and conservation of the building should be defined. This is essential for the refurbishment process and each target or priority should be considered and defined as far as possible. The need for an intervention is then defined on the basis of the difference between the present energy performance of the building and the objectives that have been identified by residents and the building surveyor. Before moving on with the identification of measures a first gross list of measures (e.g. defined on the basis of EPC recommendations as well as input provided from the residents) should be narrowed down by excluding inappropriate alternatives. This leaves an opportunity to conduct a full assessment of the remaining net list of measures with respect to risks and benefits respectively. The outcome of this is one or several optional packages of measures that in turn can be assessed and adjusted iteratively in relation to targets. When the package of measures is in agreement with the targets, a proposed solution has been identified. Upon coming to a conclusion, making a decision and implementing the solution, post occupancy evaluations should be carried out to address user behaviour, tuning systems and further encouraging awareness.

Refurbishment policy instruments such as the EPC system represent much potential for energy saving. However, for the EPC system to be rewarding rather than restraining, it should be supplemented with procedural decision support systems, i.e. toolkits such as presented in the LEAF project, which take into account aspects regarding economy, priorities and (energy) targets. Such a bottom-up approach will most likely contribute to the decision making behind the refurbishment process as well as raise awareness with respect to cultural heritage significance of the historic buildings.

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Posters session

POSTERS SESSION

“Deep assessments” before “deep renovations”: saving money, time and Cultural Values

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Abstract – *Deep assessments, contextualized neighbourhood scale views of the energy audit, are proposed as a source of new insights for Historic Buildings intervention. Their feasibility is briefed for a 14-16th century residential building in Coimbra’s UNESCO Heritage area to demonstrate that effective energy savings, globally reduced intervention costs and added value can be achieved. Historical investigation frames the context and expectations; tools like 3D laser scan, drone flights and IEQ online assessment supply raw data; BIM/BEM (Building Information/Energy Model) streamline the evaluation of intervention options; visualization tools like thermography and dynamic heat flow illustrations facilitate knowledge dissemination; and the whole process becomes a chance to engage local stakeholders in neighbourhood-specific Energy Efficiency measures. Deep assessments, and resulting tailor made interventions, are proposed as valid alternatives to deep retrofits in the needed contemporization of Historic Buildings and neighbourhoods; and opportunities to intertwine daily practices and Cultural Values towards effective, and inclusive, Climate Change mitigation.*

Keywords – Historic Buildings; BIM; BEM; energy efficiency; quality of life

1. INTRODUCTION

Significant energy consumption reduction is necessary to meet the targets for a Low Carbon Economy in 2050 [1]): all new and existing buildings have to reduce their energy consumption, and/or progressively transition towards low carbon energy supplies while guaranteeing their users comfort and adequate Indoor Environmental Quality (IEQ) conditions. Residential buildings represent 75% of the built area in Europe and 68% of total buildings energy consumption [2] accounting, in large estimates, for around 27% of the European energy consumption in bulk. Energy efficiency related renovation is now a growing scenario, but misconceptions about Historic Buildings still endure.

The EPBD-2002 defined goals, the 2010 EPBD -“recast” defined targets stricter targets for new buildings and “cost effective thresholds” for existing ones, but the IEA EBC Annex 56 on “Cost Effective Energy and Carbon Emissions Optimization in Building Renovation” [3] shows that retrofit costs, integration issues, lack of specialized craftsmen and users’ engagement make interventions on existing fabric hard to start. Although a mismatch between expectations and results occurs 14 years after the EPBD publication, the 2030 goals, 14 years from now, rely mostly in increased requirements. Alternatives emerging from the Historic Buildings context exist [4], but demonstrations are needed.

2. METHODOLOGY

A brief chronological tour by the work performed for the Ph.D thesis on “Upgrade Opportunities for Ancient Buildings (in City Centres)” demonstrates that deep assessments, here defined as contextualized historical approaches [4] recurring to tools like thermography, Indoor Environmental Quality and Building Information/Energy Model (BIM/BEM) depictions can enable new economically viable renovation approaches at neighbourhood scale: Energy Efficacy as a driver, not a goal by itself.

Figure 1. A first look at Montarroio case study, in a degraded area of Coimbra, Portugal

3. A “DEEP ASSESSMENT”

The Montarroio case study lower portion dates back to 14th century, while the upwards extension denotes stone-embellished windows and a chimney, 16th century exterior signs of comfort [5]. As in over 800 ancient buildings nearby (and millions in Europe), stacked masonry walls provide peripheral support to wooden floor levels and roof structures, covered by ceramic tiles. Thick walls sliming towards the upper levels define growing internal areas: 13,7m² (p00) in a semi-buried level with separate entrance, 15,3m² (p01) on the intermediate level and 20,6 m² on the top level (p02). Only 36 sqm are habitable, as the semi-buried level (p00) suffers from severe humidity issues, and was commonly used to shelter animals. Wood doors and interior shutters prevail, while the simple glazing sash windows introduced in the 19th century assure high infiltration from lack of maintenance.

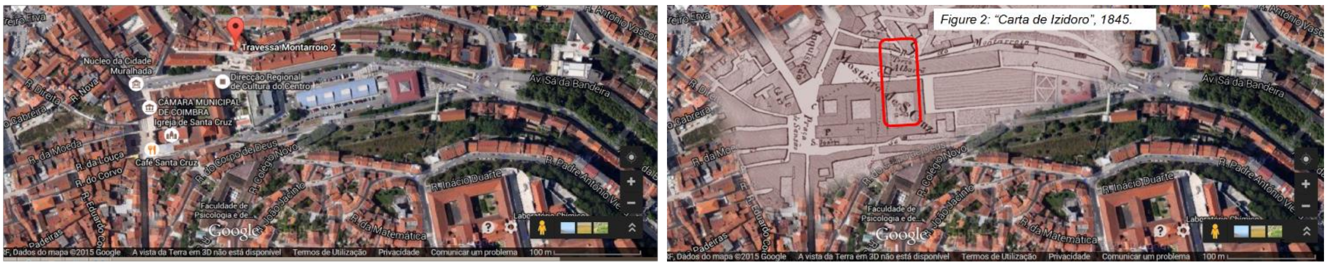

Figure 2. A contemporary Google satellite map (left) and the superposition of 1845 “Isidoro Chart” (right)

Montarroio still stands in the ancient city centre of Coimbra, within the UNESCO “University of Coimbra –Alta and Sofia” and “Jardim da Manga” National Monument protection areas [6].

Figure 3. Panorama view of Montarroio case study: another look into the same reality? (source: author)

The Montarroio case study dimensions were assessed using current and modern technologies like tape measurement, terrestrial laser scanning, photogrammetry and drone flights, depicted in Fig. 4.

Figure 4. Tape measurement (left), Laser Scan and Photogrammetry (middle), and drone aerial views (right)

Digital reconstructions from the point clouds were processed, BIM models constructed and 3D printing of scale models (Fig. 5) executed to illustrate the complex reality and varying wall widths.

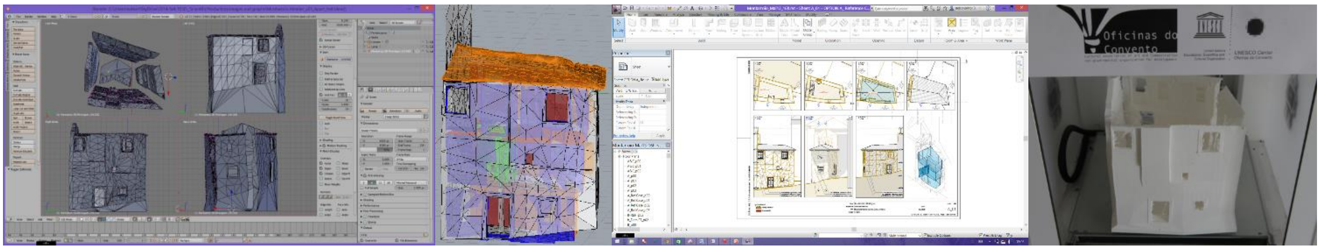

Figure 5. 3D views in Blender (left), Rhinoceros and Autodesk Revit 2012 model that was exported to the dynamic simulation software using gbXML middle) and 3D print of the model (courtesy of Oficinas do Convento) (right)

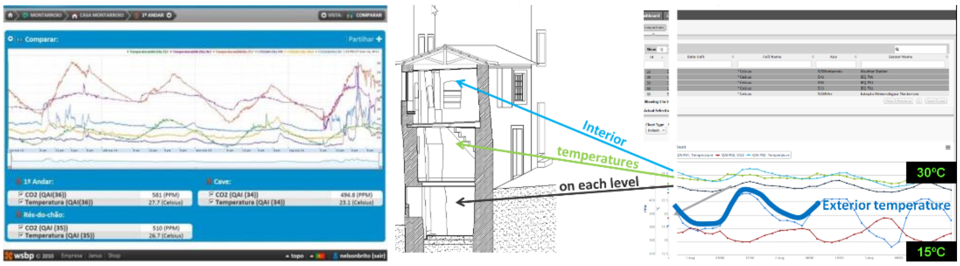

Figure 6. Initial online display of Indoor Air Quality parameters (left) and new software version that depicts foul use (increased solar gains and reduced ventilation) of a well-balanced building in the summer season (left).

Online monitoring of indoor and outdoor thermal, relative humidity and CO_2 parameters (Fig. 6) composed a detailed picture of the building behaviour to fine-tune dynamic simulation models and confirm the influence of vernacular materials inertia, illustrating the potential for savings.

3.1 From data to information

Five intervention scenarios were superposed using BIM "chronological dimension": each column in Figure 7 represents the same cut, now (Opt.0) and in four virtual futures (Opt.1 to 4).

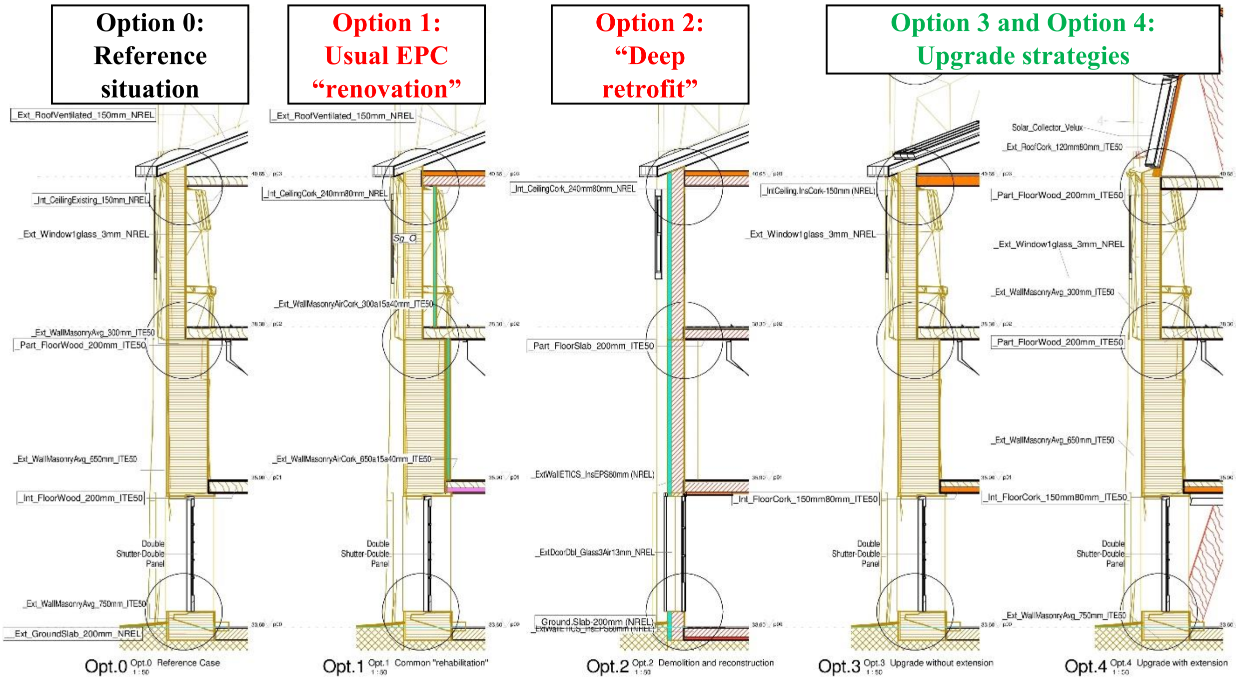

Figure 7. Montarroio studied intervention options (more detail in [4,7]

The methodology jointly developed within the IEA Annex 56 [3] was extended to include demolition and reconstruction, the "**deep-retrofit**" practice that needs to be evaluated to demystify its advantages. Economic indicators like "Initial Investment Cost" (IIC), "Life Cycle Cost" (LCC) in a 30 years period and environmental impacts like Global Warming Potential (GWP) portrayed in Figure 8:

Simplified versions of the models were exported for dynamic simulation purposes, while the development of project continues using parametric tools like Revit/Dynamo or Rhino/Grasshopper.

Results [4,7] show that "Historical" Buildings' efficacy in energy use and comfort must be valued [8], yet informed interventions are often reserved for monuments. The deep assessment of the neighbouring protected areas (and people that give them meaning) can bring new insights, and contribute to their systematization into recognized science and constructive practice.

