DYNASTEE

EBC

Energy in Buildings and Communities Programme

Seminar

Real building energy performance assessment

Wednesday 16 April 2014 - 14:00-18:00 – Gent, Belgium

Proceedings

The seminar is organised by the DYNASTEE platform (www.dynastee.info) which is facilitated by INIVE (www.inive.org), in the framework of the IEA Annex 58 6th international expert meeting in Geent. The practical organisation is in the hands of University Ghent and BBRI, under the auspices of the Technical Committee Hygrothermics.

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The energy performance of a building is essentially determined by the (1) thermal characteristics of the building envelope, (2) installed services and (3) building usage. As the latter is not easily predicted nor controlled, the first two are decisive in achieving the envisaged building energy performance, both for new buildings and renovations.

The theoretical energy use calculated on the basis of building plans and specifications, in order to meet building regulations or specifications by the builder, determines the anticipated performance.
It may differ, however, from the actual 'as-built' performance in a significant way.
The IEA EBC Annex 58-project on ' Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements' is working on this gap between actual and calculated performance of the building. A consortium of researchers and industries from 15 countries are developing knowledge, tools and networks to achieve reliable in-situ dynamic testing and data analysis methods that can be used to characterise the actual thermal performance and energy efficiency of building components and whole buildings.

This seminar gives an overview of the current knowledge in the field of energy performance assessment. It aims also at looking into the future of new applications and answers how to close the gap between calculated and real performance.

The seminar is organised by the DYNASTEE platform (www.dynastee.info) which is facilitated by INIVE (www.inive.org), in the framework of the IEA Annex 58 6th international expert meeting in Ghent. The practical organisation is in the hands of University Ghent and BBRI, under the auspices of the Technical Committee Hygrothermics.
The seminar is open to all professionals interested in the real performance characterization of buildings.

About Dynastee

Dynastee is a platform of information exchange on dynamic analysis, simulation and testing of the energy performance of buildings. Dynastee is closely linked to the activities of the IEA ECB Annex 58 project; it is responsible for the subtask on dissemination and the Network of Excellence. This is done through activities such as training of researchers on dynamic methods (Summer School), bringing its expertise from earlier projects (PASSYS-PASLINK) into the Annex 58 project, publication of a newsletter and a website, and organising workshops and webinars.

About INIVE

INIVE EEIG (International Network for Information on Ventilation and Energy Performance) a European Economic Interest Grouping has 11 member organisations (BBRI, CETIAT, CIMNE, CSTB, ERG, ENTPE, IBP-Fraunhofer, SINTEF, NKUA, TMT US and TNO) (www.inive.org).
INIVE is coordinating and/or facilitating various international projects, e.g. the AIVC (www.aivc.org), the European portal on Energy Efficiency (www.buildup.eu), TightVent Europe (www.tightvent.eu), Venticool (www.venticool.eu) and Dynastee (www.dynastee.info)

DYNASTEE
NEWSLETTER ISSUE 2013/3

Foreword

Dear reader,

With pleasure we present you the 3rd DYNASTEE Newsletter. Dynastee is a platform of information exchange on dynamic analysis, simulation and testing of the energy performance of buildings. Dynastee is closely linked with the activities of the IEA ECB Annex 58 project; it is responsible for the subtask on dissemination and the Network of excellence. This is done through activities such as training of researchers on dynamic methods (see the Summer School 2013), bringing its expertise from earlier projects (PASSYS-PASLINK) into the Annex 58 project, organising workshops (see the High Performance Buildings event in Brussels, June 2013), and this newsletter. This issue is dealing largely with the intermediate results and the progress made in the Annex 58 project. Bit by bit the expertise is growing and we are quite confident that the research community involved will find the right answers how to bridge the gap between the real performances of a building and the calculated or designed ones. The building industry is welcome to forward its questions to this growing Network of Excellence.

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DYNASTEE

Newsletter Editors

- **Hans Bloem**
- **Luk Vandaele**

Summary report of the workshop on
HIGH PERFORMANCE BUILDINGS
Design and Evaluation Methodologies

The EU Sustainable Energy Week (EUSEW) is an initiative of the European Commission coordinated by the Executive Agency for Competitiveness and Innovation, in close cooperation with the European Commission’s Directorate-General for Energy. It showcases activities dedicated to energy performance, efficiency and renewable energy solutions. During that week, INIVE-DYNASTEE, EC-JRC-IET and ENEA organized a series of 4 half-day workshops on the theme "High Performance Buildings - Design and Evaluation Methodologies". The workshop was held in Brussels at the BBRI offices from 24 - 26 of June 2013. About 125 experts from all around the world registered for the workshop.

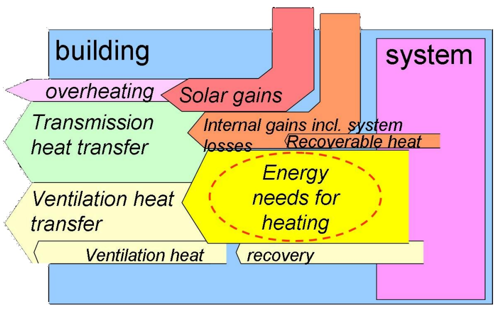
The aim of the event was to focus on the energy related part in the design process of new or renovated buildings. Four consecutive sessions dealt with dynamic aspects of performance assessment including cost analysis, monitoring, evaluation and modelling of high energy performance buildings, various aspects such as renewable energies and consumer behaviour, design case studies and EPBD related CEN energy standards. Experts from CEN TC371, working on the revision of the standards, were invited to participate as well as project leaders from IEA-EBC Annex 52 (nZEB), Annex 53 (Monitoring) and Annex 58 (Performance characterisation).

An overview of the IEA EBC-Annex 58 activities was given, focussing on characterization of thermal performance of building fabric based on full scale experiments to develop the necessary knowledge, tools and networks to characterise the actual energy performance and thermal response of building components and whole buildings based on full scale dynamic measurements.

This activity is highly relevant for achieving in-depth knowledge to the properties and features of different approaches to energy performance assessment.

Statistical methodologies were presented which are applicable for modelling building energy performance assessment based on measurements of heating in buildings, e.g. from smart metering. The range of methods spans from modelling based on simple daily readings of heat load, to detailed modelling based on high time-resolution data. Key performance indicators need to be coupled with knowledge of uncertainty provided by statistical techniques.

All papers and presentations from the workshop are available. Find the link on **www.dynastee.info**



IEA EBC Annex 58-project

"Reliable building energy performance characterization based on full scale dynamic measurements"

Since 2011, international experts from all over the world are working together for four years within the research project IEA EBC Annex 58 on the topic of 'Reliable building energy performance characterization based on full scale dynamic measurements'. This project takes place in the framework of the 'Energy in Buildings and Communities Programme' of the International Energy Agency. The addendum of one of the previous Dynastee-newsletter gave an overall overview of the project and its main objectives (see www.dynastee.info/download/DYNASTEE-NL-2012-A-Addendum.pdf).

At the latest expert meeting in Hong Kong October 2013, the project was halfway; time for an update on the status of the project. The aim and progress of subtasks 1 and 2 is described in more detail further on in this newsletter. In this article the general progress and ongoing research on dynamic data analysis and energy performance characterization is described.

Characterising the actual performance and dynamic behaviour of building components and buildings is an essential part to obtain – not only on paper, but in reality – high performance buildings. Furthermore, dynamic data analysis methods have shown to be a valuable tool to deduce simplified models of e.g. advanced components and systems to integrate them in a reliable way into Building Energy Simulation (BES) models or when optimizing smart grids for building communities. Investigating possibilities and limitations to characterise building (components) based on dynamic data is one of the key topics within Annex 58. This research is driven by case studies. As a first simplified case, an experiment on testing and data analysis is performed on a round robin test box. This test box can be seen as a scale model of a building, built by one of the participants, with unknown properties for the other participants. The test box is shipped to different partners (different climatic conditions) with the aim to perform a full scale measurement of the test box under real climatic conditions. The obtained dynamic data are distributed to different institutes who have to try to characterize the test box based on the provided data. The first result show how different techniques can be used to characterize the thermal performance of the test box, going from a simple stationary analysis to advanced data analysis methods starting from the measured dynamic data.

As a second case study, an experiment has been set up in the twin houses at IBP Fraunhofer in Holzkirchen, Germany. The data of this experiment will both be used as validation data for BES-models, as well as case study to characterize the thermal performance of the houses based on so-called grey box modeling. As up till now, BES-models are typically validated by intermodel comparison, there is a lot of interest in participating in the current real validation case, both from inside Annex 58 as from external partners. The blind run for the validation case should be finished by January 2014, afterwards the data is made available within the project for the thermal characterization of the dwelling. Results are expected spring 2014.

Further information about IEA EBC Annex 58 can be found at **www.ecbcs.org/annexes/annex58.htm**

State of the art on full scale testing and dynamic data analysis

The IEA EBC Annex 58 is an international research collaboration on the topic 'Reliable building energy performance characterization based on full scale dynamic measurements'. The ultimate goal of the Annex is to develop the necessary knowledge, tools and networks to achieve reliable in situ dynamic testing and data analysis methods that can be used to characterize the actual energy performance of building components and whole buildings.

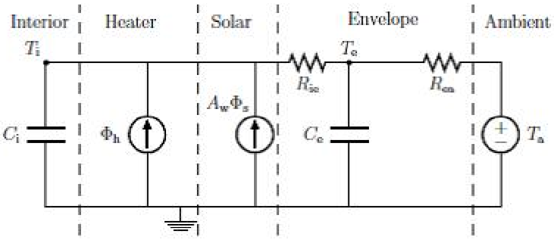
It is since September 2011 that the Annex has been active, which means that the project is halfway at the moment of writing (fall 2013). At the working meeting in Hong Kong in October 2013, one of the first outcomes of the project was presented: the state of the art report on full scale testing and dynamic data analysis, which was the result of the work of participants of subtask 1.

In subtask 1 an overview and evaluation was made of previous and ongoing in situ test activities based on a literature review and existing reports. An inventory was made of full scale test facilities available at different institutes all over the world. Common methods were described to analyze dynamic data, with their advantages and drawbacks. The overview of full scale testing and dynamic data analysis relates to energy performance characterization of either building components or whole buildings.

The data analysis methods discussed in the first section of the report range from averaging and regression methods to dynamic approaches. The methods are discussed in relation to their application in following in-situ measurements:

- measurement of thermal transmittance of building components based on heat flux meters;
- measurement of thermal and solar transmittance of building components tested in outdoor calorimetric test cells;
- measurement of heat loss coefficient and solar aperture of whole buildings based on co-heating tests;
- energy model characterization of whole buildings based on monitored dynamic energy and climatic data.

Left: Round Robin Test box at Almeria, Spain and right: one of the twin houses at IBP, Germany used as controlled test house for validation of BES-models.



Example of RC-network representing a two-state grey box model for energy characterization of a building

Calorimetric facility at IBP-Holzkirchen

The 25 test facilities described in the second section of the report are subdivided in three main groups, depending on the scope and scale of the testing:

- Test facilities for evaluation of (hygro)thermal building envelope performances
- Facilities for evaluation of building component energy performances
- Building integrated energy performance testing of components and systems

Within each group, facilities with a long tradition as well as recently developed or planned platforms are described. Compared to the previously published book on 'Full scale test facilities' (see Dynastee newsletter 2012/1), the subtask 1 report contains 10 new test facility descriptions.

More information:
www.ecbcs.org/annexes/annex58.htm

International Energy Agency: Annex 58: **Subtask 2**

The overall intention of Subtask 2 is to conceptualise the optimisation of full scale dynamic testing, based on the State of the art information gained from Subtask 1 and expert input obtained from annex members. When addressing the subject of building performance testing there are two key elements which must be appreciated in order to ensure reliable, accurate results are obtained:

1. Ensuring the test environment and experimental set up are correct and fit for purpose. This includes correct monitoring equipment, accurate sensor placement and robust control procedures.

2. Correct methods of data handling and analysis.

In order to present these concepts in a manageable, user-friendly way, Subtask 2 involves the production of a decision tree to aid researchers in their decision making when considering a full scale dynamic test. The decision tree acts as a guide to ensure the user has considered all possible aspects of their chosen environment, and by following the line of questioning within the decision tree they will ultimately arrive at documents which offer more information. These include published academic papers, ISO documents and test protocols. The researcher is questioned about a range of parameters, from broad considerations such as such as the test environment and conditions to the level of accuracy required from the results, allowing the most appropriate documents to be presented at the end.

During development, the decision tree is using the Xmind programme, a simple to use tool which allows wide ranging decision trees to be constructed and presented in a manageable way. Moving forward, the intention is to take the decision tree to an online platform, or possibly a living Wiki, with easy access for users.

The layout of the decision tree follows a question/response format, with a common route of questioning. For most topics this is:

1. What do we want to characterise?

2. The specific aspect.

3. Test Environment.

4. Test Conditions.

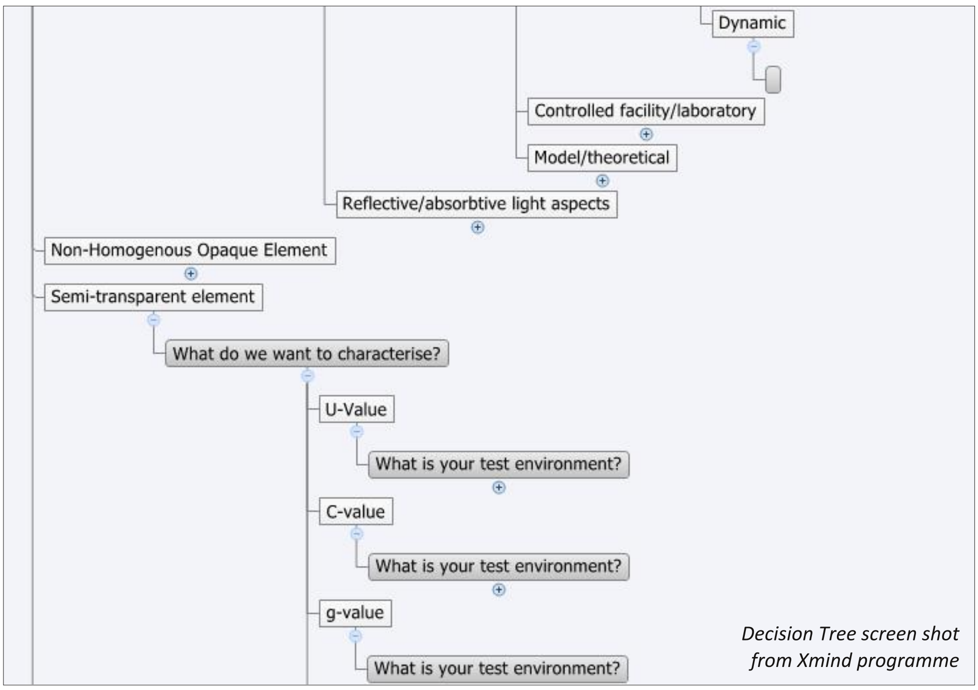
5. Degree of accuracy required.

Each question offers multiple responses for the user. Each path follows the same questioning logic. The number of **specific aspect** stages depends on the topic, for example within whole building envelope there are fewer sub topics than for specific building components. This is a weakness to the decision tree as it is a non-standard question with limitless answers. Components are often more defined and accompanied with test procedures. Going forward, the test environments with less content are those which Annex 58 will focus, capturing information that are necessary to realise a good reliable test environment.