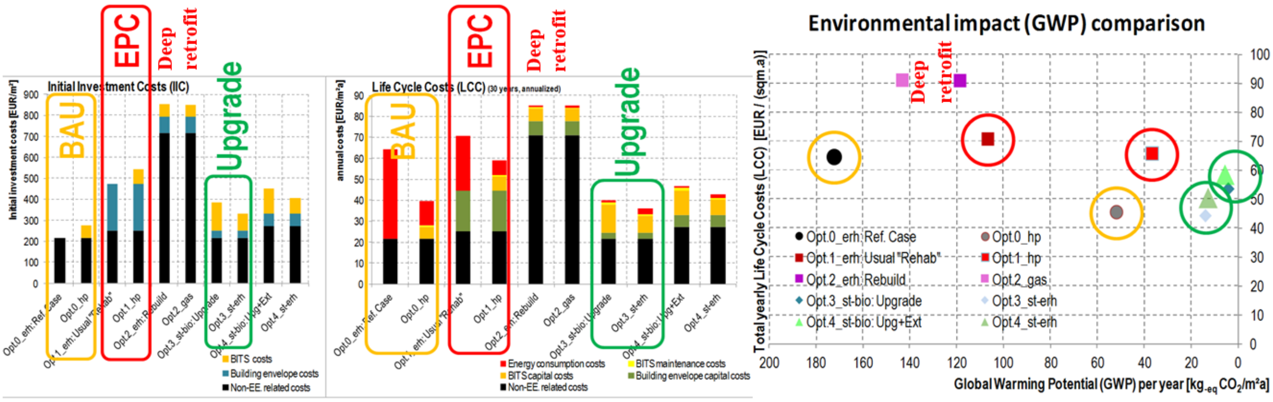

Figure 8. Initial Investment (IIC) (left), annualized Life Cycle Costs (LCC) in 30 years (middle), and Global Warming Potential (GWP) comparison in the same period using (EcoBat, 2014) (right). More detail and information in [7].

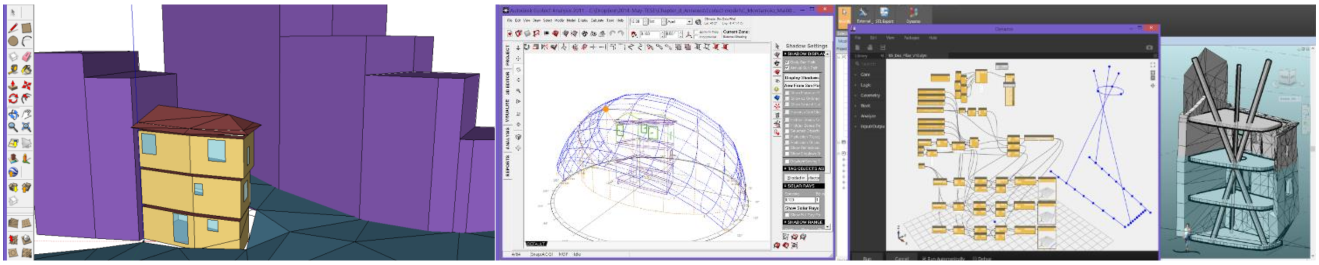

Figure 9. Montarroio OpenStudio/EnergyPlus™ dynamic simulation model, visualized in Sketchup™, Autodesk Ecotect™ sun path and Revit/Dynamo™ visual programming schematic study for structural security (author)

3.2 Visualization: Enhanced information, understandable by others.

Fig. 10 demonstrates that "tailor-made" depictions of invisible forces like heat flows and global warming potential facilitate effective communication between stakeholders.

"Buildings don't use energy, people do" [9] is a reminder that Historical Buildings must team up with their users´ needs and expectations to deliver results. The investigation proceeds reducing time and cost to collect data, smarter ways to retrieve information and to make information more attractive, and feasible [10]: actions to facilitate effective interventions in Historic Buildings areas.

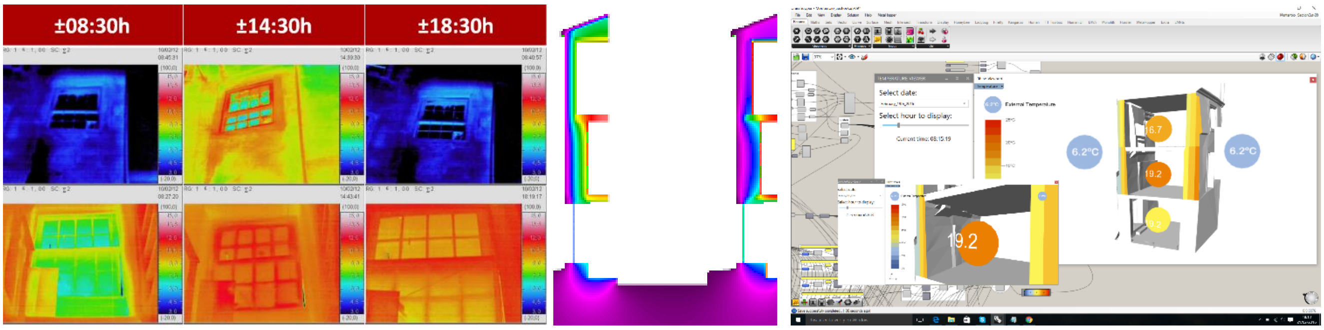

Figure 10. Visualizing concepts. The (left) group of thermographic images depicts the same window in the winter (3 to 15ºC range) at different hours (columns) and from the exterior and interior (rows), illustrating the potential of thermal inertia to keep indoor wall temperatures constant. The (middle) image uses THERM (LBNL) to illustrate the heat flow on the original situation (Opt.0) and the thermal stress that wall insulation may impose (Opt.1) on levels connection. A Rhinoceros/Grasshopper/Arduíno readout (right) of temperatures inside the walls is visualized using the "Human UI" (thanks to student E. Aguero for this add-on suggestion): by browsing dates and hours, the relation between interior and exterior temperatures and the heat flows inside the wall (thermal lag) becomes visible.

4. SAVING MONEY, TIME AND CULTURAL VALUES

Historic buildings were designed to fulfil human needs within specific climatic factors without the use of fossil fuels, although that does not necessarily mean that they were "sustainable", as acknowledged in [11]. Although human needs and expectations change throughout the centuries, the majority of Historic Buildings were able to answer to that change, and can do so now.

This paper proposes that Energy Efficiency[9] is a threat that can be bent into an opportunity. Energy Efficacy[10], meaning effective and measurable results, can be attained by using deep assessments to harvest Historic Buildings' architectural and cultural constraints into comparable alternatives: a collective approach needs collective reasoning, and interdisciplinary knowledge and perspectives.

Deep assessments save money and time as better decision-making is possible by comparing short and midterm costs and impacts [4,7,12]: the replication of other buildings in the neighborhood becomes easier as scale, optimization and practice do result in speed, quality and smaller costs; and can yield neighborhood scale intervention opportunities towards reduced installation, operation and maintenance costs. Moreover, what is the value of correctly informing the neighborhood inhabitants on the best actions to perform, and to accelerate/influence of these projects with detailed information?

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[9] Efficiency: "The state or quality of being efficient: *(...)* An action designed to achieve efficiency: *(...)*; The ratio of the useful work performed by a machine or in a process to the total energy expended or heat taken in: *(...)* (Of a system or machine) achieving maximum productivity with minimum wasted effort or expense: *(...)[17]*.

[10] Efficacy: "The ability to produce a desired or intended result" *[17]*.

Deep assessments save culture by protecting existing assets and knowledge, being in themselves, cultural moments. History is revisited and embedded knowledge reinterpreted, dialogues favor bi-directional information transfer, later facilitating neighborhood scale studies. Results are debated in conferences were the issue of "Traditional Knowledge" is valued [12-14], and suggestions integrated in a neighborhood scale collective approaches. All these helped "Common Efficacy" to achieve recognition [15] in the 2015 VINCI Innovation Awards-"Urban Services and the Connected City" [16]

5. CONCLUSION

Despite all the potential of deep assessments, unjustified "deep retrofits" still prevail, as after establishing a *tabula rasa* — by vacating buildings, relocating people, shattering communities, striping interiors and memories — all regulations can be fulfilled, and new inhabitants placed in.

Energy Efficiency can become a tool to protect Historic Buildings, neighborhoods and users from risks like energy poverty and discomfort. Deep assessments emphasize their value and cultivate collective pride, creating the perfect setting for collective actions. Then it will be up to the stakeholders — users, communities, policy makers, markets and culture — to make an informed choice.

6. ACKNOWLEDGEMENTS

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Feel free to contact: this investigation can only evolve with new perspectives, and sites.

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The potential for implementing a decision support system for energy efficiency in the historic district of Visby

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Abstract *– A prototype for a decision support system (DSS) for energy efficient historic districts has been developed within the European project EFFESUS (ENERGY EFFICIENCY FOR EU HISTORIC DISTRICTS).The DSS is an expert system that aims to identify and prioritise retrofit measures to improve the energy performance of a specific historic district. This paper will discuss the possible implementation and assessment of the DSS in the historic district of Visby, Sweden. The objective is to investigate how the DSS could work in planning and management of the small world heritage city seen from a stakeholder perspective. The study is conducted through a workshop and interviews. One outcome of the study is how the stakeholders interpret the direct or indirect use of the DSS depending on their field of expertise and their professional role in society.*

Keywords – Decision support system; energy efficiency; historic urban districts; stakeholder perspective

1. INTRODUCTION

The 7th European framework project EFFESUS (Energy efficiency for EU historic districts' sustainability) aims to find solutions to the complex problem of managing energy saving and safeguarding historic urban districts. One of the main objectives of the project is to develop a Decision Support System (DSS) to assess energy retrofitting interventions in historic districts. In the early stages of the project, a conceptual solution was defined. The objective of the research upon which this paper is based is to contribute to the final design of the DSS by learning more about the needs of the end users and investigating how the proposed decision support system (DSS) would work in relation to the local planning and management of a small world heritage city.

The need for well informed and balanced decisions taking into account both energy efficiency and heritage significance in historic buildings has been in focus for several research projects on a European level [1]. In the field of energy efficiency in historic buildings a considerable amount of research has been carried out with a focus on single buildings concerning; retrofit solutions, energy performance, climate control, management and legislation. Often these studies have been performed as case studies.[2][3][4] So far, less attention has been paid to historic urban districts and building stocks. An attempt to approach this matter was undertaken by Arumägi et al [5]. The modelling of building categories to serve as a basis for optimizing different scenarios for energy saving actions and their effect on categorised building stocks has been developed within the Swedish national context [6] The attitude towards change within the heritage sector as one of the principles of conservation has been a focus for research and discussions both in theory and in practise, and also in the context of change due to measures to improve the energy efficiency of built heritage. The values of the built heritage need for this reason to be assessed and evaluated together with other aspects such as energy, use, function, economy etc. [7]

In the EFFESUS project, a step is taken towards a more holistic and multiscale approach to sustainable energy strategies for historic urban districts. A web based tool is being developed to support decision making where many parameters need to be taken into account and where analogue methods is not sufficient for handling many different systems of data. [8]

The intended users of the DSS are municipalities, property owners and other governmental and non-governmental organisations that are developing strategies and policies for historic urban districts. The present investigation is based on seven interviews and a workshop with three main groups of stakeholders; experts representing the municipality as the legal authority, property owners and private consulting experts in the fields of architecture, energy and heritage. The main questions are;

- What are the perceived requirements in order to improve energy and heritage management in general and decision making in particular?
- What is the potential for implementing the proposed Decision Support System; Is it useful on the district level from a stakeholder point of view?

2. THE EFFESUS DECISION SUPPORT SYSTEM FOR ENERGY EFFICIENT MEASURES IN HISTORIC URBAN DISTRICTS

The DSS is one of the main outcomes of the EFFESUS project. The software tool is an expert system that assists users to identify and prioritise retrofit measures to improve the energy performance of a specific historic district. The DSS has three levels of decision making (LoDM). At low levels of decision making (LoDM I) information is introduced by the user, but at higher levels (LoDM II and III) location-specific information is stored in a multiscale data model.

For the higher levels of information, a Categorization Tool has been developed as a web application that is used to categorize the building stock and select typical buildings as representative of the whole district[9]. The possible retrofit measures are characterised with regard to their impact on the different decision making criteria such as heritage significance, energy saving or thermal comfort. This data is structured and stored in a technical solutions repository. The inputs from the data model and the repository are used by the DSS to produce;

- A current state of the district regarding energy demand and carbon emissions
- A list of possible solutions classified by their applicability
- A priority list of packages of retrofit measures which are likely to be suitable in the context of a specific historic district and their impact at district level.

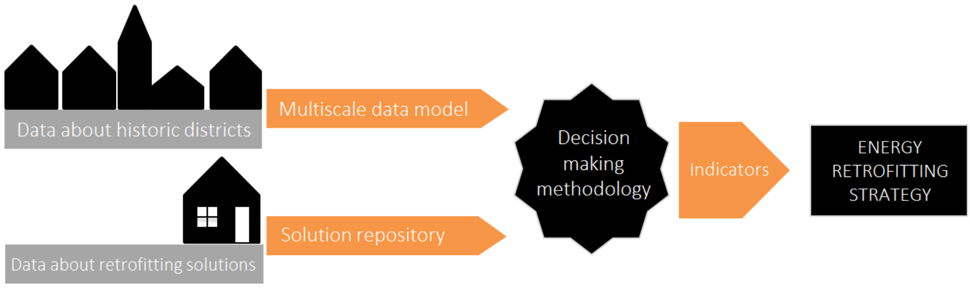

Figure 1. Principle layout of the EFFESUS Decision Support System

The DSS works on different levels of detail as described above. On a general level there is a possibility to use the system for strategic support for decisions as well as for guidance. On the first level of decision making (LoDMI) the user of the DSS is asked to answer twelve questions that will limit the possible applicable solutions due to the active choices that are made. The user of the tool needs for example to have knowledge about the legal situation of the district, if there are specific restrictions concerning changes to the buildings and whether the district is characterised by stone or wooden buildings. The input to the twelve questions will generate a list of suggested energy measures that would be a first step towards a strategy for energy improvements. On the more advanced levels of decision making (LoDM II and III) the DSS is provided with more detailed building stock data and the user also needs to decide on weighing factors between for example cost, energy saving, low impact solutions, indoor air quality etc.

3. THE VISBY CASE STUDY

Visby is a UNESCO world heritage city situated on the island of Gotland in the Baltic Sea. It is a medieval city surrounded by a city wall. Based on an inventory made in the EFFESUS project there are 1235 built properties and 314 listed buildings within the city wall. The character of the historic urban district is connected to the medieval influences but also to the 18th and 19th century periods.

The case study of Visby was conducted in relation to the development of the DSS to clarify the stakeholder needs and the potential of the DSS to serve as a strategical and practical tool within the managerial system connected to energy efficiency and built heritage.

The case study consisted of one workshop and interviews with seven individual stakeholders. The participants in the workshop were divided into groups for short intensive discussions and then asked to give individual written feedback as well as in an open discussion. In the next stage semi-structured qualitative interviews were carried out in order to get a deeper understanding of the results from the workshop. The stakeholder input was divided into two parts; the first part dealt with the perceived general needs of knowledge, support, guidance etc. within the multidisciplinary field of energy efficiency and historic urban districts. The second part (in the context of the EFFESUS project and the

DSS) considered how the implementation of the DSS could fulfil the perceived needs. In total 19 different stakeholders participated in the study. The stakeholders represented different fields of expertise; architecture, heritage, energy, politics and engineering. They were mainly employed by the municipality or worked as private consultants.

Figure 2. The cityscape of the world heritage city of Visby

There is a division in responsibility between different areas of interest within the municipality such as architecture, cultural heritage, environment and energy and building survey. This division is a result of how work is organised in relation to the national legislation mainly in the field of physical planning and building. Local policies and guidelines concerning energy measures in the historic urban district of Visby are provided by the building regulations for the city.[10] In short the building regulations contain de facto restrictions on exterior changes related to energy retrofits. There is also a higher requirement regarding the demand from the municipality for building permits concerning changes to the buildings than for the normal building stock which gives the municipality a possibility to control and minimize the visual/exterior changes of the built environment within the historic district.

4. RESULTS ANS DISCUSSION

The results are grouped according to the research questions. First the perceived needs to improve energy and heritage management and secondly the potential for implementing the proposed DSS.

4.1 Energy and heritage management in Visby

The municipal responsibility for questions concerning energy efficiency, environment and climate is distributed within different fields of expertise (heritage, planning, permission, building regulations and technical demands etc.) and also on different levels in society from user level to the political level. The communication between different fields of expertise and on different societal levels was expressed by the stakeholders as inadequate and could result in non-optimized decisions on energy efficiency.

A common knowledge base, both in the sense of understanding each other's field of expertise and also a need for developing better guidelines, in the multidisciplinary field of architecture, conservation and energy was addressed as one important need mainly from the stakeholders representing the experts at the municipality. The idea was that a common knowledge base would reduce the barriers between different fields of expertise, which was seen as an obstacle for introducing a strategic approach to energy efficiency in the historic centre of Visby. Understanding and respect between different fields of knowledge was also discussed as a challenge by a mixed group of stakeholders in the workshop.

Stakeholders not representing the municipality, mainly consultants, said that they found it difficult to get information and guidance on how to interpret what heritage values meant in reality and how they are connected to the possibility of making alterations to a building. Access to information about solutions applicable to historic buildings is needed by consultants and property owners.

The stakeholders representing the municipality could see a need for information about best practice as guidance for sounder decisions and in communication with residents. Modern technical solutions and traditional building constructions are not always compatible and this is a challenge that needs to be taken seriously according to the majority of the respondent stakeholders from the municipality. These statements are connected to the existing and future demand on existing buildings to perform as close as possible to the near-zero carbon objectives. The house owners in the historic city of Visby have the possibility to use district heating as a 100% renewable energy supply. In spite of this, heat pumps, with both visual and acoustic impact, have been increasing in popularity. The installation of ground source heat pumps can be made in most cases without building permission since the visual impact is almost none. The energy expert saw this as a problem regarding conflicting strategies of the systems for energy supply to the historic district.

The awareness of energy efficiency as a way of meeting the complex objectives of the overall climate challenge is not, according to one of the interviewed heritage experts, common knowledge among property owners and residents living inside the historic district of Visby neither is the knowledge about life cycle costs and analysis in order to relate small improvements to a bigger picture.

4.2 A proposed implementation of the EFFESUS decision support system in Visby

The expressed need for decision support among stakeholders can be categorised into three main themes; information and knowledge, technical solutions and a life cycle perspective. There were differences in focus among stakeholders between the three themes depending on their professional background. Energy experts were more occupied by how technical solutions were compatible with existing material and the architectonic character of the historic environment. Heritage experts saw a need for relating to bigger issues of management for sustainable development and especially in relation to the work being done on the management plan that is under development for the world heritage site. Stakeholders representing the municipality addressed issues about knowledge and information both within the municipality between expert groups but also as a service for citizens. Overall the most frequently raised issue during the workshop and the interviews was the need for applicable and useful support on different levels.

The stakeholders could see the possibilities of the decision support system, which are under development within the EFFESUS project, to be a useful tool supporting complex decisions about strategies and retrofitting solutions for energy efficiency in historic buildings and districts.

Representatives from the municipality could see the tool as a support for development of local guidelines more than a tool for supporting decisions on specific energy efficient retrofits. This could in turn support the actual decisions made by the individual house owners. Consultants found the tool potentially useful in their business relation with private property owners. Doubts and questions about the future management of the tool and the flexibility to accommodate new data were raised both in the workshop and in the interviews.

Finally there is a line between the direct and indirect presumed use of the DSS. Representatives from the municipality observed that it would be helpful to use the DSS outputs for producing policies and guidelines that would benefit the improvement of buildings to become more energy efficient. This is an indirect advantage of the decision support system. The direct advantages of the system were estimated by the property owners and consultants. They could see the DSS as a tool for supporting decision making in relation to a technical solution or package of solutions for a specific object or project. This was mainly due to the Swedish legal context where the right over property is strong individual right and where municipalities work on surveying and strategic level.

5. CONCLUSION

This study aimed to investigate the perceived need to improve energy and heritage management in general and more specifically the usefulness of the proposed EFFESUS Decision Support System for energy efficient strategies in the historic urban district of the world heritage city of Visby. The uncertainty among all stakeholders about how to deal with energy retrofits in the historic urban district according to national and local regulations shows that a tool like the DSS addresses a fundamental need among all stakeholders. The current decision context is fragmented. Competence and authority are divided between different professionals, on different societal as well as organisational levels and also with different interests to watch over. The decision support system could in this context work as an intersectional tool, a knowledge breaker and as a platform for dialogue towards sounder decision processes.

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Retrofit internal insulation at New Court, Trinity College, Cambridge: options, issues and resolution through material sampling and modelling

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Abstract *– New Court in Trinity College, Cambridge, UK (Grade I listed) has been retrofitted with vapour open internal insulation. This paper describes the moisture modelling exercise undertaken to inform the strategic choices and evaluate risks. The use of in-situ monitoring and material sample data to improve modelling accuracy is discussed.*

Keywords – Insulation; WUFI; heritage; moisture; retrofit

1. INTRODUCTION

Trinity College Cambridge was founded in 1546 by Henry VIII. Its buildings are made up of a number of quadrangular 'courts' of medieval, sixteenth and seventeenth origin. New Court was added to the college in the 1820s by the architect William Wilkins. The buildings of the college are listed as grade I and are afforded the highest level of statutory protection within in UK planning law in recognition of their architectural and historic significance.

This paper is one of three that describe the project and focuses on the key aim to improve the thermal performance of the solid walls at New Court from the measured, existing U-value of 0.69 W/m^2K (average). Here, we provide details of the technical approach to defining the insulation strategy, including material sampling and WUFI modelling. The other papers concern the planning and design work by 5th Studio architects and the *in-situ* monitoring work undertaken by ArchiMetrics. Collectively, these papers (100, 102 and 103) describe the parallel exercises in policy and design research, modelling and monitoring that led to the formulation of the integrated package of proposals that were successfully granted Listed Building Consent in January 2013 and have been implemented and completed on site. It is thought that this is the first grade I listed building in the UK to have been the subject of such an extensive low energy refurbishment. As a result, the processes and outcomes of this project may have important influences on this sector of the built environment for the future.

2. SETTING THE STRATEGY: THE CASE FOR VAPOUR OPEN INSULATION

2.1 Introduction

Retrofitting internal insulation of solid masonry walls tends to focus on the use of vapour barriers to prevent internally-produced moisture from condensing on the cold outer side of the insulation – deemed to be the critical surface. The vapour barrier is conventionally installed on the inner "warm" side of the insulation to prevent this moisture path to this critical surface, with the most risk predicted during winter. However, this assumes the movement of moisture from the outer wall surface to the critical surface is negligible. Saturated conditions on an external facade due to rain exposure can reverse the vapour pressure gradient and can drive moisture inwards. This phenomenon is enhanced by incident solar radiation and can lead to critically high RH levels on the reverse side of the vapour barrier if the condition persists for long enough.

Standard approaches to condensation analysis using the vapour diffusion or *Glaser* method (EN ISO 13788:2012 [1]) also ignore the moisture capacitance of building materials. Most brick types have a high moisture capacity. Saturated walls can store large volumes of water all year round, driving moisture inwards for significant portions of the year.

The application of internal wall insulation fundamentally changes the properties of the wall with regard to the moisture transport in both directions and heat transfer from inside to out. The hindrance of moisture transport and/or the reduction in heat transfer lead to cooler temperatures and higher relative humidity which can lead to persistent higher moisture levels, interstitial condensation, the germination and proliferation of mould, rotting of timber elements and, in extreme cases, freeze-thaw weathering of the external façade.

The nature of the intervention and the physical properties of the insulation materials were therefore the subject of a preliminary review to determine whether or not the proposed retrofit strategy could lead to damaging conditions and to assist in defining a strategy which balanced risk and benefit.

2.2 Methodology

The constructions at New Court vary both in orientation and nature. Although generally constructed in brick, different finishes were applied to the brick facades based upon their significance. The prominent river facing façade, adjacent to the Wren library, was finished in sandstone, the walls facing the courtyard were rendered and the rear (south) facing wall was left as exposed brickwork (see Figure 1). Furthermore, the thickness of the walls varied throughout. The assessment of moisture levels was therefore performed for six reference test cases. In each of these cases a number of internal insulation strategies were assessed; this included vapour closed as well as varying thicknesses and materials of vapour open insulation options. For the preliminary assessment the available brick and limestone options available within the WUFI database were assessed and the sample found to produce the 'worst case' response in the insulated case was chosen [7].

Figure 1. The River, Courtyard and rear facades are finished with different materials, with differing characters related to their urban significance and differing characteristics of vapour and moisture resistance and permeability.

All preliminary modelling was undertaken using WUFI Pro 5.0 - an international industry standard transient heat and moisture simulation tool for assessing condensation and mould risk in walls. Modelling inputs used a typical meteorological year weather file created for Cambridge using Meteonorm, with more challenging conditions used to test a variety of climate change scenarios. Internal conditions were generated from the weather file using the algorithm described in EN 15026:2007 [2] built into the WUFI model. The “normal” internal moisture load was selected, which is considered acceptable for mechanically ventilated spaces. All simulations were run for a minimum of 15 years to minimise the dependence of results on chosen initial conditions.

The most challenging of the risk factors to assess was the potential for mould growth. The critical interface to study this risk was found to be the interstitial material boundary with the highest calculated RH levels and in all cases was where the inner face of the brickwork met the insulation. Criteria for this assessment were determined from information published in Sedlbauer [4]. This is recognised internationally as the major relevant work and is referred to in other publications and reviews on the subject [5]. Most other guidance refers only to critical humidity levels: 80% (EN ISO 13788 [1]) or 75% (Building Regulations Part F [6]) are quoted typically. However, this more detailed approach considers four variables – Relative Humidity, Temperature, Type of Substrate and Duration of exposure to critical conditions. Sedlbauer identifies three substrate types as described in Figure 2.

Temperature, relative humidity and critical duration of exposure can be read from isopleth diagrams (Figure 2) for each substrate type. The diagrams show that warm temperatures coinciding with high relative humidity levels create the ideal conditions for mould growth. However when temperatures are low, high relative humidity levels can be tolerated without spore germination. This has further implications, as temperature and relative humidity are critically linked. As air temperature increases, its capacity to hold water vapour also increases and its relative humidity drops. Conventionally we expect the greatest risk of high relative humidity in walls to occur in winter when temperatures are lowest; although hygroscopic materials can act as a humidity buffer, keeping RH levels constant as temperature fluctuates.

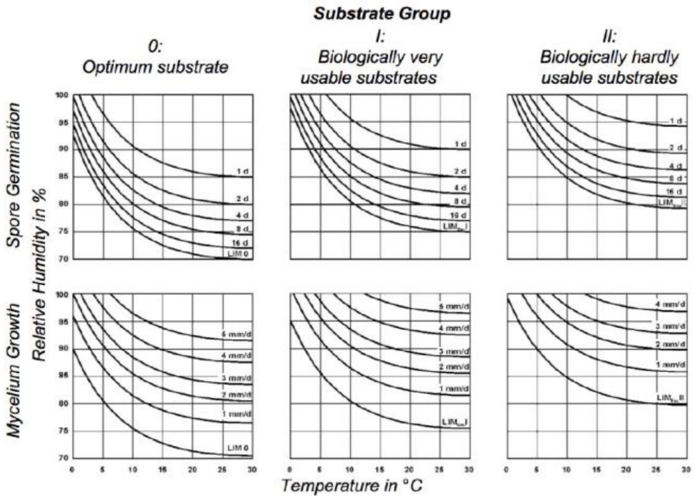

Figure 2. Reproduced from Sedlbauer [4]. Category 0 : e.g. Laboratory Agar, Substrate category I : e.g. wall paper, plaster cardboard, materials made of biologically degradable raw materials, and material for permanently elastic joints; Category II : e.g. mineral building material, certain wood as well as insulation material not covered by I.