It is the intention that all pathways terminate in a document offering further guidance. Guidance will be taken from the work of Subtask 1 (State of the Art) which covers current aspects of dynamic building testing. It is appreciated that not all pathways will be covered (particularly with regards to novel technologies) input from Annex members will be used to populate the decision tree as reliable guidance is developed.

The degree of accuracy, element of the decision tree is an area which is under constant investigation and develops with technology and better understanding of test procedure and data. Some forms of testing are not fully developed and confidence cannot be guaranteed. It is the case that later versions of the decision tree and guidance contained in the road map will offer information on accuracy when it is known.

Further information can be obtained from **Martin Fletcher, Sub Task 2 leaders: Professor Chris Gorse and Dr Aitor Erkoreka**



Decision Tree screen shot from Xmind programme

Group picture taken at mini-Hollywood (cowboy-city) near PSA-Tabernas.

Outcome of **Summer School 2013** that took place 9-13 September in Almeria, Spain

The second edition of the DYNASTEE Summer School on **Dynamic Calculation Methods for Building Energy Assessment** has been another very successful event with more than expected participants (36 students from 10 EU and 3 non-EU countries, China, India and Canada). The week-long Summer School was devoted to daily lectures by 5 lecturers on building physics and theory of time series analysis as well as plenty of time to guided exercises for improvement of skill of the students.

The ambience of Mediterranean climate, the high quality of the organisation and the sympathy of the student group made the outcome of the whole week, very positive and made the organisers conclude to organise a third Summer School in 2014 (follow us on www.dynastee.info). The requirement of a dedicated book on the lectured topics available at the next edition (probably before Summer 2014) was emphasised as well as the importance of the Open Source software tool environment **R** for future work on the application of dynamic mathematical techniques for energy performance assessment. One of the applied tools, **CTSM-R**, is partly an outcome of DYNASTEE and PASSYS initiatives.

The students were lectured on building physics as well as the applied mathematical and statistical techniques to basic building energy transfer problems. The problem, how to translate a physical energy system into mathematical equations and to assess the corresponding parameters was addressed and the dynamic methodologies were discussed. An in-situ wall exercise was provided and a simple building energy study also for a common approach while applying R-scripts for solving the mathematical equations to assess the thermal characteristics of the parameters in subject.

OPEN COMPETITION

Energy Design of High Performance Buildings

Organised by EC-JRC and ESRU for DYNASTEE

SUMMARY: The objective is to assess for a simplified high performance building (a cube), in a freely chosen climate and associated building energy regulations, the minimum primary energy consumption and GHG emissions for local boundary conditions by optimising thermal characteristics of the building envelop and the choice of building energy systems. The design freedom is in the building construction composition, the specific thermal parameters, the available energy resources and building system technologies. The energy design approach should follow three steps that deal with

1. building energy needs (envelope and its volume),

2. building system operational energy and

3. optimisation for available energy resources (feedback to step 1 and 2)

A High Performance Building (HPB) is a building that consumes as little as possible energy during a whole year for heating, cooling, ventilation, light, hot water and copes with the presence of people and domestic appliances. Such a building is expected to have a climate optimised insulation of the envelope, profits from environmental energy resources and uses thermal mass to balance thermal energy flows. The building energy systems are high efficient and innovative technologies that optimise the use of the available energy resources, delivered to the building or available in the environment of the building.

Each Member State has its national and sometimes regional building codes and regulation. They differ for particular parameters based on specific conditions such as climate, energy-mix and calculation methodology. As an example, Member States differ for the dimensions used for floor area, e.g internal, external or heart to heart dimensions. This will affect the reporting of energy performance expressed in kWh/m2. In the scope of this competition it has been decided to apply the external dimension which is limited to 10 by 10 meters. The minimum requirements set by the Member States in the building codes influence a lot the calculation methodology and results for reporting. The level of comfort that includes indoor temperature settings, temperature control regime, the air change rate etc. might differ even from one part of the country to another.

Beside the applied climate and building parameter settings, the results of primary energy consumption and GHG emission figures have to be reported.

The full description can be downloaded. For more detailed information please contact: **info@dynastee.info**

Target group: under-graduate, postdoc, PhD students and researchers level

ABOUT DYNASTEE

DYNASTEE is an informal grouping of organisations involved in research and application of tools and methodologies for DYNAmic Simulation, Testing and Analysis of Energy and Environmental performances of buildings. DYNASTEE provides a multidisciplinary environment for a cohesive approach to the research work related to the energy performance assessment of buildings in relation to the Energy Performance for Buildings Directive (EPBD).

DYNASTEE, being a network of competence in the field of outdoor testing, dynamic analysis and simulation, has over 25 years of experience through a series of EU research projects. DYNASTEE is an open platform for sharing knowledge with industry, decision makers and researchers.

DYNASTEE has the expertise needed to support the developments and design of Nearly-Zero Energy Buildings as required by the EPBD. Specific outdoor experimental work needs knowledge of the analysis process in order to optimise the dynamic information in the measurement data. Simulation requires results from analysis in order to be able to scale and replicate the results from analysis and testing to real buildings in different climates.

DYNASTEE functions under the auspices of the INIVE EEIG. For more information visit the DYNASTEE web-site at **www.dynastee.info**

Programme

Wednesday 16 April 2014 - 14:00-18:00

THE IEA EBC ANNEX 58-PROJECT ON

'RELIABLE BUILDING ENERGY PERFORMANCE CHARACTERISATION BASED ON FULL SCALE DYNAMIC MEASUREMENTS'

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ABSTRACT

Since 2011, international experts from all over the world are working together for four years within the research project IEA EBC Annex 58 on the topic of 'Reliable building energy performance characterization based on full scale dynamic measurements'. This project takes place in the framework of the 'Energy in Buildings and Communities Programme' of the International Energy Agency. Major aim of the project is to develop the necessary knowledge, tools and networks to achieve reliable in situ dynamic testing and data analysis methods that can be used to characterize the actual thermal performance of building components and whole buildings. Characterising the actual performance and dynamic behaviour of building components and buildings is an essential part to obtain – not only on paper, but in reality – high performance buildings. Furthermore, dynamic data analysis methods have shown to be a valuable tool to deduce simplified models of e.g. advanced components and systems to integrate them in a reliable way into Building Energy Simulation models.
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KEYWORDS

Building performance characterisation, dynamic data analysis, in situ testing

1 INTRODUCTION

The rise of living standards, the scarcity of natural resources and the awareness of climate change resulted in an international pressure to significantly reduce the energy consumption of buildings and communities. In several countries more stringent requirements are imposed by energy performance legislation and also an increased awareness for environmental issues in building codes can be noticed. Mostly, requirements and labelling of the energy performances of buildings is done in the design phase by calculating the theoretical energy use. Several studies showed however that the actual performance after realisation of the building may deviate significantly from this theoretically designed performance. Part of the deviations can be attributed to the user behaviour, but the main part has to be attributed to the physical features of the building and its systems. For the latter, building performance characterisation based on full scale testing – testing of building components or whole buildings under realistic dynamic conditions – could help to bridge the gap between theoretically predicted and real life performance of buildings. Full scale dynamic measurements are e.g. helpful to investigate the performances of building components and whole buildings as built in reality, including the influence of workmanship. This is illustrated in Figures 1 and 2. Figure 1 shows the impact of air looping due to poor workmanship on the U-value of a cavity wall [Hens et al., 2007]. While the designed U-value corresponds to a high insulation level (U=0.2 W/m²K), the actual value based on full scale testing measures 0.8 W/m²K, which corresponds to an increase of more than 300%. Figure 2 compares the designed and realised overall heat loss (W/K) of 18 dwellings in the UK. The overall heat losses are obtained with in situ co-heating tests [Wingfield et al., 2011]. As can be seen none of the houses realises the intended performance and the measured heat losses of the houses may be up to 200% of the designed value.

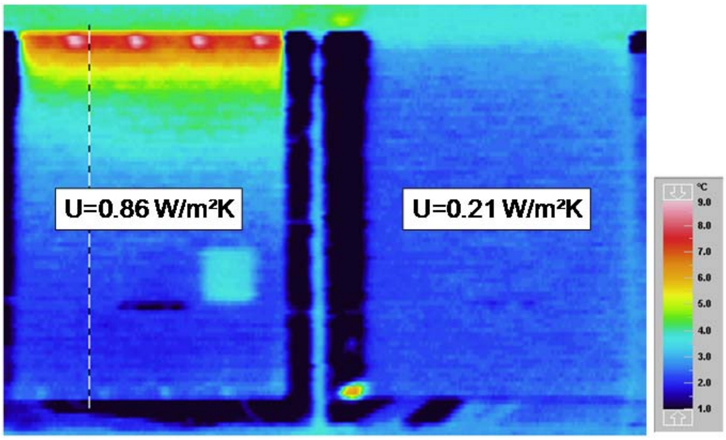

Figure 1. – Infrared pictures of the outer leaf of two full scale highly insulated cavity walls in the VLIET-test building at KU Leuven. The impact of workmanship on the thermal performances of the walls is clearly visible (left: poor workmanship resulting in air looping around the insulation, right: good workmanship). The numbers present the overall measured in situ U-value, the designed value of both walls corresponds to 0.2 W/m²K.

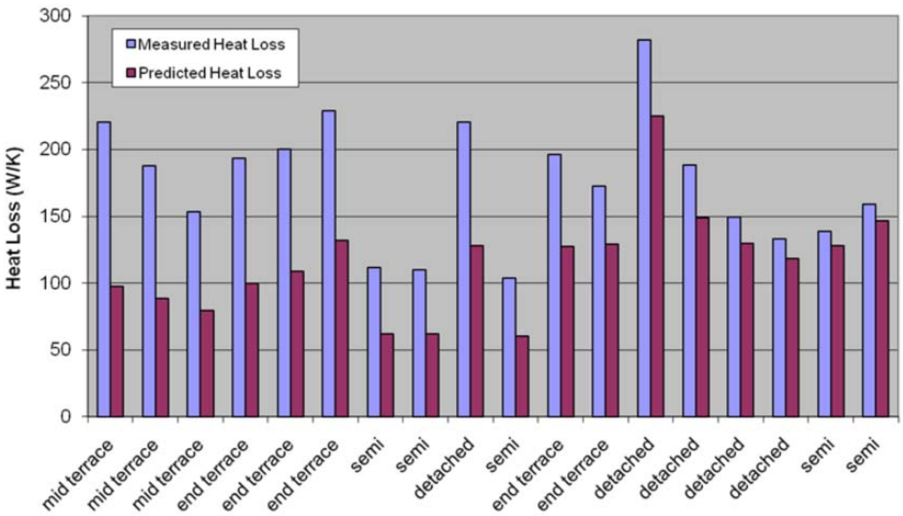

Figure 2. – Measured versus predicted whole house heat losses (W/K) for 18 new build dwellings in the UK. None of the houses is able to reach the designed values and deviations may go up to 100%.

Examples as those mentioned above, explain why at present several in situ testing activities are going on. A recent international workshop showed the interest for full scale testing from all over the world [Janssens et al., 2011]. A growing activity is observed in both full scale testing on building components (as e.g. in Paslink-cells or in situ on components of real buildings) and on whole buildings (to characterise thermal performance and energy efficiency of either test buildings or real buildings). So it is clear that, contrary to what was expected, the numerical building component and building energy simulation models did not make full scale testing of building (components) redundant. On the contrary, together with an increased application of numerical simulations, a renewed interest in full scale testing can be observed.

This is not so strange, because dynamic full scale testing showed not only to be of interest to study building (component) performances under different real conditions – and as illustrated, quite often a huge difference is observed between predicted and realised performances –, it is also a valuable and necessary tool to integrate advanced components and systems into simulation models. As an example figure 3 shows the full scale testing of BIPV (Building Integrated Photovaltaic Cells). Based on the dynamic data analysis of the measurement results a so-called grey box-model has been deduced [Lodi et al., 2011]. A grey box model is based on a combination of prior physical knowledge and statistics by identifying the unknown parameters of the system with dynamic data analysis. Once identified, the grey box model is able to predict the thermal dynamic response of ventilated photovoltaic double skin facades under different climatic conditions. This way it can be ensured that the behaviour of new advanced building components is integrated in a correct way in building energy simulation (BES) models.

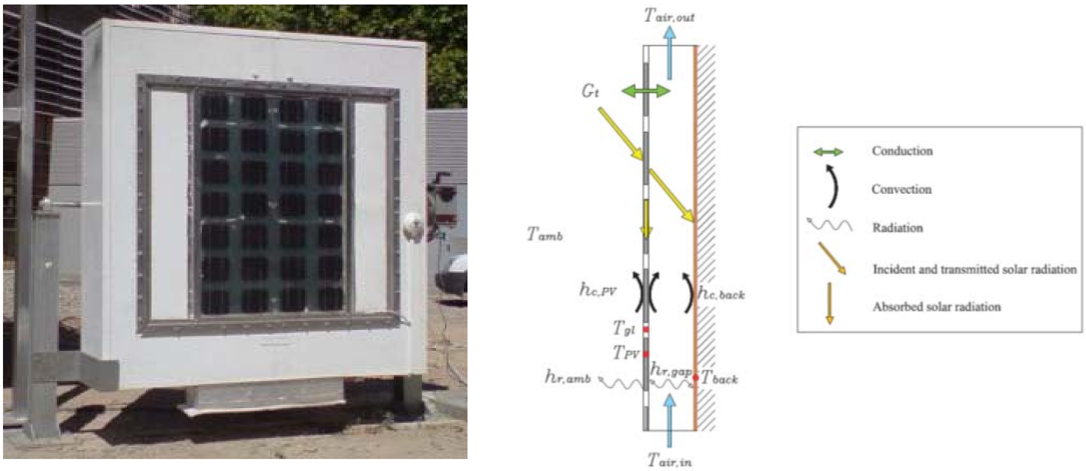

Figure 3. – Left: test set-up to measure the thermal response of ventilated photovoltaic double skin facades under real climatic conditions. Right: schematic overview of the heat transfer processes appearing in the facade, which serves as a basis for the grey-box model [Lodi et al., 2011].

A similar approach of parameter identification based on dynamic measurements can be used to identify suitable models to describe the thermal dynamics of whole buildings including building systems [Bacher and Madsen, 2011]. Characterising the dynamic behaviour of buildings is an essential and very valuable input e.g. when optimising energy grids for building communities.

2 OBJECTIVES OF THE PROJECT

The previous section showed that a better characterisation and prediction of the actual building performance is essential to realise the world wide intended energy reduction in building communities. Quantifying the actual performances of buildings, verifying our calculation models and integrating new advanced energy solutions for nearly zero energy or positive energy buildings can only be effectively realised by in situ testing and dynamic data analysis. But, notwithstanding the renewed interest in full scale testing, practice shows that the outcome of many on site activities can be questioned in terms of accuracy and reliability. The focus of nearly all full scale testing activities is on the assessment of the components and buildings, often neglecting the necessity of reliable assessment methods and quality assurance issues. Full scale testing however, requires quality on all topics of the process chain [Strachan and Baker, 2008], starting with a **good test environment** (test cells or real buildings, accuracy of sensors and correct installation, data acquisition software,…). Only when this is present a **good experimental set-up** (e.g. test lay-out, imposed boundary conditions for testing,…) can be designed, which produces reliable data that can be used for **dynamic data analysis** based on advanced statistical methods in order to come to a characterisation with reliable accuracy intervals and final **use of the results**. As soon as the required quality fails on one of the topics, the results become inconclusive or might even be wrong. Therefore, an international collaboration in the context of IEA EBC has been set up to develop common quality procedures for full scale testing and data analysis to come to a reliable performance characterisation and prediction of building components and whole buildings. In the light of the importance of actual building performance characterisation, the current research project has two main objectives:

- Develop common quality procedures for dynamic full scale testing to come to a better performance analysis
- Develop models to characterise and predict the effective thermal performances of building components and whole buildings.

The ultimate goal of the Annex 58-project is to **develop the necessary knowledge, tools and networks to achieve reliable in situ dynamic testing and data analysis methods that can be used to characterise the actual energy performance of building components and whole buildings**.
As the focus of the Annex is on the development of the testing and analysis methodology, no limitations are set to the type of components, nor to the type of buildings. So the methodology will be applied to old, renovated and new buildings and both dwellings and office buildings ranging from small to high rise are aimed at.

3 ORGANISATION OF THE PROJECT

To reach the final goal and different objectives of the project it is necessary to keep in mind that successful full scale dynamic testing requires quality over the whole process chain: a good test infrastructure, the setting up of a good experimental set-up, a reliable dynamic data analysis and appropriate use of the results. Therefore, the research project is organised around this process chain as illustrated in Figure 4 and the following **subtasks** are defined:

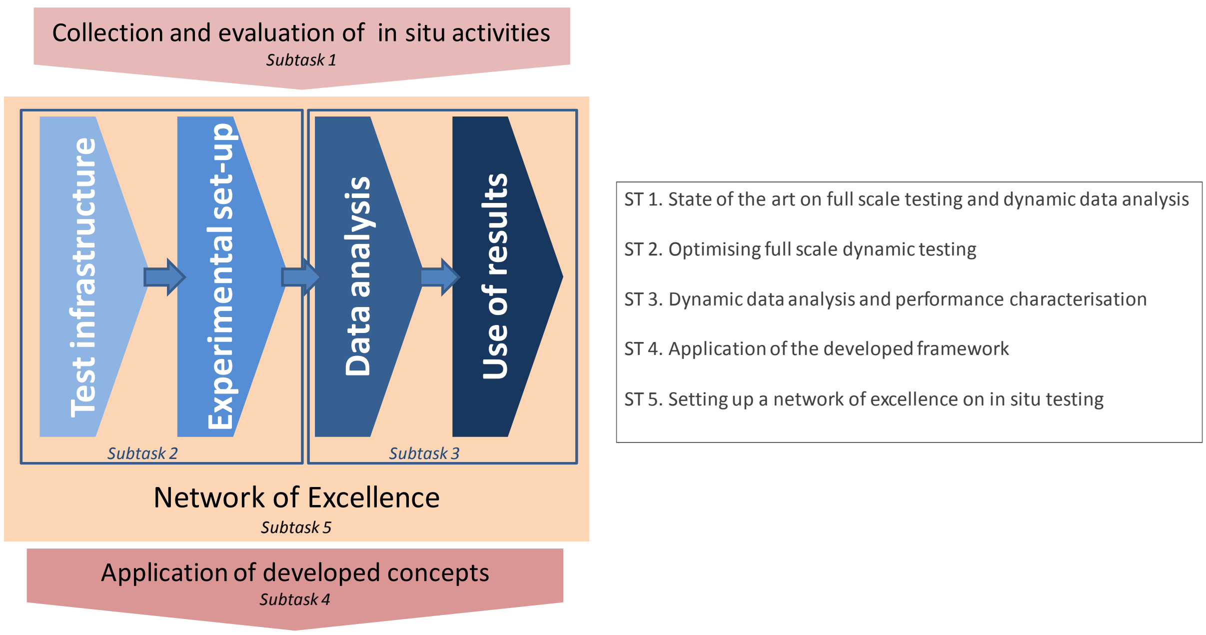

Figure 4. – Schematic overview and organisation of the different subtasks.

3.1 Subtask 1 – State of the art on full scale testing and dynamic data analysis

Subtask 1 is an introductory subtask. Based on a literature review and existing reports an overview and evaluation is made of previous and ongoing in situ test activities. An inventory is made of full scale test facilities available at different institutes all over the world and the common methods with their advantages and drawbacks to analyse the dynamic data will be described. This allows to give an overview of the current state of the art on full scale testing and dynamic data analysis and to highlight the necessary skills within the different knowledge fields to manage the whole chain of activities related to on site test activities.

3.2 Subtask 2 – optimising full scale testing

Subtask 2 establishes the procedure how to realise a good test environment and test set-up. Currently a decision tree is being developed on how to measure the actual thermal performance of building components and whole buildings in situ. This means under realistic boundary conditions (field exposure or artificial climate) and taking into account workmanship. The decision tree will help to decide what kind of data set needs to be collected in order to obtain a certain characterisation at component level (new or existing) or whole building level. As such, this subtask will focus both on the requirements of a good test environment as well as on the setting up of good full scale tests. Included topics are the quality of the test environment, measurement sensors (types, number of sensors, positioning, calibration), monitoring systems, possible performance disturbance of sensors, controls during measurements,... A specific topic of attention is the use of numerical models for the design of good full scale testing: how can simulations help to investigate the influence of the experimental conditions, to optimise the set-up, the positioning of the sensors, the frequency and duration of measurements,...

3.3 Subtask 3 – Dynamic data analysis and performance characterisation

Subtask 3 focuses on quality procedures for full scale dynamic data analysis and on how to characterise building components and whole buildings starting from full scale dynamic data tests. To do so, common exercises have been launched within the project. After two exploratory exercises, one of the main common exercise focused on the characterization of a round robin test box (Roels and Jiménez, 2014). This test box can be seen as a scale model of a building, built by one of the participants, with fabric properties unknown to all other participants. Full scale measurements have been performed on the test box in Belgium and Spain under real climatic conditions. The obtained dynamic data are distributed to all participants who have to try to characterise the thermal performance of the test box’s fabric based on the provided measurement data. Apart from the characterization of the box also a cross validation and blind run was included in the exercises.

3.4 Subtask 4 – Application of the developed framework

Subtask 4 applies the developed concepts and shows the applicability and importance of full scale dynamic testing for different issues with respect to energy conservation in buildings and community systems. One of the main applications is full scale testing to verify and validate common BES-models based on in situ dynamic data. For this goal, a well-documented high quality data set was obtained by setting up an measurement experiment in two testhouses at the Fraunhofer site in Holzkirchen, Germany.
Apart from this, subtask 4 will show applications of the developed methodology for e.g. characterisation of buildings based on in situ testing and smart meter readings, which in turn can be applied to optimise smart grids.

3.5 Subtask 5 – Setting up a network of excellence

Previous and current networks such as PASLINK and DYNASTEE have shown the relevance of a network of excellence for knowledge exchange and guidelines on testing. Within this IEA EBC Annex 58-project the Dynastee-network (http://www.just-pm.eu/dynastee) will be strengthen on 'in situ testing and dynamic data analysis'. Together with Dynastee a summer school on data analysis methods has been organised at DTU (Denmark), CIEMAT (Spain) and KU Leuven (Belgium). At the same time, within the framework of Dynastee and INIVE, different webinars and workshops, as the current one, have been organised.

4 CONCLUSIONS

The Annex 58-project of the IEA EBC-programme shows that there is currently a larger international interest in full scale testing and dynamic data analysis. This can be explained by the fact that full scale testing remains necessary for several reasons. It is for instance the only way to verify our numerical BES-models. Furthermore, full scale testing allows evaluation and characterisation of the thermal performance of building components and whole buildings in reality.
Some of the ongoing research and intermediate results of the Annex 58-project will be presented in the following papers of this workshop.

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THE GAP BETWEEN CALCULATED AND REAL PERFORMANCE: EXPERIENCES FROM THE FIELD AND THE MEASURES REQUIRED TO ADDRESS THE DIFFERENCE

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ABSTRACT

One of the most important challenges faced by the construction industry is to gain better understanding of the building stock, how it performs and how individual building types and systems behave. Over recent years the coheating test has become the accepted method of acquiring building thermal performance data in the field, and was instrumental in recognising that many buildings did not perform as expected. While the method itself has been criticised for being too intrusive and resource intensive for commercial use, it is still regarded as the most reliable way of determining the whole building U-value or heat loss. In addition to the results from coheating, the heated, and notionally ‘steady state’ conditions under which buildings are tested provide opportunity to use thermography while pressurised, depressurised and under natural conditions to explore thermal bridges, bypasses and infiltration/exfiltration paths. Much has been gained from research that explores heat loss under such conditions. The factors that have contributed to the performance gap, which have been recognised through research, now provide a body of knowledge that inform element, junction and whole building design. The demands for a quicker measurement of whole building heat loss are being met by dynamic methods and in-use measurements. The alternative methods provide relatively fast or more instantaneous indications of overall building performance. Initial results from QUB and Integrated test, compared with coheating data, suggest they are useful tools and, although not as accurate as coheating, they could provide a commercial solution. The new tests will reveal different characteristics of performance and behaviour that will continue to build on the knowledge already amassed. The situation has changed from one that denies the performance gap, to one that has tools to address it. The discussions that surround performance testing should not lose sight of the models, simulations and forensic tools that expose the reasons for underperformance and help to predict solutions. Coheating, has become a term used synonymously with building performance and is expected to explain a host of behaviours which it does not. The other tools and research that the Leeds Sustainability Institute use to understand building performance are outlined.

KEYWORDS
building performance, building forensics, in-use monitoring, zero-carbon buildings

INTRODUCTION

Maintaining a comfortable internal environment within buildings of poor thermal performance creates an unnecessary impact on the natural environment, such buildings are energy demanding, add unwanted emissions and exacerbate the problem of fuel poverty. Currently, the work to improve building performance is relatively exploratory with an inconsistent approach to measurement.

The European Energy Performance of Buildings Directive, 2010/31/EU, and the demand for a nearly zero standard for dwellings by 2018, represents a significant challenge to the construction industry. The gap between the design theory and reality, that which is actually built, can be double that expected (Stafford *et al.,* 2012a; 2012b). Evidence from field trials shows that it is not uncommon for dwellings to experience 60% greater heat loss than designed (Gorse *et al*., 2013). The findings do not provide an example of an industry that is in control of 'actual' performance. The range of performance across the dwellings is dispersed and represents a significant problem. European and country-specific targets will not be achieved unless tolerances are set and buildings are designed with enhanced standards of performance that accommodate suitable safety margins. It is also essential that tools are available to measure performance and can be accommodated within a framework that allows the industry to reduce the performance gap.

Coheating: Reliability, validity

Methods of measuring building performance have become a topic of considerable discussion. The coheating test has been influential in recognising that many dwellings were not achieving their expected energy performance. However, following a report published by the NHBC Foundation which sought to investigate coheating (Butler and Dengle, 2013) and comments made (NHBC Foundation Media Centre, 2013), some doubts were raised over the reliability of the test results. The work undertaken by the NHBC Foundation, brought into focus what can go wrong where research methods are not applied and analysed correctly. Analysis of heat loss needs to take account of irradiation, humidity, moisture, temperature change and wind as well as many other naturally occurring phenomena. In some instances the building or conditions may not provide suitable test conditions. As with all methods there are limitations, those surrounding coheating are identified in the method (Johnston *et al.*, 2013) and observations from all the tests undertaken are available in the reports on the web site (CeBE, 2014). The coheating method is just one tool that is used to assess building performance. The responses to the critiques that followed the NHBC work have raised this and identified some of the many tools used to understand building performance (Building, 2014). Furthermore, with the application of all methods the need for suitable training and understanding of analysis methods should not be overlooked.

When undertaking performance testing it is necessary to check that the method used is reliable and producing valid results. The work used to identify the performance gap was based on results from multiple methods of investigation and analysis, building surveys as well as the coheating method to measure whole building performance. While there was common agreement between the models and elemental results, where opportunity allowed the coheating method and results have been checked (See technical reports on the CeBE web site).

A number of tests have been conducted to explore the reliability and validity of the coheating test. In January 2010 a research team from the Centre of the Built Environment (CeBE) at Leeds Sustainability Institute undertook a coheating test on a 2 ½ storey detached dwelling using the Leeds Metropolitan University Whole House Heat Loss Test Method (Wingfield *et al.,* 2010). The test was undertaken as part of a project designed to test the thermal performance of prototype dwellings in situ for the Derwenthorpe housing development. The Heat Loss Coefficient (HLC) resulting from the January 2010 coheating test was 132.9 (± 1.5) W/K. In December 2012 a different CeBE research team undertook a coheating test on the same dwelling in accordance with the 2012 iteration of the LeedsMet Coheating Test Method

(Johnston *et al*, 2012). The HLC resulting from the December 2012 coheating test was 133.8 (± 1.9) W/K.

The two coheating test results obtained 35 months apart and with differing research teams differed by < 1%. An independent sample T-test of the 24 hour solar corrected HLCs obtained from both tests showed no statistically significant difference (P = 0.432) between the HLCs obtained in each test, this suggests a reasonable level of precision (repeatability) in the coheating test in this instance.

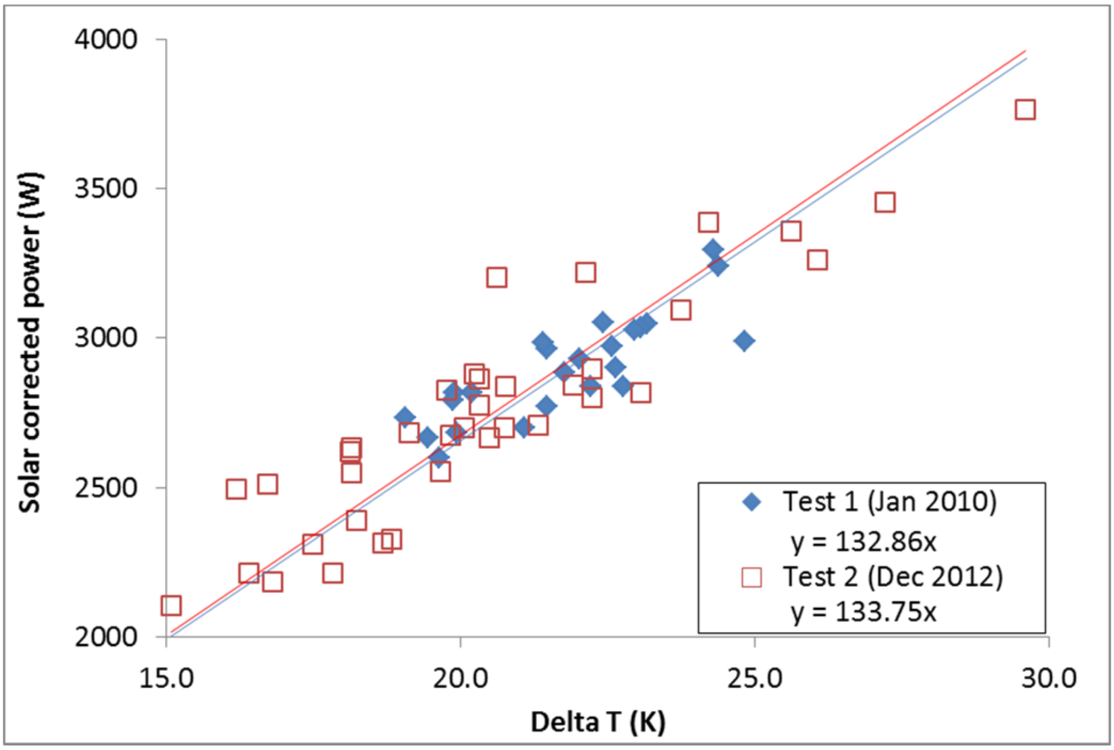

Figure 1: Plot of 24 hour solar corrected power vs. ΔT for both the coheating tests of the Derwenthorpe prototype dwelling.