2.3 Results and conclusions

The results presented in Figure 3 show isopleth predictions at the critical interface for a brick façade comparing vapour-closed (a) insulation with vapour-open (b). The predictions demonstrated a case against vapour-closed in favour of vapour-open constructions: in case (a) the moisture levels at the critical interface are well in excess of the Lim II curves identified in Figure 2. The levels for a vapour-open approach suggested a reduced risk of mould growth. This strategy was developed with improved accuracy in order to more accurately quantify risk as described in section 3.

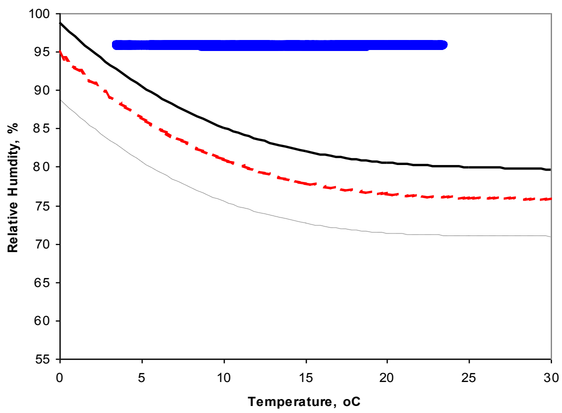

Figure 3(a). Brick Facade – 150mm Phenolic Foam insulation with vapour control layer. Temperature and humidity isopleth showing one year of hourly simulation data for conditions at the inner face of the original brickwork.

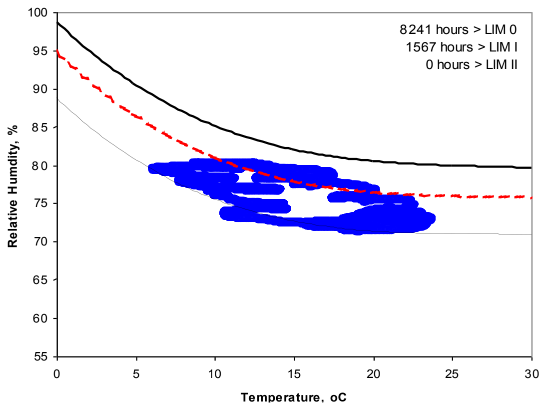

Figure 3(b). Brick facade – 100mm Pavadentro breathable insulation. Temperature and humidity isopleth showing one year of hourly simulation data for conditions at the inner face of the original brickwork.

It should be noted that, in the assessment of less exposed and porous façades, vapour-closed approaches did indicate an acceptably lower level of risk and suggested different approaches for each façade might be possible. However, it was agreed that the risk arising from the use of the wrong insulation in each location during construction was significant and to be avoided, so a single, common approach was sought for all facades.

The preliminary assessments undertaken identified a number of areas for further consideration and development:

- Insulation thickness and target U-value – The lower the U-value the lower the heat transfer and the greater the RH within the wall. The selected strategy would need to be mindful of the balance between moisture risk and meeting the strategic aim to reduce heat transfer.
- Internal moisture load – high internal moisture loads increase moisture levels within the wall considerably and need to be managed through careful planning and ventilation strategy.
- Future climates – a significant increase in driving rain can elevate moisture levels and will need to be observed and corrected if this materialises.

3. QUANTIFYING THE RISK THROUGH DESIGN DEVELOPMENT

3.1 Introduction

Having established the preference for a vapour open insulation strategy, the assessment was developed from that strategic aim to a more considered proposal that demonstrated a reduction in the inherent risk to a level that could be effectively managed to the satisfaction of the heritage authorities.

3.2 Model inputs and residual risk management

Material properties (density, porosity, water absorption coefficient, thermal conductivity, sorption moisture contents, vapour diffusion resistance factor) vary considerably, even for a given material type. WUFI software allows the user to input specific information about the materials in the wall build up to improve accuracy of the hygrothermal simulations. Properties of the actual materials were therefore measured from two brick samples, the inner courtyard render and the stone façade. Material testing took place at the School of the Built and Natural Environment at Glasgow Caledonian University (GCU). The sample results showed material properties that differed from the WUFI database values and so were incorporated to improve model accuracy [3].

Density and moisture content measurements from wall core samples from the monitoring locations were also made by ArchiMetrics. The data obtained presented a rare opportunity to improve modelling confidence and the recommendations resulting from it.

To compare the model to the real-life data, each wall build-up was simulated in WUFI. By interpolating the material sorption curves, measurements of relative humidity in the walls are used to set the initial material moisture contents in the simulation. The model is run over the same length of time as the monitoring period with the actual internal and external site climate data used as dynamic boundary conditions. The average relative humidity in the simulated walls is compared to the average relative humidity observed in the real walls over the measurement period. An example is shown in Figure 4 and Figure 5, and should be read alongside the full technical paper [3]. These show that the WUFI model appears to predict relative humidity with reasonable accuracy in most cases, although it is noted that the conditions were quite stable and the period of monitoring is not long enough to validate the model over a full annual climate cycle. The difference between the brick types appears insignificant in the un-insulated case represented in the monitoring period. However, the modelled predictions of the insulated cases varied considerably when using different brick properties.

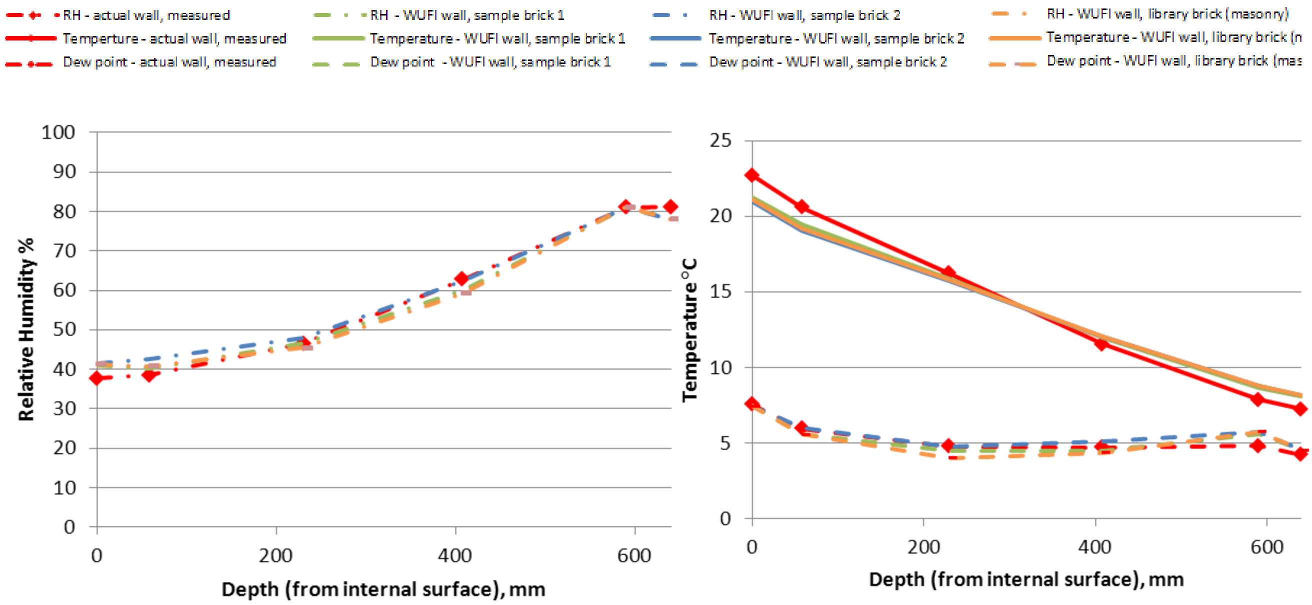

Figure 4. Comparison of in-situ measurements of relative humidity (in red) with simulated data as averages over the measurement/simulation period. Simulations compare three sets of brick properties: two obtained from laboratory testing of site samples and one from the WUFI material database.

Figure 5. Same data as figure 3-1, displayed as average temperature and average dew point (equivalent to absolute humidity) values.

The comparison allowed further refinement of the model. Initially all walls were simulated using default surface convection coefficients for a reasonably sheltered building (h_c = 0.0588 m^2K/W). The comparison revealed that this led to a higher average external surface temperature than observed. It was concluded that these walls are more exposed to wind and higher speed air movement and subsequently the surface transfer coefficients were reduced to reflect the greater exposure (h_c = 0.02 m^2K/W). This yielded significantly closer agreement between the simulations and monitoring data although it is acknowledged that there is uncertainty remaining in this and other input parameters.

Having refined the model it was possible to assess the risk associated with the intervention with greater certainty. It was used to evaluate:

- The appropriate insulation thickness to balance the reduction in heating loads with the moisture related risk. The chosen insulation strategy was calculated to reduce the U-value to 0.38 W/m^2K (average).
- The expected conditions in the unheated floor voids and impact on the joist ends
- The requirement to provide ventilation to the service voids created by the new furniture.
- Conclude that the risk of freeze thaw having a damaging effect was low
- Quantify the effect of variability in the properties of the bricks.
- The importance of ensuring internal conditions stay within sensible thresholds through the use of automatic controls on the heating systems and continuous ventilation.

This work resulted in a robust technical proposal with a quantified, low residual risk associated with the properties of the installed bricks. This enabled an informed appraisal to be undertaken by the technical advisor appointed by the regulatory authorities (*Colin King, BRE).* The result of this review was that the risk would be continuously monitored *in use* using a variety of techniques and approaches that offered a reasonable sample of the construction and exposure types in the courtyard.

4. HEADLINE CONCLUSION

This project has set a benchmark for improving the thermal performance of historic buildings. The rigorous process should lead future heritage projects to explore similar aspirations. In particular the use of *in-situ* monitoring and material sample testing to inform the WUFI modelling and increase confidence in the exercise has been critical to the acceptance of the scheme by the heritage authorities.

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NOTE – References [3] and [7] are Technical appendices E and H respectively and can be found here: https://idox.cambridge.gov.uk/online-applications/applicationDetails.do?activeTab=documents&keyVal=M6JJ7ZDX3E000

Energy efficiency retrofit of historic buildings: concepts, approaches and interventions

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Abstract – *The concept of retrofitting existing buildings is getting more attention, primarily due to data indicating that the building sector is one of the key consumers of energy, and the targets for greenhouse gas emissions set by the legislative branch. However, in case of historic buildings there is a great concern regarding valuable architectural heritage that has to be considered prior to making any decisions that could permanently harm the heritage value in question.*

There have been many individual and joint research projects trying to examine the gap between energy efficiency legislation and heritage protection, consequences of use of different retrofit scenarios and technologies, and establishing a methodology of assessing possible strategies for the energy efficiency upgrade of historic buildings not officially heritage-designated. This paper aims to give a brief overview of the research conducted, with special emphasis on the complex issues regarding retrofitting historic buildings with regard to their sensitivity.

Keywords – Historic buildings; energy efficiency; heritage protection; retrofit strategies; unintended consequences

1. INTRODUCTION

1.1 Background

The energy consumption of the building sector is significant all over Europe, accounting for a large percentage of the overall energy consumption. The existing building stock accounts for over 40% of final energy consumption in the European Union (EU) member states, of which residential energy consumption represents 63% of total energy consumption [1]. The improvement of the energy efficiency of buildings has become a priority in recent years. When it comes to new buildings, there are various opportunities, in the design, construction and operation phase, to reduce their energy consumption. The goals set out by the relevant institutions seem to have had a big impact on developing the building sector in terms of sustainable design and materials in use. However, more attention has recently been turned towards the existing building stock, as most buildings which will be standing in the next few decades have already been built [2].

The Housing Statistics in the European Union 2010 [3] shows that of today's European building stock, 24% of residential buildings were built prior to 1945. These buildings can be defined as *historic* [4], and even if they are not protected by heritage legislation, they are often considered as being of cultural significance. That means that the cultural, architectural, historical, aesthetic, social or other values are attributed to these buildings – either a group of buildings, a single building or certain building elements. Building owners and inhabitants, in addition to city planners and heritage protection institutions, have an interest in their refurbishment.

Improving the energy performance of historic buildings to the levels required by the building regulations can often be difficult to achieve. The understanding of the building's thermal performance is crucial for any retrofit scenario, but the knowledge of its heritage value is important for creating adequate upgrades, which brings an additional challenge into the topic of retrofitting. In case of these buildings, their value could be heavily affected by the interventions carried out without their sensitivity in question.

1.2 Energy efficiency regulations and heritage protection

Following the Kyoto Protocol [5] several actions have been taken by the European Commission through two Energy Performance Building Directives (EPBD). Directive 2002/91/EC raises important issues regarding energy efficiency in new buildings and promotes the adoption of a methodology for the calculation of the energy performance of buildings. The Directive's regulations apply also to the existing buildings when subjected to major renovation [6]. The EPBD's recast, Directive 2010/31/EU, expands on the issue of historic buildings: "...buildings officially protected as part of a designated environment or because of their special architectural or historical merit, in so far as compliance with certain minimum energy performance requirements would unacceptably alter their character or appearance" [7].

Many discussions have been raised, following the publications, but the main outcome was general acceptance of the necessity of energy retrofits of existing buildings. However, the number of officially protected buildings is considerably small in contrast to number of historic buildings not officially heritage-designated. This became one of the major issues regarding energy retrofit of historic buildings.

The Declaration of Amsterdam (1975), includes "towns or villages of historic or cultural interest" in the definition of architectural heritage [8]. The Granada convention (1985) extends the protection to buildings which are culturally significant, even if not yet officially designated [9]. The principal cause was that such buildings should be treated as being protected from alterations (demolition and even actions affecting its surroundings) prior to their heritage status being agreed upon [10]; if not carefully planned and adequately carried out [11], such alterations can have adverse impacts on the cultural significance, jeopardize their building fabric, and create health risks for the inhabitants.