Alternative approaches to whole house heat loss

In addition to checking the repeatability of the coheating method on the same dwelling in the field, opportunity also presented itself to cross check alternative methods through the Saint Gobain Energy House project (Farmer *et al.*, 2014; Weaver and Gibson, 2014). At each of the six stages of the retrofit project, blind tests were undertaken independently by the Centre for the Built Environment (CeBE at Leeds Sustainability Institute) and Saint Gobain Reserché. The Saint Gobain team used their QUB (Quick U-value of Buildings) method (Pandraud *et al.*, 2014) and the Leeds Metropolitan team used the coheating test. Due to the unique facility offered by the Salford University Energy House, it was possible to perform each test separately and sequentially, under the same controlled external conditions, something which is not possible to achieve in the field. QUB is a very simple diagnostic method that enables the heat loss coefficient to be calculated over one or two nights. It measures the temperature response during a heating and free cooling period. A level of uncertainty is estimated to be ± 15% when performed on a single night which becomes less as the test period is extended (Pandraud *et al.*, 2014). Cross checking of the methods at the energy house showed a much closer fit than the level of uncertainty suggested. With the exception of one test, where the QUB test was terminated too early (after just 30 mins), good agreement was found between the results of both testing methods (Farmer *et al.*, 2014).

These results suggest there may be merit in developing a limited yet reliable and more commercially viable alternative to the coheating test which may encourage more widespread performance checks in the industry.

Other methods, based on in-use monitoring data have also been cross checked with the coheating tests and show comparable results. The *Integrated coheating*, currently being developed by Leeds Metropolitan University at the Leeds Sustainability Institute. The test is a variation on electric coheating that uses the test dwelling's own heating system to provide the heat input, and control of internal temperature, throughout the test. A heat meter is used to measure the space heating energy delivered to the test dwelling; this allows the efficiency of the heating system during the test to be measured. This means that an integrated coheating test has the potential to quantify both fabric and system performance, hence it tests the dwelling as an integrated system. Initial tests show a reasonable agreement between the heat loss coefficient (HLC) obtained from integrated coheating and the HLC obtained from electrical coheating. Though, it must be noted that criticisms directed towards current analysis methods used in the electric coheating method will be equally valid for the integrated coheating method. However, as the provision of heat to the test house during an integrated coheating test is more likely to resemble what is experienced during the dwellings operation, the HLC estimate obtained is likely to be more representative of how the dwelling will perform in-use. As integrated coheating requires less equipment and manpower, and can utilise cheaper forms of heating, it has greater potential than electric coheating to be used as a commercially viable commissioning test. The importance of measuring the energy delivered for space heating, was something that was previously missing from similar work that did not show the same capability in providing HLC (Sutton *et al.,* 2014). The Integrated coheating, utilising heat meters, represents a considerable change in the potential data that can be extracted.

Validity: Aggregating and disaggregating data

Whilst alternative methods of measuring the HLC of a building might hold commercial advantage the real power of using a coheating test to determine thermal performance, and the performance gap, is its ability to disaggregate the building's heat transfer. In particular, to perform an analysis of the empirical heat loss data using the standard definitions of heat transfer coefficients defined in ISO 13789 (ISO, 2007), separating ventilation heat loss as an independent factor:

So, Heat Loss Coefficient (in W/K), $\mathbf{HLC} = \boldsymbol{H}_\mathbf{V} + \boldsymbol{H}_\mathbf{T}$ (1)

Where:

$\boldsymbol{H}_\mathbf{V}$ is the ventilation heat loss
$\boldsymbol{H}_\mathbf{T}$ is the transmission heat loss as defined in ISO 13789 below

From ISO 13789: **BS EN ISO 13789:2007: ISO 13789:2007(E)**

Transmission heat transfer coefficient: **Basic equation**
The transmission heat transfer coefficient, H_T, is calculated according to:

Equation (1): $\boldsymbol{H}_\mathbf{T} = \boldsymbol{H}_\mathbf{D} + \boldsymbol{H}_\mathbf{g} + \boldsymbol{H}_\mathrm{U} + \boldsymbol{H}_\mathbf{A}$ (2)

Where:

$\boldsymbol{H}_\mathbf{D}$ is the direct heat transfer coefficient between the heated or cooled space and the exterior through the building envelope, in W/K;
$\boldsymbol{H}_\mathbf{g}$ is the steady-state ground heat transfer coefficient, in W/K;
$\boldsymbol{H}_\mathrm{U}$ is the transmission heat transfer coefficient through unconditioned spaces, in W/K;
$\boldsymbol{H}_\mathbf{A}$ is the transmission heat transfer coefficient to adjacent buildings, in W/K.

The prolonged steady state internal environment demanded for the coheating test provides ideal conditions for accurate heat flux measurement to ISO 9869 (ISO, 1994) and thermographic analysis. This disaggregation of the results is crucial when it comes to analysing and understanding the performance gap. Rather than simply listing how much the whole house HLC measured exceeds the predicted figure, by splitting both measured and predicted figures into these component values the tests can provide quantitative information regarding which building elements are responsible for the performance gap occurring and where best to concentrate efforts when attempting to minimise the gap. In existing buildings this methodology is undertaken by the CeBE research group at Leeds Sustainability Institute to assess the efficacy of retrofit upgrades and renovations. In all buildings it is used in conjunction with thermal bridging computation to "close the loop" between measured elemental and whole house heat loss values thereby providing additional validation of results.

Testing enclosures that don't act like enclosures: Air leakage

Initial tests on a small and varied sample of existing buildings in the UK (Gorse *et el.*, 2014), found some buildings to be so leaky that it would not be possible to perform tests using standard electrical resistance heating equipment. The power requirement to elevate the whole house to a sufficient temperature above its surroundings would have overloaded the property's electric supply. This has important implications as structures of this nature cannot be accurately tested using portable electrical heating.

In relatively small buildings, air changes rates of 16 – 29 h^{-1} @ 50 Pa were found in properties that had been previously occupied. In the most leaky buildings the conditions observed suggested that it would not be possible to adequately heat the whole building during winter conditions without excessive heat inputs. In such enclosures it would be difficult to achieve any reasonable level of comfort. The problem of airtightness, is one which is often overlooked, as is the need to have air barriers and thermal barriers that act as one. Much of the research carried out, that shows high levels of underperformance identifies a failure to maintain continuous and contiguous air and thermal barriers. In renovated properties the problem of sealing floors and floor perimeters, behind fitted units and boxed-in services, around openings and service penetrations, and within cavities in the fabric means that a number of air penetration and circulation routes are consistently missed. This oversight is manifest in the omission of draught proofing from conventional retrofit packages which can receive financial assistance from government energy efficient schemes.

In retrofit projects, it is attention to design detail and workmanship that makes the difference; contractors sealing the gaps and ensuring insulation and air barriers are taped and fitted properly. In one retrofit property where a wet plaster finish on the external masonry wall was removed and replaced with dry-lining plasterboard on adhesive dabs and the suspended timber ground floor insulation was not supported with an effective seal, the improvement of air permeability went from 24 – 20 $m^3/(h.m^2)$@50Pa (Table 1), achieving a very limited improvement. The air barrier was not effective; the air simply passed through and around the insulation, and flowed through the cavity behind the plasterboard, percolating through the brickwork and cavities. In similar properties, where due attention was given to detail and workmanship stepped changes from around 19 to 4.73 ($m^3/(h.m^2)$@50Pa (Table 2) and 16.77 to 6.43 ($m^3/(h.m^2)$@50Pa (Table 3) were achieved. Understanding if airtightness has been achieved is a relatively straightforward commercial test. Furthermore the introduction of a thermal survey during the heating season under depressurisation will provide valuable information on the building's behaviour. The tools required to undertake such tests and surveys are becoming commonplace, coupled with the right level of professional competency, it is not beyond reason that such tests could be performed on most properties.

Table 1 Pressurisation Test Results: poor results post intervention

Test no.	Date	Depressurisation Only			Pressurisation Only			Mean	
		Air Permeability	Air Change Rate	r^2	Air Permeability	Air Change Rate	r^2	Air Permeability	Air Change Rate
		$m^3/(h.m^2)$ @ 50 Pa	h^{-1} @ 50 Pa		$m^3/(h.m^2)$ @ 50 Pa	h^{-1} @ 50 Pa		$m^3/(h.m^2)$ @ 50 Pa	h^{-1} @ 50 Pa
01	30-Sep-13	22.87	28.39	0.999	25.27	31.37	0.997	24.07	29.88
02	21-Oct-13	23.78	29.53	0.999	25.34	31.45	0.998	24.56	30.49
03	02-Apr-14	19.45	24.15	0.999	20.97	26.03	0.998	20.21	25.09

Notes: Test 01 and 02 were performed at the start and end of the pre-refurbishment coheating test, test 03 conducted during the heat-up stage of the post-refurbishment coheating test.

Table 2 Pressurisation Test Results: reasonable and good results post intervention

Property	Date	Depressurisation Only			Pressurisation Only			Mean	
		Air Permeability	Air Change Rate	r^2	Air Permeability	Air Change Rate	r^2	Air Permeability	Air Change Rate
		$m^3/(h.m^2)$ @ 50Pa	h^{-1} @ 50Pa		$m^3/(h.m^2)$ @ 50Pa	h^{-1} @ 50Pa		$m^3/(h.m^2)$ @ 50Pa	h^{-1} @ 50Pa
16 HV (contractor retrofit)	11-Mar-13	19.14	22.82	0.992	19.27	22.96	0.994	19.21	22.89
	14-May-13†	12.96	15.45	0.998	13.60	16.21	0.999	13.28	15.83
	21-Nov-13	11.48	13.69	0.999	12.70	15.13	0.998	12.09	14.41
18 HV (system retrofit)	11-Mar-13	Unable to completed test due to incomplete air barrier, leakage detection only.							
	21-Nov-13	7.31	8.71	0.991	7.47	8.90	0.997	7.39	8.80
	28-Nov-13	4.70	5.61	1.000	4.76	5.68	1.000	4.73	5.64

†Additional temporary sealing applied around the cellar door.

Dwellings tested in original state, at initial air barrier completion, at finished state.

Table 3 Pressurisation Test Results: good results post intervention

Property	Date	Depressurisation Only			Pressurisation Only			Mean	
		Air Permeability	Air Change Rate	r^2	Air Permeability	Air Change Rate	r^2	Air Permeability	Air Change Rate
		$m^3/(h.m^2)$ @ 50Pa	h^{-1} @ 50Pa		$m^3/(h.m^2)$ @ 50Pa	h^{-1} @ 50Pa		$m^3/(h.m^2)$ @ 50Pa	h^{-1} @ 50Pa
11 ST (system retrofit)	26-Feb-13	15.34	19.07	0.998	18.2	22.63	0.995	16.77	20.85
	20-Jan-14	6.25	7.78	1.000	6.60	8.21	1.00	6.43	7.99

Tests performed at end of coheating tests prior to and post-refurbishment

Test and measures

There are many tests, models and measures that can be used to understand building performance. The methods adopted should meet the needs of the performance criteria being investigated and be appropriate for the building type and environmental conditions. Use of the tools does require an understanding of buildings so that the results can be appropriately investigated and understood. Tools often used by the CeBE team when undertaking field work include:

- Building, photographic, endoscopic, video and thermal survey (thermography); design review and building process analysis, and engaging with those involved.
- Construction or retrofit observations, regular visits, chronologically recorded, supported with photographic of video records, with meta data (date, time, position and orientation).
- Coheating, heat flux, surface temperature and moisture measurement: exploration of energy signatures and behaviour.

- Air pressure tests, air leakage detection - smoke tests, localised smoke and whole building smoke tests, use of differential pressure sensors.
- Thermal and hygrothermal modelling and simulating construction observations to check if the behaviour resembles that anticipated and evaluating new designs.
- External and internal temperature, CO_2, NO_x, humidity sensors, wind, solar, rain. In-use monitoring for energy, comfort and performance.
- Cross checking whole building with disaggregated element and whole building tests and where opportunity allows using two or more methods such as QUB and the Integrated method.

A more detailed study of tests and appropriate methodologies is being undertaken by the International Energy Agency Annex 58. Early iterations commenced in 2012 (Fletcher *et al.*, 2012) however, a more complete version of the decision tree and road map is in the latter stages of development.

Decision tree and road map

To accurately evaluate the performance gap, it is essential that testing methods are robust and reliable. As research into the performance gap increases and expands across different sectors, it is critical that practitioners use the correct procedures to ensure that a reliable test environment is achieved; experimental design and test set up are maintained when undertaking performance testing. Due to the nature and implications of the performance gap, the use of incorrect methods presents a significant risk to research findings, as highlighted by the recent publications of the NHBC Foundation.

The International Energy Agency: Annex 58 aims to address this through the production of a decision tree to ensure accurate testing methods and data handling are identified. The decision tree will act as a guide to ensure the user has considered all possible aspects of their chosen environment prior to undertaking testing. By following the line of questioning within the decision tree they will ultimately arrive at documents which offer further information specific to their needs. These include published academic papers, ISO documents and test protocols which are determined to be of sufficient academic quality to provide useful guidance.

The decision tree (samples shown in Figures 2 and 3) can be used to assist academics and industrial researchers in determining the correct test procedures required to obtain accurate results. At present these are limited to building components and whole house testing in-situ, however there is potential to expand the decision tree to include building services. The decision tree will not provide a testing methodology outright, but the documents suggested will outline the requirements for the development of a robust methodology.