Another issue raised is the open interpretation for each Member State, which could bring more controversy in terms of evaluating these interventions. Each country has its own systems of heritage protection as well as energy efficiency regulations [12]. In addition to comprehensive analyses [13] and constructive criticism [10], there have been attempts to supplement the EPBD within EU funded projects [14].

2. RETROFITTING HISTORIC BUILDINGS

Beside the concerns of interpretation of the wording "officially protected" buildings and "unacceptably alter their character and appearance" [7], historic buildings do not allow a unique approach to retrofitting. They require a case-to-case treatment instead [13]. The importance of cooperation between different institutions and professionals for undertaking such retrofit projects should be additionally pointed out. There are many aspects to take into account when retrofitting historic buildings. In this section only three will be briefly described and analysed.

2.1 Heritage significance

As mentioned above, there is no standard, agreed upon, among the European countries for evaluating heritage significance. Each country has its own heritage protection system [12]. Historic buildings not officially protected are rarely documented in detail. Yet, in order to assess the impact of retrofit measures, it is beneficial to have a detailed overview of the manner in which a building "works". This means that altering certain components of the building could affect other components or the building as a whole. For instance, replacement of windows can lead to changes in visual appearance of the facade, which could cause a loss of heritage significance of the building, and consequently of the entire building block; in addition, if not carefully investigated prior to replacement, it could cause long-term fabric deterioration, since old windows often provide for necessary ventilation. Therefore, in order to preserve the heritage values from careless treatment, a more detailed conservation plan and detailed assessment of different strategies provided would be beneficial [15] [16].

2.2 Analysis of the current state

For the assessment of potential retrofit goals, it is important to understand the tight connection between the current energy performance, climate conditions and existing building fabric [17]. The analysis of these aspects with building simulation will provide valuable insights for the development of different retrofit scenarios [18]. Due to the sensitivity of historic buildings, the techniques for evaluating energetic and environmental performance of buildings should be non-invasive [19]. For the same reason, building simulation of historic buildings requires careful consideration of many different aspects and sets of criteria which need to be taken into account [15] [20].

The most common intervention to be proposed is to improve the building envelope. Actions such as adding insulation layers, renewing the roof, and changing the windows, thus taking care of the thermal bridges, can reduce the energy demand effectively. However, these interventions are to be carefully assessed prior to installation. Historic buildings are built mostly of porous building fabrics, and if insulated in an inadequate manner with non-compatible materials, excess moisture could lead to mechanical, physical and chemical damage [21]. Adequate ventilation and appropriate retrofit materials should be able to tackle this problem [22] [23]. As previously stated, visual impact and conservation issues play an important role in choosing the scenario which provides a well-balanced solution for improving energy efficiency [4].

Adequate ventilation is important in order to prevent the accumulation of excessive moisture in the building fabric [24]. The original windows and doors of historic buildings are often the opposite of being airtight, albeit their role in ventilation, together with the use of chimneys, flues, attic construction and roof covering can be crucial [21][10]. However, if not controlled, draughts can appear and thermal performance of the building could be compromised. Some studies suggest the use of passive ventilation for cooling[25][26].

Whether or not windows should be replaced has been widely debated over the past years [4][27][28][29]. The impact on the appearance, authenticity, durability, change of the airflow in the building and the daylight factor, as well as the financial aspect, play a role in the decision making process.

3. CONCLUSIONS

Following the targets for greenhouse gas emissions set by the legislative branch, the energy efficiency improvement of the existing building stock is one of the major points. In case of historic buildings, these targets are only one of the parameters in the decision making process. The retrofitting strategies and technologies should be decided after careful consideration and multi criteria approach, considering the impact of every solution, and a case-to-case approach.

This brief overview highlights some existing work, but also reveals certain concerns. This is with reference to, first of all, the legislative and protective measures which are currently not synchronized in a proper manner. Secondly, more cooperation among various actors, particularly experts in the fields of conservation and energy efficiency, is what is needed to advance the current knowledge on the decision making process. It would be beneficial to conduct more research on the topic of materials compatible with the historic building fabric, and also on the unintended consequences of retrofitting historic buildings.

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Representativeness of indoor climate monitoring for the target microclimate definition in museums

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***Abstract** – For decades indoor climate management for heritage buildings has been mainly based on static and generalized hygrothermal thresholds. The EN 15757 Standard in 2010 introduced a new praxis based on the evaluation of the peculiar building historic microclimate. The standard proposes the calculation of the building target microclimate as a function of the registered seasonal hygrothermal fluctuations already experienced by the materials in the past years. The presented study wants to investigate if one-year hygrothermal parameters monitoring, can be representative of the building microclimatic history, as well as appropriate for establishing on its basis the microclimate target calculation. The research, performed in a museum in Antwerp (Belgium), is based on the analysis of the target microclimate variation when considering one or multi-years hygrothermal data sets. This study does not aim at invalidating the standard propositions, but at raising awareness when proposing a target microclimate when it has been calculated on the basis of the last segment of the building historic climate.*

Keywords – Museum environmental monitoring; historic microclimate; target microclimate; EN 15757:2010

1. INTRODUCTION

Microclimate is the local climate of a specific environment of part thereof, as defined by a set of physical environmental parameters, the way they are distributed in the three spatial dimensions and how they evolve throughout the time, in section 1.2 [1]. Despite the definition of microclimate stays unvaried through the years, the scientific agreement on the allowable hygrothermal variations to be maintained in a heritage building or a museum as well as the professional know-how to be involved into the decision making process, have been reasonably amended in the last years and finally recommended by the EN 15757:2010 standard. For decades, the microclimate control of museum and heritage buildings, was an issue belonging to conservators and restorers as being traditionally responsible for preserving artworks and collections. As a consequence, the microclimate control had to respond to the sole objective of ensuring optimal climate for collection conservation. This task was generally undertaken by tightly limiting the indoor hygrothermal fluctuations to constant single target values. However, the practical impossibility and environmental unsustainability of such a praxis moved over the microclimate management, from a single-objective problem to a multi-objective one. With the publication of the EN 15757, the heritage buildings microclimate control, starts being integrated into a wider concept of heritage buildings sustainable management: "high standards of preservation of historical buildings can be maintained through the use of affordable and efficient low energy solutions despite the increase in the cost of energy", in [2]. The current interest in merging optimal microclimate for collections preservation with a sustainable museums management strategy, has brought to the redefinition of the methodology for identifying the target microclimate. No longer ideal hygrothermal thresholds should be maintained, but rather it should be allowed the microclimate variability the materials have already experienced during the past. With this purpose the standard introduces the concept of *historic climate*, considered as the "climatic conditions in a microenvironment where a cultural heritage object has always been kept, or has been kept for a long period of time (at least one year) and to which it has been acclimatized", in [2-3]. The historic climate measurement, according to the standard, is the preparatory activity before the calculation of the microclimatic *target level* and *target range*[11] for a specific building or building space.

However, despite a rigorous procedure for the target values calculation has been introduced by the standard, few methodological recommendations to be considered during the calculation procedure, leave room open to interpretation and arbitrary decisions, admitting potentially biased results, hence inaccurate target microclimate definition. More specifically, the standard recommends: 1) To calculate the hygrothermal target range on basis of all the available past climate records covering a period of at least one calendar year; 2) To evaluate whether the monitored indoor climate is harmful to the materials or not; 3) To discard, during the target microclimate calculation, the climate records when excessively affected by indoor climate disturbance.

2. RESEARCH OBJECTIVES

The still ongoing study wants to discuss the practical difficulties in the interpretation of the above listed Standard-recommendations, especially with regard to points 1 and 3 (mentioned in section1) as being the ones directly affecting the calculation process, and to finally evaluate the effect these might have on the resulting target microclimate. This contribution, by discussing an example of target microclimate calculation related to a museum in Antwerp, describes the methodological issues emerging both either when datasets with different time intervals are considered (point 1) or when indoor climate disturbances are experienced during the monitoring period (point 3). It is out of the aims of this work the verification of the calculated hygrothermal target range effectiveness for the purpose of the preservation of the artworks into the investigated space.

[11] The target level and target range are considered, by the EN 15757, as the hygrothermal level to be maintained (the first) and the range of fluctuation that should be not exceeded (the second), to best ensure materials preservation.

3. RESEARCH METHODOLOGY

The ongoing study is performed in the *Mayer van den Bergh* museum in Antwerp. For analyzing the aspects described in the previous section, the Bruegel room has been selected among the fourteen building exhibition spaces (Fig. 1). In this room, for preserving the precious paintings from the popular Dutch painter and the wooden finishing and furniture, a stable indoor climate is required.

However, even if this room was found as one of the most stable in the museum[12], the indoor climate cannot be effectively controlled throughout the entire year; especially during the building free running period (spring and autumn). The air water vapor is controlled in the building by movable air de-humidifiers (type PH26 Defensor), one of these is located into the studied space. Nevertheless, due to the presence of three always open doors (one of this towards the staircase), is practically impossible to control the moisture transport to and from this space.

Figure 1. Bruegel exhibition room in Museum Mayer van den Bergh, Antwerp (Belgium)

Temperature and Relative Humidity have been continuously monitored by Hanwell data loggers with 15 minute sampling time and Wi-Fi-transmitted to the server. Seasonal cycles related to temperature and relative humidity are then obtained by the Central Moving Average (CMA), see Eq. (1) in [4] and Annex A in [2], calculated for the recorded parameters throughout the monitored period.

$$\bar{\varphi}_{30}(k) = \frac{1}{2N+1}\sum_{j=1}^{N} \varphi(k+j) \tag{1}$$

[12] The building is equipped with centralized heating system, no mechanical ventilation is installed with the only exception of a space dedicated to temporary exhibitions in which Air-conditioning is present.

Where $\varphi_{(j)} = \{-N, \ldots, N\}$ are the measured values of the hygrothermal parameters in the time (k) within the considered period.

On basis of the seasonal cycles, the short term fluctuations are calculated as the absolute difference between the instantaneous recorded parameter and the instantaneous seasonal value. Finally, the target (microclimate) range is calculated by excluding the 14% of extreme short fluctuations: the obtained values for the 7^{th} and 93^{rd} percentile are algebraically added to the current 30 days central moving average.

The first part of this study is aimed at evaluating the effect of cumulative hygrothermal fluctuations (throughout a long period) on the microclimate target range variation. It has been studied whether hygrothermal target ranges calculated on basis of 1 calendar year, can be deliberated as representative segment of the building historic microclimate (point 1, section 1). With this purpose, the dataset of hygrothermal records for the year 2015 was considered for calculating the target microclimate. The obtained target climate was compared to the one calculated on the basis of a 5-years climate dataset: from 2010 to 2015[13]. The hygrothermal stability of the space for the year 2015 was assessed by means of percentage inside the range analysis using the indoor climate targets resulting from both the considered time intervals: 2015 and 2010-2015.

The second part of the study is aimed at evaluating the influence of excessive indoor climate variability on the target range variation (point 3, section 1). Because the EN 15757 does not define what "excessive disturb to the indoor climate" means (see *environmental monitoring- data set* in [2]), it is difficult to distinguish which phenomena can be defined as excessive variation and if excessive has to be considered in terms of time-recurrence or fluctuation- amplitude. Any decision at this stage is arbitrary and can strongly affect the results. Moreover, by discarding the hygrothermal records of a period influenced by unforeseen indoor climate circumstances, it might be possible to generate unbalanced target microclimate ranges [2]. For responding to the second research objective, the 2015 microclimate has been evaluated on basis of independent target ranges calculated on 1-year datasets for 2010 and 2012 (when documented failures of the heating system as well as summer overheating occurred). The effect of *excessive disturb to the indoor climate* on the target microclimate was, hence, quantified by means of percentage inside the range analysis, using the hygrothermal targets from 2010 and 2012.

[13] It is worth mentioning that throughout the 5 years, due to temporary loss of communication between loggers and server, some data gaps occurred. However these gaps did not affect the data distribution.

4. RESULTS DISCUSSION

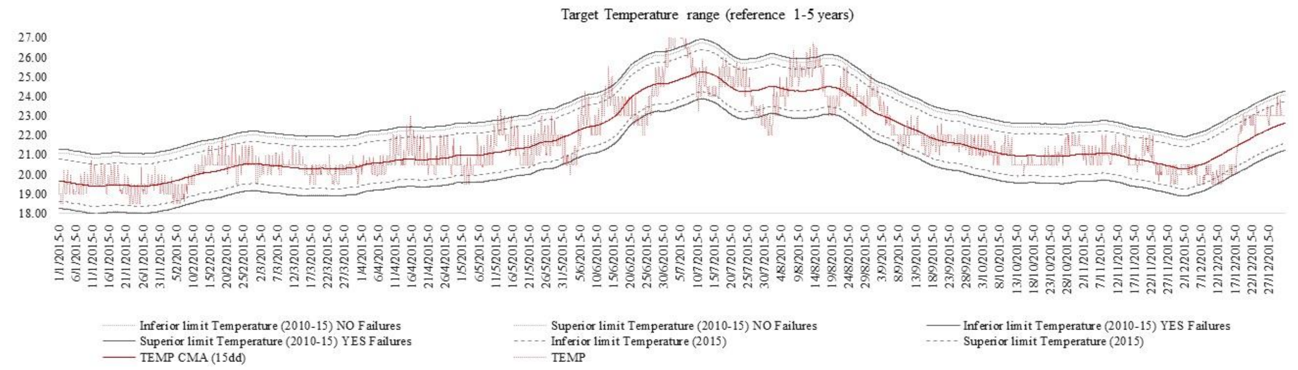
In Table 1 the lower and upper percentile according to the two datasets, considering or not the system failures, is shown. The short term risky fluctuations calculated on 5-years dataset enable the relaxation of the target range for both temperature and relative humidity independently from considering or not the indoor climate perturbations occurred in 2010 and 2012 (see graphs 4.1 and 4.2). In the specific case, the consideration of the 5-years dataset, brings up to 25% *temperature lower percentile* reduction compared to the 1-year one; moreover if considering the perturbation events, the *temperature upper percentile* increases up to 32%.