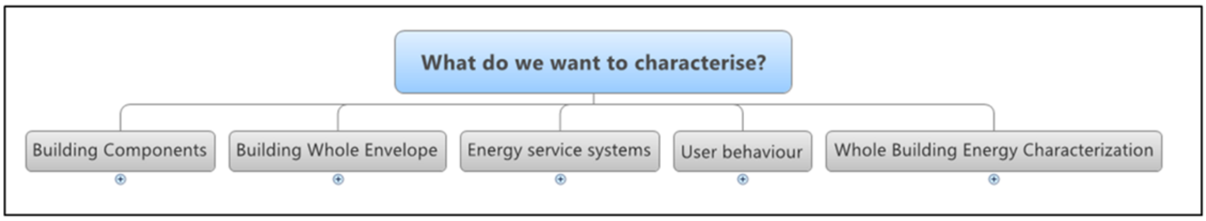

Figure 2. Main categories of the decision tree

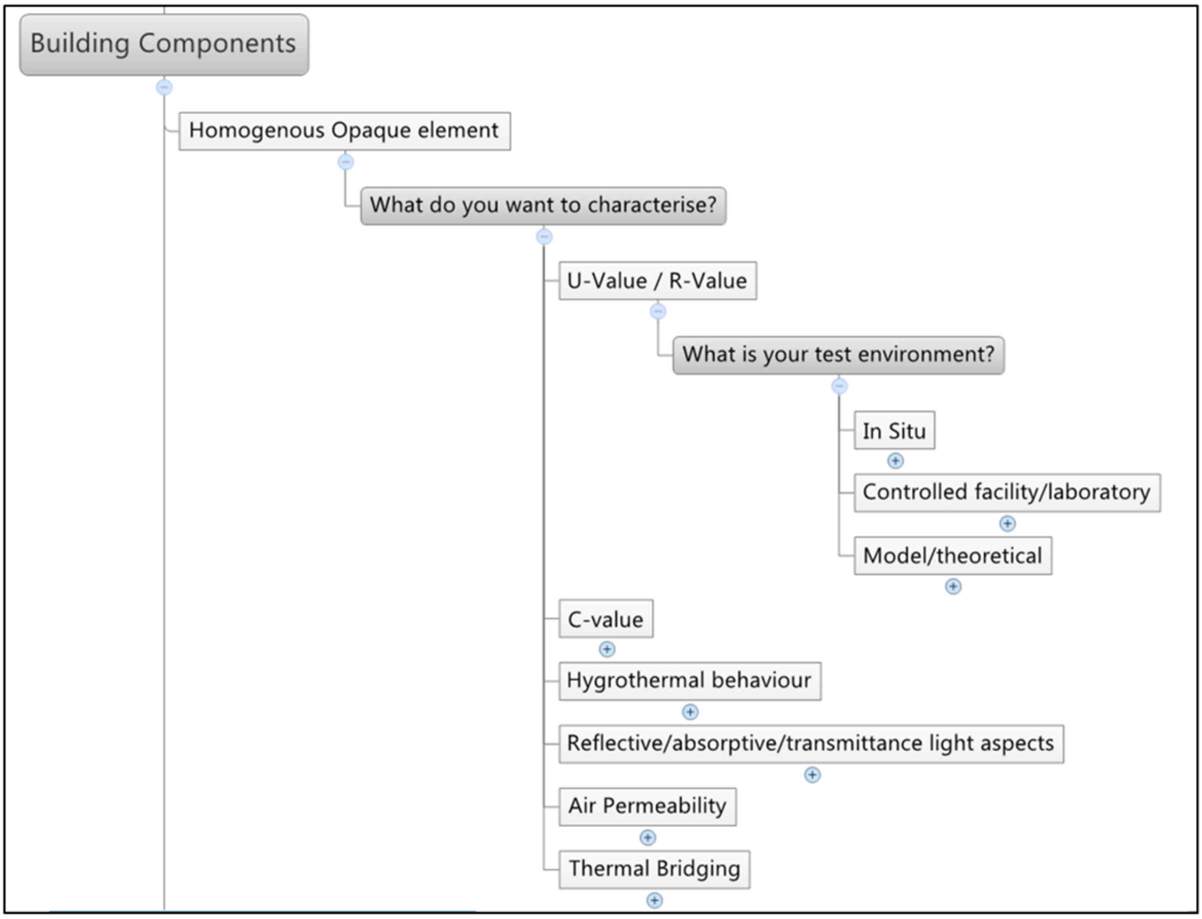

Figure 3. Examples of parts of the tree expanded.

Addressing the challenge: Interventions and effects

The tools that we use to measure the performance gap are of limited use if not applied in a systematic way to understand the effects of the intervention. There are some notable examples of research that clearly show the step change in behaviour.

The Temple Avenue project (CeBE, 2010) is a typical example of staged intervention demonstrating where and how improvements can be made. At the same time as undertaking the refurbishment of an existing 1930's property to the same thermal and energy performance as two highly energy efficient new-build prototype dwellings the Joseph Rowntree Housing Trust also developed and tested prototypes before producing the final designs for a new 540 home award-winning development (CeBE, 2010).

This scale of the research does not need to be applied to whole buildings and their component parts can be examined in some detail. Work with Knauf Insulation on the effectiveness of different products has offered a lead in this area. An example from a recent study focusing on party wall interventions is shown below. The results clearly show how the intervention of retro-fill blown mineral fibre significantly changes the thermal behaviour of a masonry cavity party wall, this was achieved without detriment to the wall's acoustic performance. Prior to the insertion of full cavity insulation, the unfilled cavity was allowing virtually unrestricted flow of air and a considerable thermal bypass, following the intervention the fabric exhibits control over the thermal movement and significantly reduces the effective heat flow, both through the wall and via the vertical thermal bridge at the junction with the external wall (R1 and R2 in Fig 4).

The results show significant improvements to the thermal performance of the wall. Prior to the intervention of full-fill insulation the wall failed to provide an effective barrier to the outside elements. The variability of the heat flow before the insulation fill was introduced suggests that the wall was not effectively sealed and experienced problems due to air infiltration, bypasses and other breaches of the building fabric. The graph (Figure 4) shows how insulation added to existing walls can created a consistent and performing fabric, offering the desired thermal resistance and creating a separation between internal and external environment conditions.

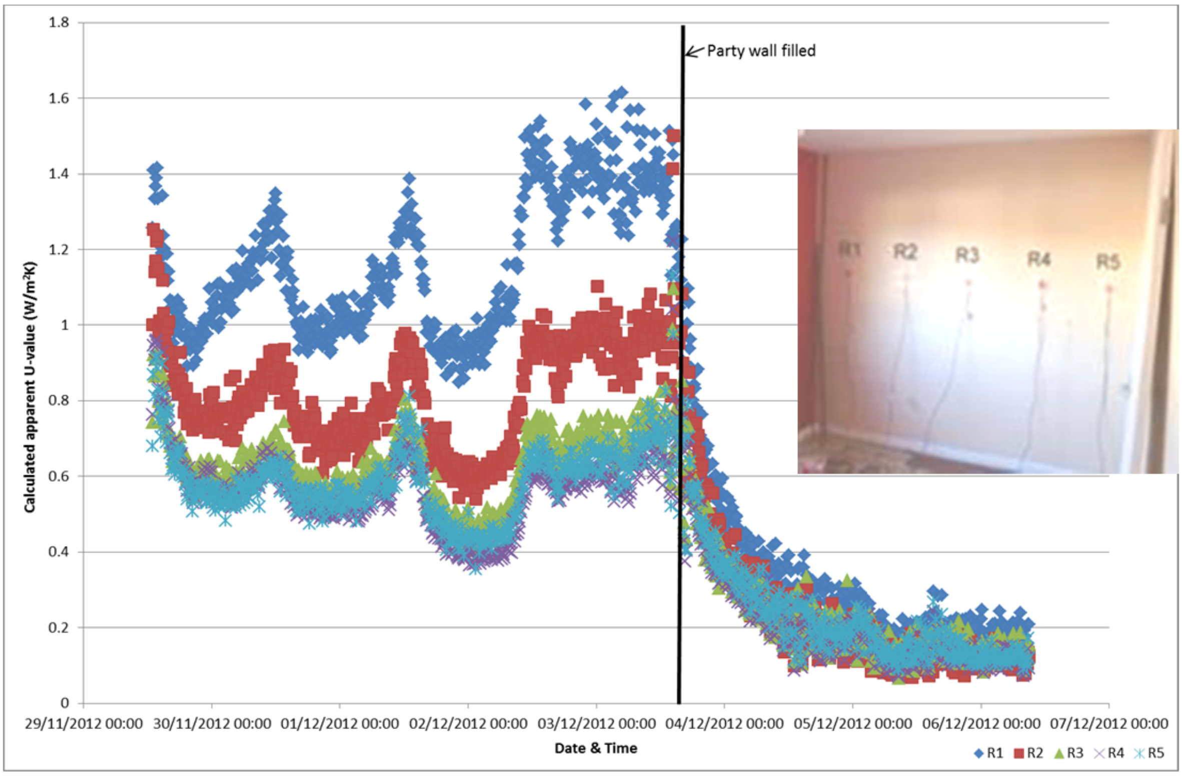

Figure 4: An unfilled cavity party wall exhibiting characteristic signs of thermal bypass and air movement, the full-fill intervention creates a fabric that controls movement and significantly reduces heat loss. (Courtesy Leeds Metropolitan University and Knauf Insulation Research programme)

The Saint Gobain Energy House Project (Farmer *et al.*, 2014) provided a full-scale and staged retrofit to the replica Victorian Terrace. The approach is also exemplar and shows the potential of taking the coheating test back into a laboratory. In the Energy House Project, the whole building, which is constructed within a controlled environment, enables the temperature and environmental conditions surrounding the property to be controlled. Different retrofit upgrades were added to the property and three expert teams using multiple methods of measurement analysed the results. The project represents an important point in building performance research; in most other retrofit trials the full retrofit is applied and it is difficult to investigate the individual contribution of the systems that make up the whole. Specifically, the Energy House project provides an example of a systematic and staged approach (Table 4) to the measurement and monitoring of thermal upgrades. The knowledge gained on the elements and whole building's performance makes a key step forward in understanding the behaviour of a building that is representative of a significant proportion of the building stock in the UK. Regardless of the further development that can be made to working practices, the whole house retrofit solution shows 63% improvement to the existing property (Figure 5). Considering that the baseline building was previously fitted with double glazing and roof insulation, the results are significant. The base building would be comparable to buildings that have been well maintained and upgraded with standard measures. By removing unwanted noise and variation, and utilising controlled internal and external conditions, the fabric was isolated and energy responses to the thermal upgrades shown.

Table 4: Configuration of the test house at each test phase (Farmer *et al.*, 2014)

Test phase	Thermal element subject to upgrade measure(s)			
	External wall	Roof	Glazing	Floor
Full retrofit	✓	✓	✓	✓
Full retrofit (no floor)	✓	✓	✓	
Solid wall 1	✓			
Solid wall 2	✓			
Glazing			✓	
Loft		✓		
Reference				

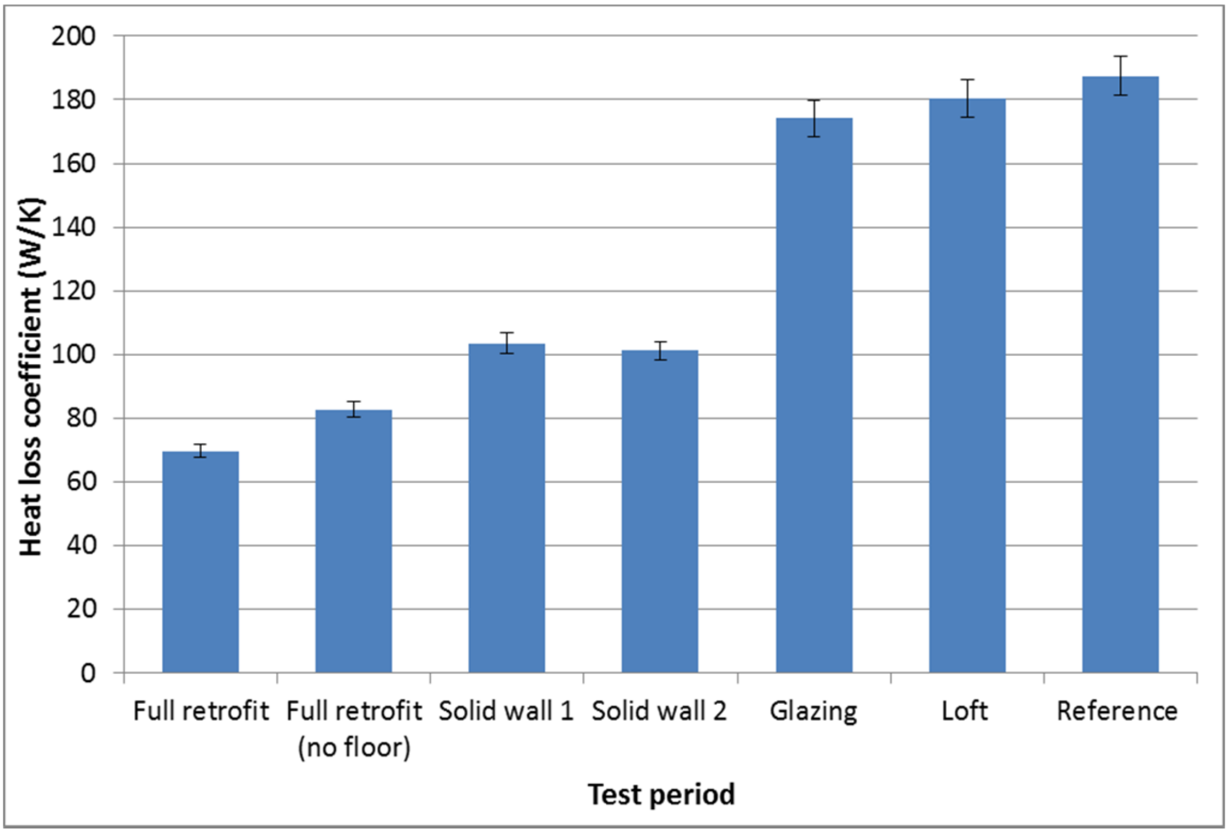

Figure 5 Heat loss coefficient for each stage of intervention (Farmer *et al.*, 2014)

The isolation of the staged interventions confirms the interventions that make the greatest contribution to reduction in building heat loss. From the individual results, 46% improvement was achieved with the solid wall interventions, this will be of national interest. Under the facility's test conditions greater certainty was achieved and ambiguity, which has previously resulted from trying to compare different houses and house types in variable climatic conditions, was reduced. The questions of whether variations were due to different types of building, behaviour of occupants, environmental variations or test methodology and analysis were also removed. There remain limitations of the test environment, as the conditions are not real, but the approach has advantages. Thus, it was possible to focus more thoroughly on the building changes introduced and measure their impact.

The Energy House laboratory allowed each thermal upgrade to be exposed to a range of conditions, the same exposure being repeated for each upgrade allowing direct comparison of six upgrades. Standardising the test environment and removing the uncontrollable conditions experienced in the field allowed the research teams to concentrate on the improvements made and the accuracy of the methods used. Both Saint Gobain's dynamic QUB method and Leeds Metropolitan University's quasi-steady state coheating tests were used, this was in addition to the measurements of heat flow through the fabric using over 100 temperature and heat flux sensors.

Currently, many of the research projects are undertaken in isolation, and although at Leeds Sustainability Institute more than 50 coheating tests have been undertaken, the buildings represent significant but isolated case studies. It is essential that the data gathered from the coheating tests are used as a base to inform future projects. Clearly some of the data is applicable regardless of building type and situation, but in many cases the data for the field tests can extend the benefit by helping to calibrate the models and simulations that inform future decisions.

Extrapolation and Calibration of simulations

A research project commissioned in 2003 by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) had the intention of developing a "...coherent and systematic calibration methodology..." (Reddy, 2006, p. 225). An output from this project was a review of existing techniques (Reddy, 2006). Calibrated models can be used to inform investment decisions for retrofit programmes (Reddy, 2006; Raftery et al, 2011). Whole building simulation techniques are also particularly important when retrofits are multiple or part of a retrofit pathway that introduces multiple options over time. Calibration approaches are split in to four categories by the review based upon: (a) manual, iterative and pragmatic interventions; (b) a suite of informative graphical comparative displays; (c) special tests/analytical procedures; and (d) analytical and mathematical methods. All of these are designed to reduce the gap between predicted and actual performance. Importantly, these calibration techniques rely on the availability of accurate records from existing buildings and, for the most accurate results, an actual weather file taken from a baseline year.

The Standard Assessment Procedure (SAP) was first cited in 1994 as an energy performance calculation methodology in Part L of the Building Regulations in England and Wales and has gone through four major updates to reach its current SAP2012 format (DECC, 2013). The Department of Energy and Climate Change (DECC) mandate that SAP is used to predict energy performance for new build dwellings in the UK (DECC, 2013); reduced SAP (RdSAP) must be used for existing dwellings. At present, SAP extensively underpins domestic building energy performance policy in the UK.

Its use was originally intended for building regulations compliance checks so that one building could be fairly benchmarked and compared with one another, it was not expected to provide accurate predictions of actual energy consumption for particular buildings. The 'standard' assumptions are not designed to be realistic but are deliberately hypothetical so occupancy rates are based on floor area (and so there may be 2.5 people living in a space for example), occupancy behaviour is assumed to be identical, weather conditions are standardised and only limited variations in external factors are allowed. However as well as being central to compliance (Part L of Building Regulations), and in the calculation of domestic Energy Performance Certificates (EPCs) it is now also used in a raft of policies including the Warm Front, Stamp Duty Exemption for Zero Carbon Homes, the Code for Sustainable Homes, the Feed in Tariff, the Renewable Heat Incentive and most recently, the Green Deal where actual energy consumption values are important (Kelly *et al.,* 2012). The success of the Green Deal relies on predictions from RdSAP as it is the magnitude of utility cost savings that will dictate whether the 'Golden Rule' of payback is achieved. Despite this crucial role in UK policy, completed research has questioned the effectiveness of SAP and whether it is fit for purpose (Carke and Reason, 2008: Kelly *et al.,* 2012).

Although designed to provide "…accurate and reliable assessments of dwelling energy performances…" (DECC, 2013), the main output of SAP, a SAP Rating, is based upon the unitised financial performance of a dwelling. This metric can result in dwellings with poor environmental performance achieving better SAP ratings than more energy efficient and less CO_2 intensive buildings; for example, the same building using coal as opposed to natural gas can achieve a better SAP rating due to the relatively low cost of coal (Kelly *et al.,* 2012). It can also be problematic in its treatment of renewable technologies and does not currently account for subsidy repayments (Kelly *et al.,* 2012). The SAP methodology has also been criticised in the past for under-estimating heat losses and over-estimating internal heat gains (Clarke and Reason, 2008) although subsequent versions have addressed some of these criticisms.

Conventions included within the SAP methodology restrict accuracy of energy consumption and CO_2 emission estimates for specific buildings. In order to allow comparison across the UK, the same weather data, occupancy profiles and heating/cooling set points are used in the calculation (Kelly *et al.,* 2012). It is therefore inevitable that there will be a gap between predicted and actual performance for any given dwelling. In practice, this gap can be widened further by conventions included in the RdSAP methodology for existing dwellings. In addition to the standard SAP conventions, there are assumptions made in RdSAP that are designed to reduce the complexity of calculation. Some of the default selections in RdSAP are the most cost-efficient options which will lead to a higher rating and inaccurate estimates (Kelly *et al.,* 2012).

Energy required for space heating, domestic hot water (DHW), lighting and ventilation are estimated in the SAP (DECC, 2013). As with non-domestic buildings, the exclusion of plug loads (equipment) from the regulatory calculations also results in a performance gap. The SAP2009 outputs do however provide an estimate of appliance energy consumption. In many non-domestic facilities plug load and lighting consumption accounts for a higher proportion of end-use energy consumption than in domestic buildings. It is also likely that there is a greater surface area to internal volume ratio in domestic properties which at a fundamental level equates to a greater potential for fabric heat losses. This places more emphasis on the fabric performance of domestic properties as it has a greater influence on total energy consumption and CO_2 emissions. However, despite the focus on plug-loads in non-domestic performance gap research, data suggests that there is scope for improved fabric performance in certain building types to help reduce space heating energy consumption.

Researchers at Leeds Metropolitan University are working on a calibration methodology that validates the fabric performance of domestic dynamic thermal simulation (DTS) models with data collected during coheating test investigations. The coheating test is described as "…a quasi-steady state method that can be used to measure the whole dwelling heat loss (both fabric and background ventilation) attributable to an unoccupied dwelling." (Johnston *et al.*, 2012, p.3). The measured heat loss coefficient can be used to compare designed with as-built performance. As the coheating analysis and results use the difference between internal and external temperatures to calculate the dwelling heat loss coefficient, the proposed calibration methodology is independent of actual weather files and occupant behaviour. It is possible to mimic the coheating conditions within the DTS model and to use this scenario to calibrate fabric performance through a series of iterative updates. It is important to note that this methodology is currently under development and requires testing on a larger sample of buildings before wider implementation.

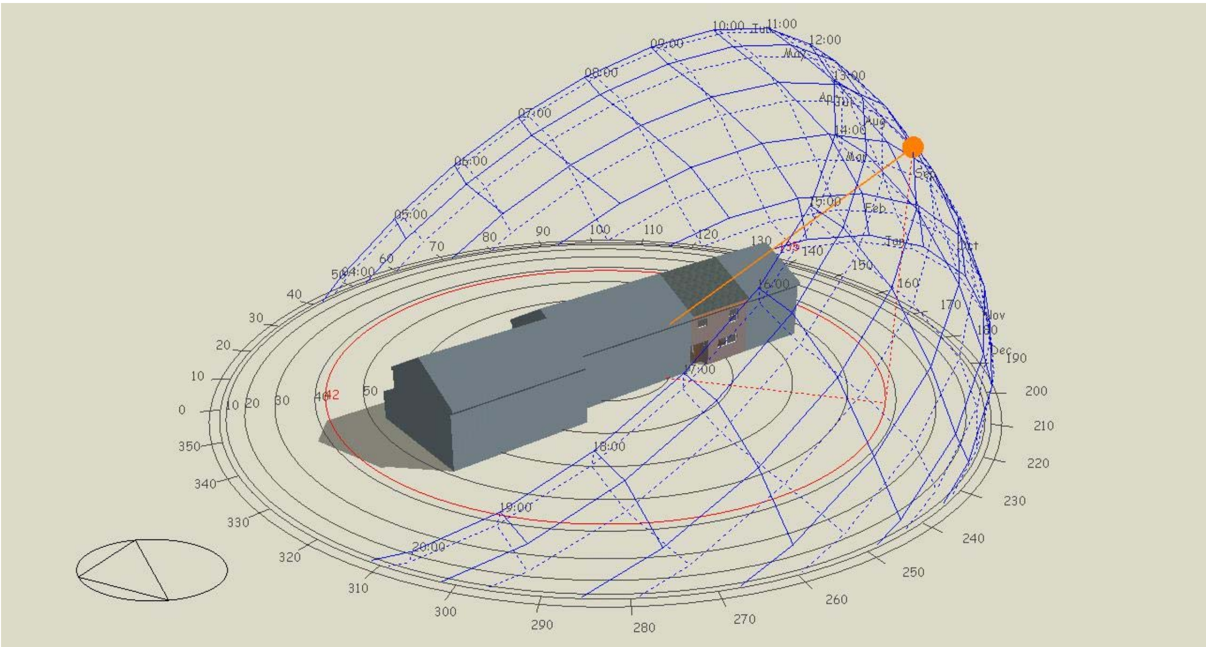

Figure 6, Calibration of building simulation models using coheating data

Conclusion

Attempting to close the loop between designed and actual energy consumption in buildings is not an easy challenge; the multifaceted approaches outlined in this paper provide an indication of a sample of tests and methods for undertaking research into building performance. It is clear that there are merits in pursuing methodologies like the coheating test to gain detailed understanding of issues at the same time as ensuring alternative commercially viable tests are developed that can support widespread, though less detailed, thermal performance checks on buildings to raise awareness and increase the chances or reducing the performance gap.

Whole building field tests have shown that buildings can provide enclosures that perform as designed when adequate sealing of thermal barriers are installed and this can reduce the heating demand of a property significantly. Indeed early work has shown that standard upgrades can half the fuel consumption. However, despite this potential success some buildings continue to underperform.

Buildings that are not effectively sealed and insulated are at the mercy of the elements; as the external environment changes the internal environment rapidly responds. The lack of an adequate enclosure means that thermal comfort is difficult, if not impossible, to achieve.

While some buildings are achieving significant success, others fail to achieve their target. The consequences of underperforming building fabrics are not limited to the detrimental impact on the environment; occupants are directly affected, incurring higher energy bills and accommodating substandard living conditions which can result in health problems and increasing risk of fuel poverty.

Understanding and acceptance of the performance gap and its many negative consequences is growing. To resolve these problems it will be essential to ensure testing methodologies evolve and are assimilated in to the psyche of good construction practices.

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STATE OF THE ART ON FULL SCALE TESTING AND DYNAMIC DATA ANALYSIS FOR BUILDING ENERGY PERFORMANCE CHARACTERISATION

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ABSTRACT

The paper gives an overview and evaluation of previous and ongoing in situ test activities to characterize energy performance of building components and whole buildings. Examples of full scale test facilities available at different institutes over the world are presented. An overview is given of common methods to analyse dynamic data, with their advantages and drawbacks.

KEYWORDS

Energy performance, building, outdoor testing, data analysis, system identification

1 INTRODUCTION

The IEA EBC Annex 58 is an international research collaboration on the topic ‘Reliable building energy performance characterization based on full scale dynamic measurements’. The goal of the Annex is to develop the necessary knowledge, tools and networks to achieve reliable in situ dynamic testing and data analysis methods that can be used to characterize the actual energy performance of building components and whole buildings.

In subtask 1 on the ‘state of the art’ an overview and evaluation was made of previous and on-going in situ test activities based on a literature review and existing reports. An inventory was made of full scale test facilities available at different institutes all over the world. Common methods were described to analyse dynamic data, with their advantages and drawbacks. The overview of full scale testing and dynamic data analysis relates to energy performance characterization of either building components or whole buildings.

2 STATE OF THE ART ON FULL SCALE TESTING

The subtask 1 report on full scale testing gives an overview and description of 27 existing test facilities according to their main functionalities: test objectives, lay-out of the infrastructure, typical equipment and operation, examples of measuring campaigns and analysis methods.

Figure 1: Examples of full scale test facilities for building energy performance characterisation (from top to bottom and left to right): VLIET test building, KULeuven (Belgium); PASSYS test cell, INES (France); LWF Façade facility, Rosenheim University (Germany); Twin houses, IBP Holzkirchen Germany

The test facilities are subdivided in three main groups, depending on the scope and scale of the testing:

1. Facilities for evaluation of (hygro)thermal building envelope performances; examples of these facilities are the VLIET test building at KULeuven, Belgium, the outdoor testing site at IBP Holzkirchen, Germany, and the ZEB test cell at SINTEF-NTNU, Norway.
2. Facilities for characterisation of building component energy performances; examples of these facilities are the PASSYS and PASLINK test cells at CIEMAT and LCCE, Spain, at INES, France or at Florence University, Italy, the Lleida outdoor test cell for double skin systems at CIMNE, Spain, and the LWF Façade facility at Rosenheim university, Germany.
3. Facilities for energy performance testing of building integrated components and systems; examples of test facilities in this group are the Twin houses at IBP Holzkirchen, Germany, the Energy Flex house at DTI, Denmark, the FLEXLAB at LBNL, USA, and the Salford Energy House at Salford University, UK.

Within each group, facilities with a long tradition as well as recently developed platforms are described (Fig. 1). Compared to the previously published book on 'Full scale test facilities' (Janssens et al., 2011), this Subtask 1 report contains 11 new and 4 updated test facility descriptions.

2.1 Reasons for full scale testing

Despite the differences in scope and scale of the test facilities, they all have the objective in common to study the building and system performance under realistic dynamic conditions. To this purpose components, systems and buildings are tested in full scale and under varying interior and exterior climatic conditions. In most existing facilities this is achieved by means of a well-controlled indoor environment and by exposing components to the real climate in

the field. However there are also examples of test facilities in which an artificial exterior climate is used and user behaviour is emulated in order to obtain realistic conditions.
The dynamic behaviour and response of the test elements may be analysed either by means of comparative testing, or by quantifying specific performances based on data analysis methods.

2.2 Common points of attention

Typically full scale dynamic testing is complemented with other test methods, such as material property measurements and steady-state experiments (eg guarded hot box apparatus). These complementary tests are needed to improve the analysis of the dynamic test data and the reliable investigation of building performance. The results of full scale dynamic testing may also help to develop new standard test methods, for example representative accelerated ageing tests, when moisture performance and durability is the scope of the investigation. Further the application and development of modelling and simulation methods is essential for the quality of full scale dynamic testing. Modelling plays an important role in experimental design, in dynamic data analysis, performance quantification, and in system emulation. Well documented experimental data sets from full scale test facilities allow for the validation of new numerical models. Validated simulation tools in return may be applied to extrapolate the experimental findings to long-term performance figures and to assess performances in other than the test conditions.
A common challenge in all test facilities is the reliable quantification of performances based on the experimental results. Following elements are important to consider:

- The accuracy, calibration, position, shielding and number of sensors
- The possibilities to control the indoor environment according to predefined schedules
- The management of large numbers of data
- The dynamic analysis methods for performance and error estimation

3 DATA ANALYSIS METHODS

Full scale testing requires quality on all topics of the process chain, starting with a good test infrastructure. Only when this is present a good experimental set-up can be designed, which produces reliable data that can be used for dynamic data analysis to come to a characterisation and final use of the results (Roels 2011). The data analysis methods used in the test facilities range from averaging and regression methods to dynamic approaches. The methods are discussed in relation to their application in following in-situ measurements:

- measurement of thermal transmittance of building components based on heat flux meters;
- measurement of thermal and solar transmittance of building components tested in outdoor calorimetric test cells;
- measurement of heat loss coefficient and solar aperture of whole buildings based on co-heating tests;
- energy model characterization of whole buildings based on monitored dynamic energy and climatic data.

3.1 Heat flow meter method (Flamant 2013)

By the use of the ‘heat flow meter method’, the thermal resistance and thermal conductance, from surface to surface, may be defined. The thermal resistance and thermal conductance (from surface to surface) of a plane element sufficiently homogeneous can be obtained by measuring the density of heat flow rate at the inner face of the component, using a ‘heat flow meter’, together with surface temperatures at both faces of the component, by means of thermocouples or flat resistance thermometers. If a certain number of requirements are met, the revised draft of ISO/WD9869-1 announces a total uncertainty between 14 % and 28%.

Both steady-state as dynamic data analysis methods are available to derive the thermal resistance from the measured data.
The average method assumes that the conductance can be obtained by dividing the mean density of heat flow rate by the mean temperature difference. The average is calculated over a long enough period of time to reach convergence. This method is a straightforward analysis technique but shows some drawbacks:

- The method ignores and yields no information on the dynamics of the component
- A long test duration is needed to obtain a relative accurate result, with a minimum of 72 h
- Estimation of conductance becomes difficult when average heat flux density or temperature difference is small. Uncertainties become too large in this case.