Table 1. 7th and 93th percentile variation for 1-year and 5- years Datasets

	WITH influence of indoor climate variations (in 2010 and 2012)					
	5 years dataset (2010-2015)		1 year dataset (2015)		Percentile variation 5 years reference VS 1 year reference)	
	Temperature (°C)	Relative Humidity (%)	Temperature (°C)	Relative Humidity (%)	Temperature (%)	Relative Humidity (%)
7th Perc.	-1.395	-2.845	-1.028	-2.617	26.33%	8.04%
93th Perc.	1.658	3.338	1.127	2.945	32.01%	11.76%
	WITHOUT influence of indoor climate variations (in 2010 and 2012)					
7th Perc.	-1.371	-2.796	-1.028	-2.617	25.04%	6.41%
93th Perc.	1.468	2.964	1.127	2.945	23.23%	0.63%

Figure 2 shows that the upper and lower target limits for the dataset 2010-2015 are larger (continuous black line and dotted grey line) than the ones for the sole 2015 (broken grey line). A greater amplitude for the hygrothermal fluctuations is admitted when using 5-years dataset instead of 1-year one. Even if, in the specific case, it appears more relevant for temperature, it holds true also for relative humidity.

The effect of wider target range on the microclimate evaluation was quantified by analyzing the indoor microclimate for the year 2015 considering the lower and upper target bounds defined with regard to both the datasets (see Table 2). When considering the target interval calculated on the basis of the long-term dataset (2010-15), it is possible to observe that the temperature falls within the interval 9.17% more than within the narrower interval calculated on basis of the sole year 2015. This percentage increases even more (10.22%) if the extraordinary perturbations are not excluded from the long-term dataset. The variation related to the Relative Humidity (RH), though consistent with the temperature one, is lower as the RH is controlled throughout the whole year by de-humidifiers units (see section 3).



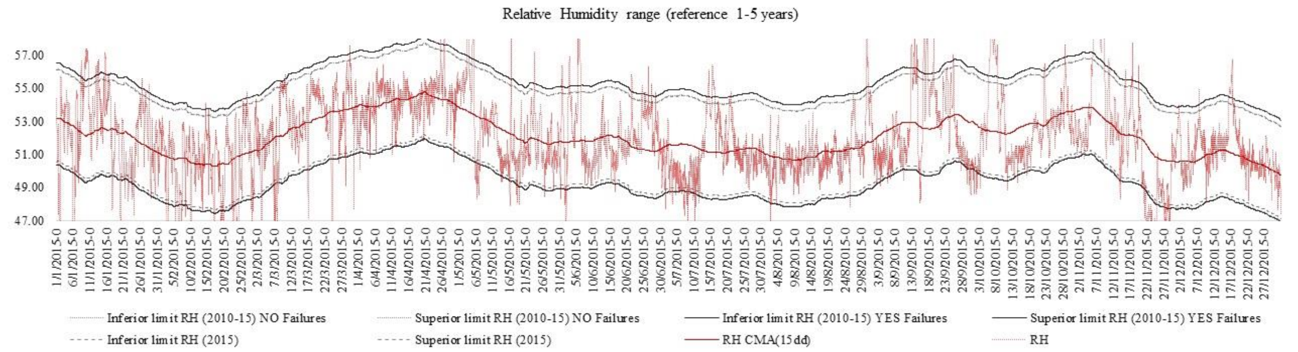


Figure 2. Target Temperature (above), Relative Humidity (below), Room 5, range 2015 and 2010-2015

Table 2. Percentage inside the Range in 2015 considering the target range from 1-year and 5-years Dataset

WITH influence of indoor climate variations (in 2010 and 2012)					
Temperature (2015)			Relative Humidity (2015)		
Interval 2010-2015	Interval 2015	Difference (%)	Interval 2010-2015	Interval 2015	Difference (%)
94.77%	85.98%	-10.22%	88.61%	85.98%	-3.05%
WITHOUT influence of indoor climate variations (in 2010 and 2012)					
93.87%	85.98%	-9.17%	87.15%	85.98%	-1.35%

In the second part of the study, through a theoretical analysis, it was evaluated the effect of target microclimate calculated on basis of past perturbed indoor climates (2010, 2012) on the certification of the current microclimate (2015).

As already mentioned, during 2010 and 2012, exceptional winter and summer indoor climate conditions were registered into the exhibition space (See Figure 3 and Table 3). In both the years, due to heating system failures, the indoor temperature was registered lower than 17.5°C for 5% of time. Furthermore, in 2010, the 20% of the measured indoor temperature was lower than 19.50°C while in 2012 and 2015 the same percentile showed temperature respectively 1°C and 0.7°C higher. As opposite to the low winter temperatures, during the summers 2010 and 2012, the 5% of the measured temperature was observed respectively between 28-32.5°C and 25.5-30.25°C.

The mentioned extraordinary too low and too high temperatures registered during the 2 years provoked the lowering of the lower short term fluctuations and the increase of the upper ones.

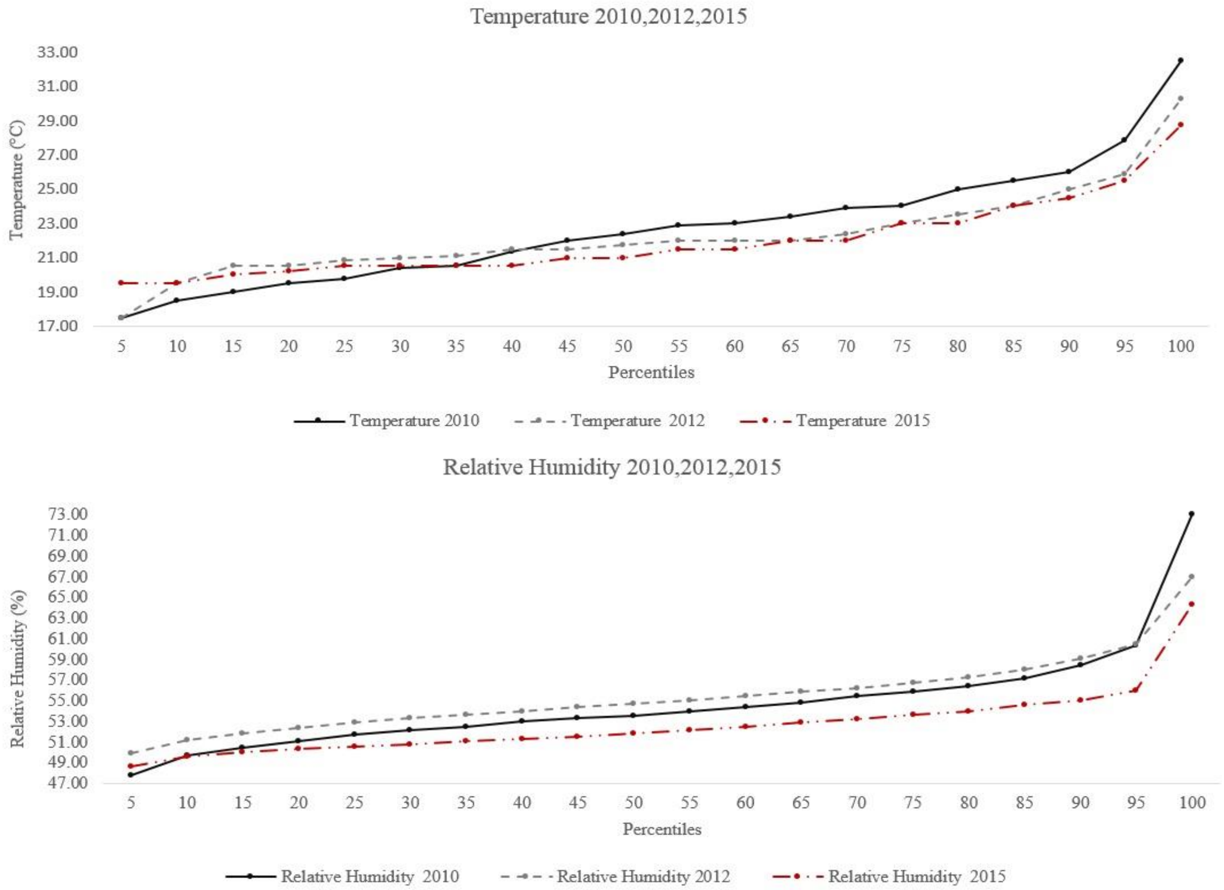


Figure 3. Temperature cumulative (above), Relative Humidity cumulative (below), Room 5, 2010, 2012, 2015

This is valid also with regard to the Relative Humidity; indeed, the existing de-humidifiers could not fully control, the occurred relative humidity picks.

Despite the abrupt hygrothermal fluctuations observable during the year 2012 (see Table 3), the persistence of perturbed hygrothermal conditions for the entire 2010 generated larger short term risky fluctuation.

Table 3. Temperature and Relative Humidity for 2010, 2012, 2015

WITH influence of indoor climate variations

	2010		2012		2015	
	Temperature (°C)	Relative Humidity (%)	Temperature (°C)	Relative Humidity (%)	Temperature (°C)	Relative Humidity (%)
7th Perc.	-2.147	-3.270	-1.432	-3.102	-1.028	-2.617
93th Perc.	2.193	3.319	1.341	3.003	1.127	2.945
measured min	15.00	29.15	13.00	22.70	18.5	38.525
measured max	32.50	73.05	30.25	66.98	28.75	64.35
Measured range	17.50	43.90	17.25	44.28	10.25	25.83

The microclimate qualification for the year 2015, assessed by using the lower and upper risky fluctuations (7th and 93rd percentiles) from the years 2010 and 2012, is compared with the one calculated by using the ones from 2015. Reasonably, the historic data series biased by extraordinary indoor climate fluctuations, enabled the increase of relative humidity and temperature percentage within the target interval respectively by 5% and 15% if compared to the 2015 (see Table 4).

Table 4. Percentage inside the Range in 2015 considering the target range from 2010, 2012, 2015

WITH influence of indoor climate variations

Temperature (2015)			Relative Humidity (2015)		
Interval 2010	Interval 2012	Interval 2015	Interval 2010	Interval 2012	Interval 2015
98.73%	93.46%	85.98%	90.09%	88.48%	85.98%

5. CONCLUSIONS

In the specific case, it has been confirmed that the use of biased historic datasets generates a less demanding but non-representative microclimate targets.

However before opting for filtering out the data, it should be carefully understood the specific building characteristics. For instance in case of historic building without cooling system or mechanical ventilation, slight positively skewed *upper short term fluctuations* should not be immediately seen as suspicious, conversely if the building is equipped with a heating system, and the *lower short term* *fluctuations* have similar absolute values like the positive ones, this might be explained by the failure of the heating system, therefore, further analysis are requested.

For overcoming the uncertainty given by *excessive variations of the indoor climate*, a good praxis can be the extension of the monitoring period rather than the elimination of the most evident fluctuations. Indeed as described in Table 4.2 the effect of abnormal hygrothermal records becomes negligible on a multiyear dataset.

On the basis of the obtained results, it can be concluded that 1-year hygrothermal parameters records can be representative of the building historic microclimate if no installations failure occurred. However, the target microclimate generated by the 1 calendar year data series might result unnecessarily stringent if compared to a longer segment of the building historic climate (more severe fluctuations already experienced by the building materials might not appear in the last exanimated year).

Conversely, if during the monitored year installations failures occurrs, the resulting target might be not representative at all of the past building historic climate, hence the dataset should not be used if not in aggregation with other years.

If it is not possible to acquire a multi-year data series, it might be a good praxis to yearly update the target range especially if it has to be decided upon the HVAC set points.

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Balancing the competing demands of heritage and sustainability, the benefits and risks involved in sustainable retrofit: New Court, Trinity College, Cambridge

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Abstract *– The paper describes the analysis required to identify and balance the benefits (in terms of heritage, comfort, amenity, and sustainability) and risks (in terms of damage to the historic fabric, character and significance) arising from the innovative retrofit of the Grade 1 listed buildings at New Court for Trinity College, Cambridge.*

Keywords – Character; design; policy; benefit-risk

1. INTRODUCTION

1.1 General

Trinity College Cambridge was founded in 1546 by Henry VIII. Its buildings are made up of a number of quadrangular 'courts' of mediaeval, sixteenth and seventeenth origin. New Court, the subject of this paper, was added to the college in the 1820s by the architect William Wilkins. The buildings of the college are listed as grade I and are afforded the highest level of statutory protection within in UK planning law in recognition of their architectural and historic significance.

New Court had been designed, and used continuously, as college residences. In 2009 the College, expressed a desire to continue this use whilst meeting contemporary standards of comfort, utility and energy efficiency. Interiors were cold and damp leading to unacceptable heating costs. Historic interventions had obscured the clarity of the original plan, and the ad hoc provision of showers, WCs, and kitchens over time had created serious fire hazards.

The client brief called for significant reduction of energy usage and carbon emissions. This arose from the need to address energy costs and Carbon Reduction Commitments, an understanding of the implications of climate change and the need to mitigate carbon emissions and to adapt for future climates. The motivation for this project also came from the critical lack of guidance available on the critical relationships between heritage and sustainability – particularly with respect to the risks to historic fabric and character potentially resulting from the improvement of fabric performance.

The college proposed to develop appropriate methodologies and expertise and to share and disseminate this with heritage agencies and other building owners in the private and public sectors.