Nevertheless the application of this simple technique can be useful as a first step in the analysis process, providing some quantitative and qualitative information about the measured data. The drawbacks mentioned above are related to the measurement of medium to heavy elements. For (very) light building components (e.g. glazing), the steady-state analysis performed on the data acquired at night (to avoid the effects of solar radiation) can deliver accurate results

The use of a dynamic method (identification method) has the big advantage to give information on the capacitance of the monitored component and shorten the test duration, particularly for medium to heavy elements submitted to variable indoor and outdoor temperatures.
Several identification methods exist and can be applied for the determination of the in-situ thermal resistance of components. Among these models, the use of lumped parameter models is convenient in many cases (Fig. 2). This model is based on a series of RC-models representing the physical system: a wall is divided into different nodes that are interconnected with thermal resistances and capacitances. These parameters comprise therefore the dynamic and steady state thermal properties of the system. The output of the actual test is then compared to the output which the model produces for the same conditions (input). The parameters are adjusted by iterations in order to reduce and minimise the deviation between measured and model output. This iterative process is carried out with the aid of specialized software tools.
The model created should be 'transparent', i.e. a model in which the main elements of the heat balance of the tested component are recognised. It is necessary to obtain statistical information on the reliability of the identified parameters. The reliability may be negatively affected by measurement and model errors and by correlation between parameters.

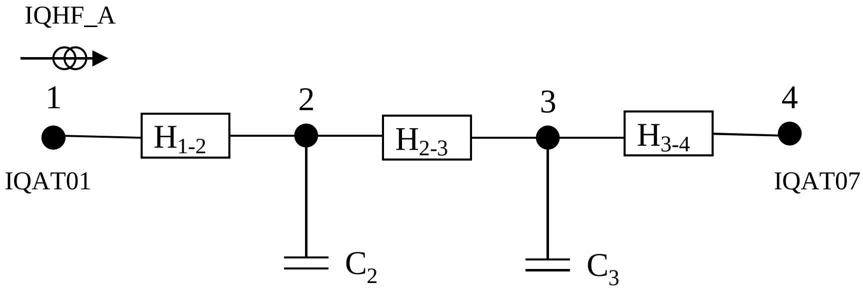

Figure 2: Model for identification of the conductance of an opaque component (IQAT01, IQAT07 are measured surface temperatures, IQHF_A is the measured heat flux at the inside surface)

3.2 Outdoor calorimetric test cell method (Erkoreka 2012)

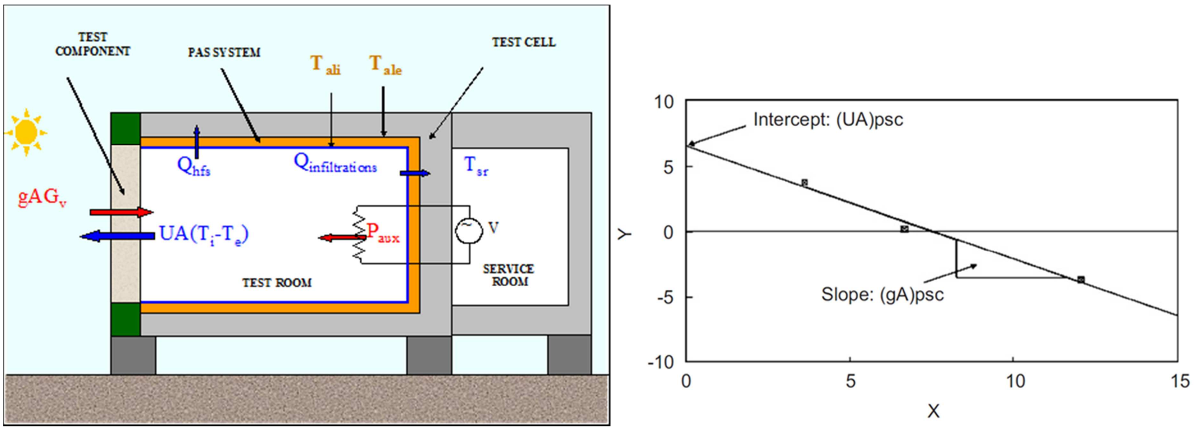

Figure 3: Schematic view of the heat balance in the PASLINK test cell (left, Jimenez et al. 2008) and illustration of a steady-state regression analysis using 10 day mean values (right, Baker and van Dijk 2008)

Calorimetric test cells like PASLINK aim to obtain the thermal and solar characteristics of opaque or transparent building components under real dynamic outdoor conditions.
In general, neither the heat loss, nor the solar heat gain through the component, can be measured directly because of the simultaneous operation of a variety of heat transfer mechanisms through the component. However, these quantities can be inferred indirectly based on the measurement of the net heat flow through the building component. Calorimetric test cells are well suited to measure this latter quantity. From measurement of the time-series of the net heat flow through the component, and of internal and ambient conditions (temperature, global solar radiation perpendicular to component, wind speed,…), the component's steady state transmission heat loss coefficient UA and solar aperture gA can be derived. The co-heating test methodology for whole buildings is based on the same principle. Based on the steady-state heat balance of the test room, successive averaged measurements under different boundary conditions allow to derive the components steady-state characteristics (Figure 3). In principle only two distinct measurement points are needed to yield the characteristics. With more points the UA- and gA-values are obtained by linear regression analysis, as illustrated in Fig. 3. While the steady state method is a straightforward, simple measurement technique, it has significant disadvantages, comparable to the drawbacks mentioned for the heat flow meter method.

In order to overcome these disadvantages, the emphasis has moved from steady state to dynamic methods with shorter test durations yielding improved information and more accurate results, with calculation of confidence intervals on the estimates in some cases. These methods are based on dynamic energy balance equations of the considered physical systems and the application of system identification techniques to obtain the parameters of interest. In parallel with improvements in test methodology, software tools have been developed to enable the identification of the component characteristics and provide statistical information on the identified parameters.
Different modelling approaches are used in system identification of building components. A lumped parameter RC model written as finite differences formed the basis for the LORD software. Whilst LORD has been tailored to the specific requirements of the PASLINK Network, e.g. test cell experiments, it can easily be used for the analysis of other thermal systems. Continuous time linear stochastic modelling (CTLSM) is a stochastic method that takes into account uncertainties in both the measurements and calculations. CTLSM is a semi-physical modelling approach using state-space models described by stochastic differential equations and has evolved into the continuous time stochastic modelling (CTSM) software.

CTSM has been used for estimating and identifying physical systems and performances, such as the heat dynamics of an entire building, the thermal characteristics of walls, the dynamics of heat exchangers, radiators and thermostats, etc. The most important issue on dynamic data analysis is the experience of the user since for the same data series, same software and same parameters to be identified, different results may be obtained depending on the user.

3.3 Energy performance characterisation of whole buildings

Nowadays several new advanced techniques such as home automation, smart meter readings,.. keep track of a lot of information about the buildings response, the energy consumption, the in- and outdoor conditions,… The availability of these data opens the way to a real energy performance characterisation of a building in use, based on analysis of on-site gathered information. This allows to assess whether the energy performance targets are met in reality, with applications in the commissioning and optimisation of building and systems, and in the feedback to the users and managers.
Also for this purpose both linear regression based methods and dynamic data analysis methods are available. Regression methods, often referred to as energy signature techniques, are used to evaluate total heat loss coefficients including transmission and ventilation losses of a building, and to derive normalized energy use intensities (Figure 4). This is done by investigating the correlation between the total energy consumption of the building over a given time step, typically a month, the corresponding averaged ambient conditions (outdoor temperature or heating degree days, global solar irradiance), complemented with measurements of internal heat gains if available. As the frequency of the data for analysis increases, to the level of using daily data for example, the dynamic performance deserves more attention, and 'dynamic heat corrections' may be introduced to improve the regression (Danov et al. 2013).

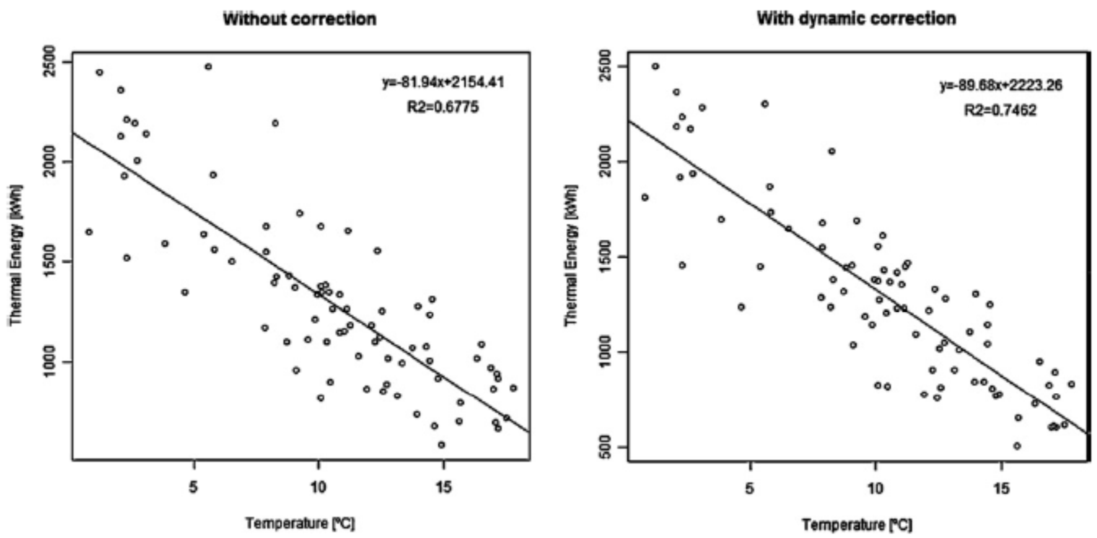

Figure 4: Total heat loss coefficient determined from energy signature (daily data), with and without correction for the dynamic effect (Danov et al. 2013)

Analyzing high-time resolution data measured in buildings requires modelling techniques which describe the heat dynamics of the building. An analysis technique that allows for energy performance characterisation without a detailed description of the building is grey-box modelling where prior physical knowledge is combined with datadriven statistical modelling techniques (Bohlin and Graebe 1995). Based on data with high time-resolution and a thoroughly developed framework for statistical inference using maximum likelihood techniques dynamical systems can be modelled, and statistical testing, model selection and

uncertainty estimation can be carried out (Bacher 2013). A grey-box model is formed by a physical lumped parameter description of the system dynamics, represented by a state-space model combined with a statistical model part (Madsen and Holst 1995). The R software package CTSM-R may be applied for this. The parameters in the physical part are directly interpretable as representing the physical properties of the lumped elements. The typical parameters in the models are heat transfer coefficients (or equivalent thermal resistances), eg representing the heat loss coefficient of the building, effective heat capacities, and effective solar aperture. An example of an RC network equivalent of a building is given in Fig. 5.
In order to excite the dynamics of the thermal building response, the heating of the building under test is preferably controlled using a forcing function (eg PRBS or ROLBS sequences). When measurements are carried out at high time-resolution, the testing period can be minimized to a couple of days.

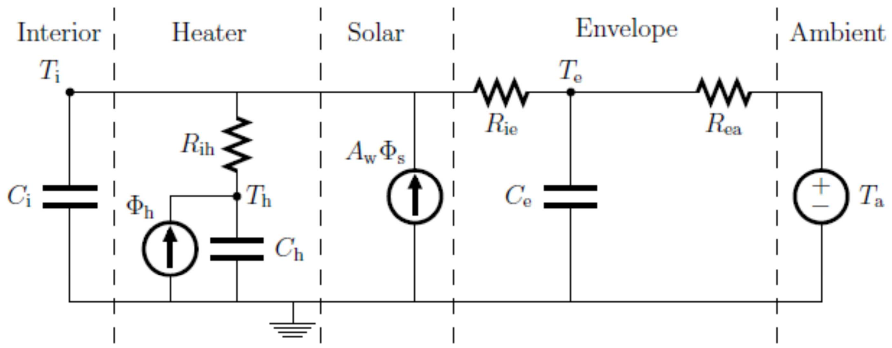

Figure 5: RC network equivalent of a three state building model (Bacher and Madsen 2011) for grey box modelling using high-resolution measurements of heat input Φ_h, indoor and ambient temperature T_i and T_a, and global solar radiation Φ_s.

4 CONCLUSIONS

This paper gave an overview and evaluation of previous and ongoing in situ test activities to characterize energy performance of building components and whole buildings. Examples of full scale test facilities available at different institutes over the world were presented. An overview was given of common methods to analyse dynamic data, with their advantages and drawbacks. In state-of-the-art data analysis methods the emphasis has shifted from straightforward steady-state and regression methods to dynamic methods based on system identification techniques.
In view of the current environmental and energy challenges, the society is in urgent need for adequate retrofitting solutions for the existing building stock, and for concepts for nearly zero energy buildings. The existing test facilities and dynamic analysis methods have the possibilities to contribute to these developments. However, since these facilities have different scopes and scales, there is a need for collaboration within a network of excellence, such that the integral multi-physics performance of new solutions may be investigated both at component level and at the whole building level.

5 ACKNOWLEDGEMENTS

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Standardisation of methods for in-situ performance assessment

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Since 2010, working group 13 of CEN TC89 is working on the elaboration of new standardized procedures for deriving in-situ test data that will complement the thermal performance characteristics of construction products, building elements and structures established by conventional steady state methods

This presentation gives the objectives, the work progress, the difficulties encountered, the issues and possible solutions considered.

Co-heating test: a state-of-the-art

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Abstract

Several studies have shown that the actual energy performance of buildings can differ significantly from its designed value. An important part of this performance is constituted by the building fabric's thermal performance. A common method to evaluate the latter for an actual building is the co-heating test. The co-heating test comprises a quasi-stationary heating experiment followed by linear regression analysis of aggregated building performance data. This paper reviews related research work and cristallises the current state-of-the-art. The physical phenomena working behind the scenes of the generally assumed simplified heat balance are discussed. Statistical constraints generally prevent these from being uncovered fully during the analysis. Multiple linear regression is proposed as the most sensible method to analyse co-heating measurement data. A novel way to visualise such analysis, deduce building performance data graphically and compare different co-heating test results is presented.

Keywords: co-heating, thermal performance, characterisation, in-situ

1. Introduction

In order to reduce the energy use of buildings, several countries have put forward more stringent demands on the energy performance of new buildings and renovated buildings. Without exception, these supervised buildings are characterised or awarded a label in the design phase: a theoretical energy use calculated on the basis of building plans and specifications determines the performance category. An important distinction needs to be made, however, between this theoretical energy performance and the actual as-built performance. Several studies have shown that these can differ significantly (Bell et al. (2010); Lowe et al. (2007)).

The energy performance of a building is essentially determined by the (1) thermal characteristics of the building envelope, (2) installed services and (3) building usage. As the latter is not easily controlled, the first two are decisive in achieving the envisaged building energy performance. Hence, thermal performance characterisation of building envelopes on the basis of real performance data represents a crucial first step towards bridging the gap between *designed* and *as-built* energy performance of buildings.