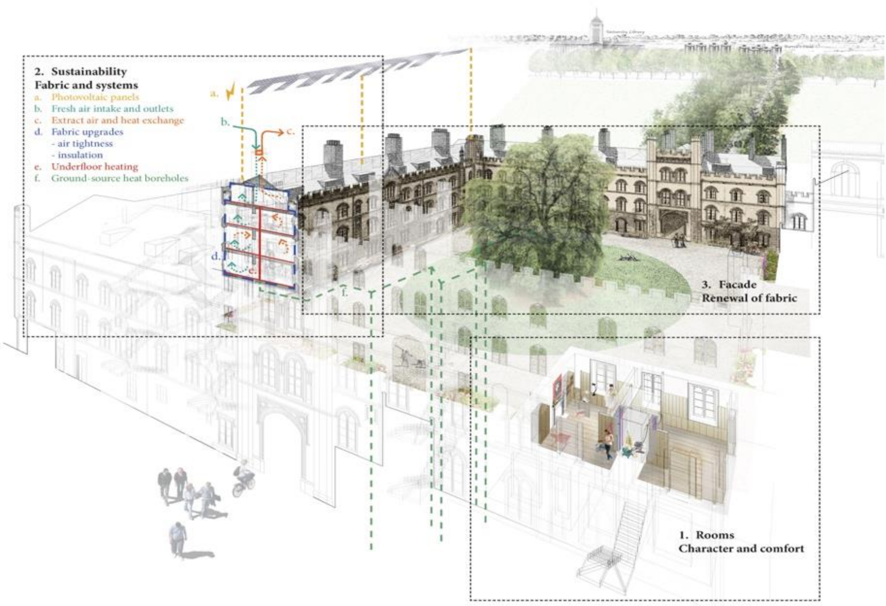

Figure 1. Overview of New Court from the north-east identifying the three main components of the client brief: Rooms with comfort and retained character, Sustainability, and Renewal of the facades.

Figure 2. The existing building. Externally the River, Court and rear facades are finished with different materials, of differing quality and character and characteristics of vapour and moisture resistance and permeability. Internally the spaces illustrate a history of iterative interventions, replannings and the ad hoc installation of services and amenties.

A three-stage approach was developed to establish a detailed understanding of the building in terms of heritage significance, character and fabric performance, evaluate a range of possible responses/inventions and, create an integrated and interdependent package of proposed measures. Both Cambridge City Council planning department and English Heritage, EH, (now Historic England) would be consulted at each stage.

This paper on the planning and design research is one of three that describe the project; the other two concern the in-situ building monitoring of the project and the material sampling and modelling. Together these papers map the parallel exercises that led to the development of integrated design proposals that were granted Listed Building Consent in January 2013 and have now been completed on site. This is the first Grade I listed building in the UK to have been the subject of such an extensive low energy refurbishment via a rigorous process of scrutiny. The processes and outcomes of this project will have an important influence on this sector of the built environment for the future.

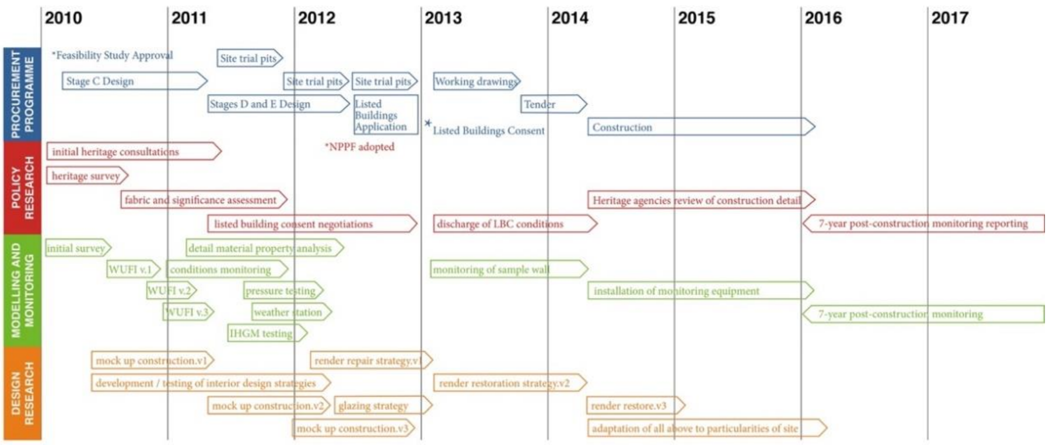

Figure 3. Chronology of parallel project and research activities explaining both the interlinkage of these processes and of the papers that describe them: 100, 102 and 103.

1.2 Policy research

The policy research into heritage and environmental policy covered the entire landscape of national and local government policy and non-statutory guidance, with particular focus on 'Conservation Principles, Policies and Guidance for the Sustainable Management of the Historic Environment'[1]. (CPPG) and the National Planning Policy Framework (NPPF)[2]. The key principles drawn from the former document were that:

The 'authenticity' of a place is derived from whatever most truthfully reflects and embodies the values attached to that place and can relate to design and function as well as to fabric. Retaining authenticity is not always achieved by retaining as much of the existing fabric as is technically possible. This suggested that the 'normal' conservation approach might be less relevant than one that maximised the viability of the usage of the building for its original purpose. It was established that the primary significance of New Court lay in its unbroken occupation by the community of students and fellows - embodying the principle of 'collegiality' that is so important to the tradition and life of the College.

Contemporary interventions to a building 'should be subtly different so as to be legible and capable of discernment and interpretation'. This suggested that new interventions might be expressed in a contemporary idiom – rather than the pastiche that has characterised much heritage refurbishment work.

Both the NPPF and CPPG policies reflect a shift in decision-making on historic building projects; away from pure heritage conservation and towards a more holistic approach to economic, social and environmental issues. This change in emphasis requires public benefits to be balanced against conservation and any loss of significance. Specifically, the plan emphasises that 'consent should be refused unless the public benefits derived from the project are substantial and outweigh the harm or loss to heritage significance'**.**

In the context of a lack of case-history, evidence, or examples of how public benefits might be subjectively weighed against perceived harms or loss to heritage significance, it was proposed that the local authority's decision-making process might be clarified if these issues were addressed as the answers to three questions:

'What are the relative heritage significances of the building?' This required input from the client as well as from the heritage agencies. Critically, it was posited that heritage significance should reflect the legacy of occupation of the buildings for their optimum viable use.

'What are the harms or benefits of the proposals to these heritage significances? This required recognition of the proposed benefits as well as the perceived harms; bringing the historic shutters back into operational use, replacement of unsympathetic cement render, the removal of the surface pipework, radiators and other service boxings, etc. and restoration of the original façade treatment and colouration.

'Are any residual harms outweighed by other public benefits?' This addresses the principal aims of the NPPF and suggests that local authorities should be responsible for determining the balance of harms against other public benefits (the reduction of carbon emissions, etc.). While informed by officers in every policy department of the local authority, it was clear that this question should be principally addressed by the elected members. The public benefits here included the reduction of carbon emissions, advancement of building research and monitoring, and knowledge transfer.

1.3 Design research

The conservation agencies were concerned that, in addition to damaging the building fabric, the introduction of an insulated lining would deleteriously affect the character and quality of the historic interiors. Detailed analysis through drawing, modelling and full-size maquettes led to a strategy that restored the original interiors, whilst delivering the technical performance and enhancing the character and heritage. The editing of previous interventions that had obscured the clarity of their original form, the removal of all old pipes and cables and the provision of new services within fitted furniture, allowed the simplicity of the interiors and the fabric of the walls to be sympathetically reinstated and provided access for future adaptation or maintenance without breaking into the old walls.

Figure 4. Photograph of 1:10 scale model and of full-size maquette of cornice detail, exploring the form of the insulated lining and joinery and the relationship of the insulated lining and historic cornice.

New interventions were planned to respect the structure of the original plan and, where possible, ensuite shower rooms or shared shower or kitchen facilities were planned away from the external walls to minimise risk to the insulated external wall fabric from occupancy-generated moisture/humidity. Where this was not possible, the condition of the fabric in these spaces was to be carefully monitored.

The details of the new interventions embody a discreet legibility - following the principles established above. Where new walls meet existing ceilings or cornices, a deep quirk articulates the relationship between new and old and the insulated lining reveals the original cornice - making clear the original footprint of the historic room.

Figure 5. Before / after images of the treatment of windows and external render. The colour of the render and cast-iron window traceries and the dark colour of the window frames reinstate the integrity of the gothick 'pierced' wall plane.

The sympathetic renewal of the building exterior addressed the visual integrity and stability of the courtyard elevations. The re-rendering of the 1960s and 70s had used cement render, unsympathetic in appearance and impermeability, trapping moisture against the brickwork fabric and leading to failure. Careful investigation determined the depth of the cement render, the details of its application to the mouldings, and the confirming the feasibility of complete removal of this material and replacement with a lime render, of more sympathetic colour, texture and performance. The sealed double-glazed units installed to the existing timber windows were provided with a traditionally drawn glass outer leaf – preserving the characterful pattern and texture of fragmented reflection around the court.

1.4 Findings

These solutions were based on the combination of close identification of the heritage values of these elements and the outputs from the technical monitoring and modelling processes. These research strands were brought together to inform financial and carbon cost / benefit analyses showing the values, cost-effectiveness and payback periods arising.

The construction cost of the project was c.£20m, creating 180 rooms at the cost per room of just over £110k per room and 5,340m2 (gross internal floor area) at £3,745/m^2. These figures include the costs of forming a new service duct around the courtyard and the restoration of the external elevations, but the costs per room and per m^2 are directly comparable with the rates for both new build student accommodation and for other conservation-led refurbishment of similar buildings in the City - of comparable room size and amenity but of lower environmental performance.

The interwoven nature of the fabric upgrades and service installations make it difficult to separate the costs and benefits (payback periods) of individual elements, however the following simple payback periods were calculated:

Table 1. Calculated Payback Periods for improvement of thermal performance of fabric elements [3.]

Measure	Payback period (domestic rates) years
Insulation of external walls	12.9
Insulation of Ground Floor	6.6
Insulation of Roof	7.8
Upgrade of windows	8.5

1.5 Site outcomes

The delivery of the technical requirements of the brief and design on site has balanced traditional and innovative building forms and construction in a contemporary manner. The site process has exhaustively tested the design approach and the team have developed construction details capable of reliable delivery by the British construction industry – with all of its strengths and weaknesses.

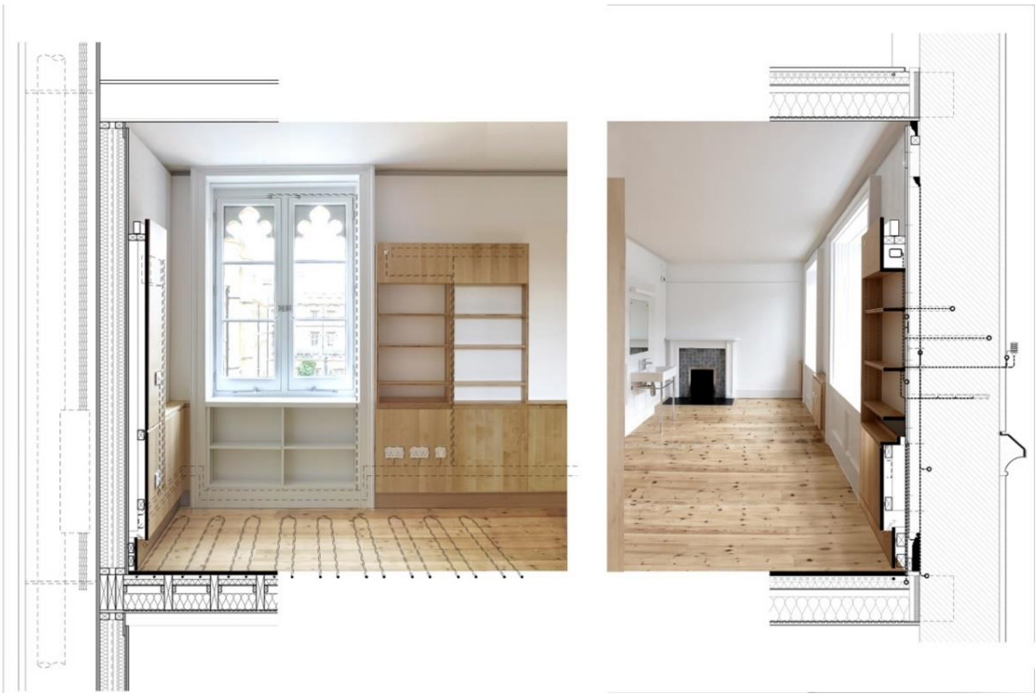

Figure 6. The combination of 21st century methods and historic constructions is illustrated in the following photographs of completed room interiors overlaid with drawing to illustrate the extent and integrated nature of the interventions

2. CONCLUSION

This project demonstrates the successful marriage of old with new and of heritage with sustainability and that the cost of making historic buildings sustainable need be no greater than the cost of a normal, conservation-led refurbishment.

This approach has been based upon analysis of the heritage and environmental policy context and a deep understanding of the original building – its character, construction, significance, and hygrothermal behaviour. This has enabled the risks and benefits of providing contemporary standards of safety, utility, comfort and fuel-economy within a historic building to be balanced and to reconcile the demands of conservation and sustainability by the use of and innovative design, construction and collaboration.

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[3] These analyses were carried out in early 2012 – when fuel prices were considerably higher than now.
The College is able to purchase gas and electricity at about half of normal domestic tariffs. This effectively doubles the Payback Periods but, as this still lies within the College's 30-year refurbishment cycle, this was acceptable.

Integral design method for Energy efficient Restoration

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Abstract *- Designs for improving energy efficiency in historical buildings are tailor made. For initiators the flexible character of design processes raises uncertainty about why certain energy measures are (not) allowed. How is decision making in the design process organised? And what mechanisms influence tailor made designs? In this paper we present an integral design method for Energy efficient Restoration. Our theoretical background draws on two sources. Firstly, we follow design theory with distinct generic and specific designs. Secondly we use the 'heritage-as-a-spatial-factor' approach, where participants with different backgrounds focus on adding value to heritage. By applying the integral design method, we evaluate decision making processes and reflect on heritage approaches. We suggest how the integral design method can be improved and question the parallel existence of heritage approaches.*

Keywords – Energy efficiency; historical buildings; design theory; 'Heritage-as-a-spatial-factor'-approach

1. INTRODUCTION

Owners of historical buildings are committed to sustain their property. Earlier research suggests [1] that many owners consider applying measures to improve thermal comfort and energy efficiency. Designs for energy efficient historical buildings are tailor made for two reasons: regular energy measures often are not compatible with conservation of heritage values, and preferences of initiators regarding functions and comfort levels vary considerable. Owners of historical buildings indicate that they find the design process fuzzy, because to them it is unclear why specific energy measures are (not) allowed. To improve the design process, we study what mechanisms play a role and how decision making is organised in this process. In this paper we follow the creation of tailor made designs for energy efficiency in three cases. As a method we use an integral design method developed for energy efficient restoration of historical buildings (further *integral design method ER)* [2], [3]. Our aim is both to evaluate this method and to discuss the 'heritage-as-a-spatial-factor' approach.

2. THEORETICAL BACKGROUND

2.1 Generic designs

A design process is a tool to develop a solution for something that does not yet exist in practice. In the literature different design theories are used to improve our understanding about designing: how is the design *process* organised, which *participants* are involved and what topics are taken into account to develop a *product* [4]? In general a distinction is made in two types of designs: generic designs that provide a protocol or framework (such as Design-Based Research [5], Design Science Research [6], and Design Study [7]), and specific designs that provide solutions for specific situations (such as Study by Design [7][8], [9]). Generic designs can be used as a framework to develop specific designs. The *integral design method ER* is categorised as a generic design method, and tailor made designs as specific designs. Design-based Research (DBR) characterizes generic design methods as a design-experiment methodology: It "focuses on understanding the messiness of real-world practice, with context being a core part of the story and not an extraneous variable to be trivialized. Further, (DBR) involves flexible design revision, multiple dependent variables, and capturing social interaction. In addition, participants are not "subjects" assigned to treatments but instead are considered as co-participants in both design and analysis. Lastly, given the focus on characterizing situations (as opposed to controlling variables), the focus of (DBR) may be developing a profile or theory that characterizes the design in practice (as opposed to simply testing hypotheses)" [5].

2.2 'Heritage-as-a-spatial-factor' approach

We use heritage approaches to understand how actors think about adjusting historical buildings. Heritage theory distinguishes tree approaches with different fundamental principles: 'Heritage-as-a-spatial-sector' where actors from a monodisciplinary perspective focus on preserving heritage as is or as is originally was meant to be [10], [11], [12]; 'heritage-as-a-spatial-factor' where actors from multiple perspectives define the design problem and criteria for assessing adding value [10], [11], [13], [14], for example for weighting energy measures; 'heritage-as-a-spatial-vector' where actors from an interdisciplinary perspective use heritage to improve the chance of success of 'something else' [11], for example socio-economic developments. In this paper we focus on the 'heritage-as-a-spatial-factor' approach since developing specific designs for energy efficiency in historical buildings focusses on adding value and involves discussing energy measures from multiple perspectives.

3. METHODOLOGY

Generic designs can be used to develop specific designs; also specific designs can be used to improve generic ones. By following the development of specific designs in case studies we gather data on the decision making process. As a framework for analysis we use 'CIMO-logic' from DBR theory [6]: "this logic involves a combination of a problematic **C**ontext, for which the design proposition suggests a certain **I**ntervention type, to produce, through specified generative **M**echanisms, the intended **O**utcome(s)." Regarding the *integral design method ER*, this is worked out as follows (after [6]):

- C – context: "the surrounding (…) factors and nature of the human actors that influence behavioural change." Interventions "will be affected by at least four contextual layers: the individual, the interpersonal relationships, institutional setting and the wider infrastructural system." In our analysis we describe the design problem in terms of usability (perspective of the initiators) of the built heritage (condition, values), its socio-economic context and how the design process was organised (the involved participants).

- I – intervention: an action to "influence behaviour". In the analysis we describe proposed energy measures to influence the performance of the historical building.
- M – mechanisms: is triggered by a (proposed) intervention in a certain context. In the analysis we describe mechanisms that are addressed in decision making.
- O – outcome: the effect "of the intervention in its various aspects." In the analysis we describe the (preliminary) results for energy efficiency in the investigated historical buildings.

We applied the *integral design method ER* (generic design) in three case studies to provide insight in decision making in the design process. One of the authors (Vieveen) took part as participant in the design team. Empirical data consists of site-visits, desk research (archival research, guidelines, technical information) and qualitative interviews. Chapter 4 describes the results of the case studies, following the components of the 'CIMO-logic'.

4. RESULTS

4.1 Saint Peters' church Eindhoven

Saint Peters' church (listed for its national importance) is one of five churches in the Saint Peters' parish in Eindhoven. The community is confronted with secularisation and decreasing income which led to the closing of churches in the region. To secure healthy operating expenses, the parish is looking for ways to increase income and decrease expenses. Urgency for energy measures arises from an outdated heating system of the Neo-Gothic church which damaged historical elements (windows, organ). Decision making is organised in two steps: a core team (the parish, supported by researchers) taking formal decisions and a more open-ended flexible team of experts from different (energy-related) fields called '*platform moNUmentaal*' suggesting specific integrated designs for historical buildings in general and more specific for Saint Peters' church.

The design process was organised in two phases. The first phase focussed on defining the design problem by a site-visit, desk research, interviewing participants and discussions on potential energy measures in the core team. Energy measures were categorised by impact on historical values: no impact (crowdfunding, control systems), low impact (measures that affect less important heritage values: a new heating system, floor isolation) and large impact (measures with major implications for important heritage values or that increased complexity in decision making: solar panels and exchanging energy in the nearby built environment) [15]. The second phase consists of co-design sessions where participants discuss their ideas and their 'homework' (applied research by the participants) for the follow-up session (in progress).

Mechanisms were identified during meetings and interviews. The parish board is committed to improve thermal comfort, reduce costs (energy, maintenance) and increase income (by secondary use).

The majority of the surveyed parishioners mentioned the importance of historical elements for worshiping. The diocese addressed preventing damage, healthy operating expenses and no secondary use (since other churches were closed). Heritage experts were willing to discuss adjusting the historical elements if it would secure heritage protection of the listed building (national importance) in the long term. Energy consultants advised ‘invisible’ energy measures: practical use and energy management, measures ‘behind walls’ and exchanging energy (introducing new participants with their interests).

As a result, the participants of the core team preferred measures with no or low impact on esthetical and heritage values. A list of energy measures was published in a report [15]. Together with the underlying data, the report was used as input in the co-design sessions which is still in progress.

4.2 ‘Dairy factory’ De Groeve

Demographic transition in the region of De Groeve raised pressure on local services and businesses. Two entrepreneurs wanted to preserve the former dairy factory in ‘Amsterdamse school’-style (non-listed building) by reusing it for leisure and tourism activities. Their ambition is zero-energy renovation of the historical building, supplied by renewable energy. A flexible integral design team with the initiators (entrepreneurs), architect, energy consultant, energy expert and researcher developed a tailor made design. Flexible since the composition of the design team was supplemented with other participants during the design process for example by financial and catering experts.

The design process was organised in two phases: the first phase focussed on a feasibility study for adaptive reuse [16], the second phase focussed on developing an energy efficient design. The second phase started with a brainstorm and site-visit where participants presented their view on preservation of the building and potential energy measures. Follow up meetings were used to discuss ‘homework’ which resulted in energy measures (insulation, indoor climate, energy supply) per space.

Mechanisms were identified by desk research and during interviews and meetings. The reuse expert advised (phase one) multiple use given the size of the building and the need to spread risks related to income. During the brainstorm and site-visit (phase two) participants used the concept *Adaptive energy efficiency* to develop tailor made solutions per space, weighting heritage values and high performance in terms of daily use (functionality), energy efficiency, and thermal comfort. For example, areas in the building with non-historical values were used for Bed & Breakfast since walls can be isolated; and the kitchen was repositioned to improve the efficiency of a heat recover system. After involving a professional kitchen consultant, the design team concluded in a relative early phase that electric ovens were too expensive, withdrawing one of the initiators main ambitions. Shortly before the plan was submitted for requesting a building permit the initiators ended the process, stating that they received insufficient support by the municipality to continue their initiative.

The first phase resulted in a business plan and pre-design for the buildings’ lay-out. The second phase resulted in an historical analysis, design sketches, and calculations on thermal comfort and energy systems that would have been used to request the building permit.

4.3 Der Aa-church Groningen

The medieval Der Aa-church in Groningen is a listed building of national importance. It is let for multiple use since the 1980s. To secure a healthy business and preserve the church on the long term, the owner of the church (foundation Der Aa-church Groningen) and semi-commercial user (Special Locations Groningen) started the project 'Future for the Der Aa-church'. This project aims to preserve heritage values, improve thermal comfort, reduce energy use (zero-energy), secure safety (earthquake proof) and secure income (adding more opportunities to let the church). The design team consists of the owner, semi-commercial user, building engineers, an energy consultant, heritage experts and a researcher.

The initiators subdivided the design process in three phases: defining the design problem and exploring potential measures; developing an integral design for thermal comfort and energy efficiency (in progress), and; safety (earthquake proof). During the first phase a site-visit, brainstorm session, desk research and interviews with different actors resulted in an inventory of potential energy measures, such as separating the choir and nave, insulation, applying curtains, secondary glazing, a new heating system, and sustainable energy sources [17],[18]. In the second phase (in progress) participants discuss 'homework' during design meetings to develop a tailor made solution to improve thermal comfort and energy efficiently such as insulation, secondary glazing, indoor climate and heating systems. New actors (architect, structural expert) will be involved after the structural design for energy efficiency and thermal comfort is developed.

Mechanisms were identified during interviews and meetings. All participants agreed that the historical ambiance should be preserved, but had different ideas on protecting heritage values. For example, in the first phase participants questioned if secondary glazing should be considered as an improvement, taking into account the effects on the indoor climate (increasing humidity) and thus the protection of heritage values (organ, medieval paintings on the high vault) on the long term. As a result participants advised to consider specific measures (such as windows) in a wider context: balancing the effects of energy measures to the indoor climate and energy as an integrated whole – the starting point of the second phase. During a design meeting in this phase the initiators (owner, user) mentioned that support of the municipality and other actors (as participant in the process) contributed to success.

Inventorying measures is executed in three phases. The results of the first phase [17],[18] are used as input for the design team that developed the integral tailor made design (in progress).

5. DISCUSSION

In this paper we used the components of the 'CIMO'-logic to analyse the results of specific design process for three case studies projects that were executed following the generic design *integral design method ER*. Firstly, we evaluate the *integral design method ER* by comparing the case study results following the 'CIMO'-logic. This provides insight in how decision making in the design process is organised and what mechanism influence the development of tailor made designs. Secondly we discuss the 'heritage-as-a-spatial-factor' approach as a generic design to develop tailor made designs for energy efficiency in historical buildings.

Context. The design problems were based on *usability* (perspective of the initiators) and were underscored by topics derived from *built heritage* (prevent damage, preserve heritage values) and *socio-economic developments* (secularisation, demographic transition, sustainable development, earthquakes). All design teams were composed with experts with multiple disciplines.

Intervention. The design teams organised the design process in phases starting by a diverging phases (analysing the design problem and developing potential energy measures) and converging phases (further development of the tailor made solution). In Eindhoven, De Groeve and Groningen, the design process is fed by research leading to a wide variety of potential energy measures. For all cases a wide variety of energy measures was discussed: financial, behaviour, building, installations.

Mechanisms. According to the design teams for all cases, an important mechanism in discussing energy measures was conserving the historical atmosphere (important value for daily use) or to preserve heritage values from a legal perspective. Also participants agreed that energy measures (to improve thermal comfort and reduce energy use) are inevitable to sustain historical buildings, but that these measures should be workout with care regarding their effects on preserving historical elements on the long term. Since the function of spaces of the building in De Groeve was not fixed during the design process, participants also discussed energy measures per space. In De Groeve and Groningen support of the municipally and other actors was mentioned as important mechanism for success or failure.

Outcome. In Eindhoven and Groningen the development of the tailor made design is still in progress, the initiators of De Groeve withdraw their initiative. Research is still in progress, for example, we did not yet evaluate the design process with the involved participants.

We suggest the further development of the *integral design method ER* in the subcategorization of the 'CIMO'-logic. For example, by nuancing the design problem in: interest of participants, context of the built environment (technical condition, values and site) and general context (socio-economic developments and natural events). As a result, decision making criteria related to energy measures can be made more explicit, thereby increasing insight in why specific (proposed) energy measures are (not) allowed.

In this section we discuss the 'heritage-as-a-spatial-factor'-approach as an approach to improve energy efficiency in historical buildings. The case studies show that a generic design can be used to develop specific designs for diverse initiatives. The *integral design method ER* can be used for multifaceted design problems, with multiple targets and it allows to improve designs by involving new participants with multiple backgrounds during the design process. Also, the method can be used to make the decision making process about energy efficient in historical buildings more transparent.

Reflecting on the heritage approaches, we find that participants in all cases used the historical atmosphere and/or heritage values to frame suitable energy measures, which is the fundamental principle of the 'heritage-as-a-spatial-sector' approach. This raises several questions: do the heritage approaches coexist parallel; are these approaches layered and do they relate hierarchically to one another? However, this paper is limited in that it represents only three cases. We suggest further research is needed to provide answers to these questions.

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