A common method to evaluate the thermal performance of an actual building is the co-heating test. This test essentially represents a *quasi-stationary test method* based on *linear regression analysis of aggregated building performance data*, acquired during appropriate heating experiments. During a co-heating test, the investigated dwelling is homogeneously heated to an elevated steady-state interior temperature, e.g. $25°C$, using electric heaters and ventilator fans scattered throughout the building. The electrical energy use, the indoor and outdoor air temperatures and relative humidities, wind speed and direction, and finally solar radiation are monitored throughout the test. The influence of transient effects induced by charging and discharging of the building's thermal mass can be reduced by sensibly choosing the experiment period and averaging the collected measurement data over a sufficient time span. Using *regression analysis*, the monitored indoor and outdoor conditions are related to the electrical heating energy needed to sustain a constant indoor air temperature. The coefficients describing this relationship represent building thermal performance characteristics of interest: the total *Heat Loss Coefficient* (HLC), in W/K and one or more characteristics relating the heating energy to e.g. solar radiation. The total HLC constitutes a combined transmission and ventilation heat loss. To decouple both, a co-heating test is generally combined with a blowerdoor or tracer gas test.

The development of the co-heating test methodology began late 1970s Sonderegger and Modera (1979); Sonderegger (1980), where it was originally applied to determine the efficiency of duct heating and cooling systems, in-situ and under realistic boundary conditions. In order to do so, real full-scale dwellings were alternately heated using the building's own services and electric heaters with known

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efficiency. Hence the name *co-heating*. Ever since it's conception, however, the co-heating test method has also been used to estimate thermal characteristics of the building envelope, e.g. overall heat loss coefficient and solar aperture (Deconinck and Leunis (2012); Bell et al. (2010); Lowe et al. (2007); Bauwens et al. (2012)), and to localise heating loads (Sonderegger and Modera (1979)).

In this paper, we cristallise the current state-of-the-art of the co-heating test, as it is applied to assess the thermal characteristics of building envelopes. Focus lies more on the data analysis methodology, rather than on experimental setup and data acquisition. Evidently, we drew considerable inspiration from literature discussed in the paper's first main section, where a brief history of the co-heating test is unfolded. For reasons of clarity, we rewrote the formulas developed in the presented research to conform to the nomenclature adopted in this paper and specified in Table 1 and 2. The co-heating test methodology is defined in Section 3. After briefly sketching the actual experiment and its setup, we dig deeper into the building's heat balance. We uncover physical phenomena that work behind the scenes as the co-heating test unfolds. Phenomena that are often neglected in related research work. In a final step, simplifications typically applied in the analysis are discussed.

2. A brief history

To our knowledge, the first building performance assessments using thermostatically controlled portable electric heaters spread throughout an investigated building are presented in Sonderegger and Modera (1979) and Sonderegger (1980). Here, real full-scale dwellings are alternately heated using the building's own services and electric heaters: in the initial and final stages of the experiment, the building's heating demand is covered solely by the latter; in an intermediate stage, the former serves to cover part of this demand. Hence the name *co-heating*. As such, the co-heating test was shown to offer a full range of possible assessment results. First, the decrease in electricity used by the electric heaters during service operation allows for an assessment of the latter's efficiency under realistic conditions. It could similarly be used to determine efficiencies of cooling systems. Secondly, as evident from Eq. 1, by dividing averages of the electric heating energy Q_h delivered to the building, by averages of the indoor-outdoor air temperature difference ΔT, the method results in a characterisation of the building envelope performance, under the form of an *overall Heat Loss Coefficient (HLC)*, a parameter of particular interest in this paper.

$$Q_h = HLC\Delta T \tag{1}$$

Lastly, by monitoring the dispersed electric heaters individually and allowing for separate thermostatic control,

Table 1: Nomenclature

Measured variables	Symbol	Unit
Heat flows towards states k	$\mathbf{Q_k}$	W
Heat flow towards indoor air	Q_i	W
Electric heating energy	Q_h	W
Direct and indirect solar gains through transparant fabric parts	Q_{sw}	W
Equivalent transmission heat loss through building fabric	$Q_{tr,eq}$	W
Total ventilation heat loss through building fabric	Q_v	W
Latent heat due to hygroscopic loading and unloading of building parts	Q_{latent}	W
Temperature states k	$\mathbf{T_k}$	K
Indoor air temperature	T_i	K
Outdoor air temperature	T_a	K
Indoor-outdoor air temperature difference	ΔT	K
Sky temperature	T_{sky}	K
Equivalent outdoor temperature corresponding to $*$ and j	$T^{*,j}_{a,eq}$	K
Global solar radiation on $*$	$q_{sw,*}$	$\frac{W}{m^2}$
Ground floor heat loss	F	W
Parameters	**Symbol**	**Unit**
Overall Heat Loss Coefficient	HLC	$\frac{W}{K}$
Transmission heat loss	$\sum AU$	$\frac{W}{K}$
Overall solar aperture coefficient	$A_{sw,*}$	m^2
Ventilation heat loss	$c_a G_a$	$\frac{W}{K}$
Heat capacity of air	c_a	$\frac{J}{(kgK)}$
Natural airflow through building fabric	G_a	$\frac{kg}{s}$
Density of air	ρ_a	$\frac{kg}{m^3}$
Air change rate at 50 Pa	n_{50}	h^{-1}
Actual air change rate	n_{actual}	h^{-1}
Air volume of dwelling	V	m^3
Latent heat of evaporation of water	h_w	$\frac{J}{(kgK)}$
Dry-out rate	G_{vP}	$\frac{kg}{s}$
Latent heat demand	c_{vP}	W
Heat capacities states k	$\mathbf{C_k}$	$\frac{J}{(kgK)}$
Heat capacity indoor air	C_i	$\frac{J}{(kgK)}$
System and measurement noise	$\mathbf{c_k}$	W
Constant heat loss term	c	W
Absorption factor fabric surface	$\alpha_{sw,j,*}$	-
Long-wave radiative heat exchange at fabric surface; assumed constant	$c_{lw,j,*}$	K
Heat transfer coefficient: U-value	U	$\frac{W}{(m^2K)}$
Surface area	A	m
Emissivity of fabric surface material	$e_{lw,j}$	-
Black body constant	C_b	$\frac{W}{(m^2K^4)}$
Angle radiation factor	$F_{sky,*}$	-
Temperature radiation factor	$F_{T,sky}$	-
Convective and radiative surface heat transfer coefficient, resp.	h_{ce},h_{re}	$\frac{W}{(m^2K)}$

Table 2: Nomenclature (continued)

Abbrevations	Symbol	Unit
Surface orientation normal to solar radiation projections:		
when not specified	$*$	-
Horizontal	H	-
East	E	-
South	S	-
West	W	-
North	N	-
Building fabric part	j	-
Opaque fabric parts	o	-
Transparant fabric parts	w	-
Weighting factors	a,b	-

heat loss contributions from building zones can be separated. An application which Sonderegger and Modera (1979) refer to as *load localisation*.

The HLC in Eq. 1 was identified to comprise two heat loss mechanisms: (1) transmission heat loss $\sum AU$ and (2) ventilation heat loss $c_a G_a$, both in W/K. To disaggregate the HLC into its parts, co-heating experiments are generally accompanied by blowerdoor or tracer gas tests to assess the actual air change rate occuring during the experiment. The air change rate is then often assumed constant over the test period.

$$Q_h = (\sum AU + c_a G_a)\Delta T \tag{2}$$

In all of the cases discussed in Sonderegger and Modera (1979), the electric heaters were placed throughout the buildings in such a way that the indoor air temperatures are distributed as uniformly as possible. Ventilation fans served to mix the indoor air and avoid stratification. A very similar experimental setup is seen in most of the research work discussed in this section.

All performance assessment methodologies essentially constitute a combination of (1) a measurement campaign and (2) consequent analysis of collected measurement data. In the remainder of this section, and paper, we will mainly focus on the latter.

In Sonderegger and Modera (1979), 40-min averaged data points were proposed as a basis for analysis. They assume a stationary heat balance, with the temperature differential inside-outside ΔT as a sole driver for heat loss. An assumption, however, which they only considered accurate under certain conditions. They briefly mention possible disturbances introduced by solar gains and ground floor heat losses. They assume the influence of solar gains to be negligible, as the measurements were performed from late evening into nighttime. Also, they neglect possible disturbances introduced by the slow dynamics of the ground floor and the rather short aggregation time.

In Sonderegger (1980), considerable variation is reported in HLC's that resulted from tests performed in different periods. Over the course of one single test, however, the variation was found to be minimal, which they identified to be intrinsically linked to the light-weight nature of the investigated dwellings. As such, they argued the system efficiency assessment to remain uncompromised.

In their effort to define performance evaluation procedures for passive solar buildings, preferably of low-cost, Palmiter et al. (1979) made a clear distinction between *one-time measurements* and *continuous measurements*. Both lead to thermal performance factors, including the building heat loss coefficient (HLC). To determine the latter, they propose following formulas as a basis for linear regression:

$$Q_h = HLCT_a - A_{sw,*} q_{sw,*} + c \tag{3a}$$

$$\frac{Q_h}{\Delta T} = HLC - A_{sw,*} \frac{q_{sw,*}}{\Delta T} \tag{3b}$$

where in this case $*$ refers to the solar radiation projection that is actually measured.
Notably, in Eq. 3a, T_i is assumed constant and $HLCT_i$ is lumped into c. For ease of comparison, we rewrite it to obtain ΔT as a driving force:

$$Q_h = HLC\Delta T - A_{sw,*} q_{sw,*} + c \tag{4}$$

In Palmiter et al. (1979), measurement data were collected whilst the investigated dwellings were in-use. The proposed monitoring time step is 1 hour. Monitored data is averaged over 5 to 10 days. They recommend to estimate an *overall furnace efficiency* by dividing the heat delivered to the indoor air and the consumed fuel energy. They also propose infiltration and capacitance measurements to validate assumed simplifications.

In Sonderegger and Modera (1979) and Sonderegger (1980), the analysis was limited to a simple linear regression with Q_h as dependent variable and ΔT as independent variable. Palmiter et al. (1979), and later Siviour (1981) and Everett (1985) suggest the use of multiple (e.g. triaxial) linear regression.
In the early 80s, Siviour (1981) built upon the work of Sonderegger and Modera (1979) and Palmiter et al. (1979), when he proposed two options to include solar gain influence in the analysis: separate *calculation* of solar gains, based on assumptions regarding geometric and physical characteristics of the investigated building and its surrounding environment; and *experimental deduction* of the solar gains, as a result of multiple linear regression.
Siviour (1981) suggested both options are best served by experiments performed during the heating season. The former is argued to endure a shorter measurement period of for instance 1 week in winter, whereas the latter might require a longer measurement period, including days with sufficient solar radiation. Notably, both Palmiter et al. (1979) and Siviour (1981) suggested a mathematical transformation of Eq. 4: by dividing all terms by ΔT, Eq. 3b is obtained.

Ortega et al. (1981) refer to the co-heating test as a well-established experimental method to determine the total heat loss coefficient HLC. They stress, however, the importance of controlling the heating energy part that is charging or discharging the buildings thermal mass. To limit this effect, they suggest keeping the indoor air temperature constant during a period with relatively constant outdoor air temperature, as such approaching stationary fabric conditions. Moreover, they argue that such conditions are quickly obtained in the case of lightweight constructions, whereas this takes considerable time in heavyweight constructions. To resolve the latter, Ortega et al. (1981) suggest pre-heating the investigated building for several days, whilst eliminating solar gains through the windows.

The method used to assess the building's total heat loss coefficient HLC and solar aperture coefficient $A_{sw,*}$, presented in the Linford project report Everett et al. (1985) builds upon the work of Siviour (1981) and looked to better assess $A_{sw,*}$. The Linford project included experimental work on a number of occupied houses and one unoccupied test house. Here, the researchers assessed heat loss through the ground floor F separately, using heat flux sensors spread over its surface. As such, the assumed heat balance is written as a *triaxial regression*, with F approximated a constant during the test

$$Q_h + A_{sw,S} q_{sw,S} = HLC \Delta T + F \tag{5}$$

To decouple ventilation heat loss $c_a G_a$ from HLC in Eq. 5, they performed pressurisation tests and tracer gas tests with constant concentration.

The authors of Everett et al. (1985) based their analysis on daily and weekly averaged measurement data. Global solar radiation $q_{sw,S}$ was measured on a *vertical and south oriented* surface. They also considered the, by now familiar, mathematical transformation of Eq. 5 into a form that allows for single linear regression, or *biaxial regression*:

$$\frac{Q_h - F}{\Delta T} = HLC - \frac{A_{sw,S} q_{sw,S}}{\Delta T} \tag{6}$$

The HLC, which in this case does not include ground floor heat loss, is then found as the intercept of the regression curve and $A_{sw,S}$ represents its negative slope. In order to extract good estimates of both HLC and $A_{sw,S}$, they proposed to select measurement campaigns that combine a good spread of $\frac{q_{sw,s}}{\Delta T}$ with a significant number of data points with low $\frac{q_{sw,S}}{\Delta T}$. The study shows that when considering daily averaged data, thermal lag effects need to be taken into account. To allow maximum time for the solar gains charged during the day to be discharged overnight, they averaged measurement data from dawn to dawn. As the air infiltration is shown to vary significantly over the duration of the experiment, they advise to measure this separately.

One of the standard works on the co-heating test methodology is Everett (1985), written to inform *"those fool enough to want to test the thermal performance of a house"*. This report is built on a vast array of earlier project work, including the earlier discussed Linford project. Also here, daily and weekly averaged data were used as a basis for analysis. He reports solar gains, air infiltration, ground floor losses and party wall heat losses as factors rendering the analysis more complex. He proposes to elevate the indoor air temperature as high as feasible: to render inside-outside temperature differential much larger than associated measurement errors, to avoid solar gains from overheating the indoor air during the day and to reduce the infuence of wind speed on air infiltration. Increased air infiltration due to stack effects is not considered here. To diminish the effect of charging and discharging of the building's thermal mass, he advises to precede the experiment by 2 to 3 days of heating. Regarding data analysis, he demonstrates that it is difficult to obtain a large spread on ΔT over a measurement period. In most cases, however, separate coefficients for HLC and $A_{sw,*}$ are shown to lie within reach, as the covariance of $q_{sw,*}$ and ΔT is generally low. To compensate for the effect of thermal lag, he proposes to relate Q_h with a Y-response weighted average of T_a and T_i.

Boogaerts (1987) mentions following factors to increase the accuracy of the measured heat loss coefficient: better interior climate control, moderately constant weather conditions over an extended monitoring period and, finally, a fabric that exhibits low thermal mass and is well insulated. The uncertainty on the actual air change rate, the actual solar gains, influence of wind and heat losses through ground floor and to unheated adjacent spaces are mentioned as possible disturbing factors.

Howard and Saunders Howard and Saunders (1989) report in 1989 of several studies revealing shortcomings in the building fabric to be primary factors in explaining poor energy performance of buildings. They identify the combination of an electric co-heating test and air leakage test as an easy to apply and low-cost method, leading to accurate parameter estimates.

Andrews (1995) mentions three aspects that determine the accuracy of the co-heating test: repeatability of results, systematic errors, e.g. when neglecting solar gains, and neglecting thermal lag. In order to increase the accuracy of the system efficiency assessment, it was suggested that the electric co-heating, as it was performed in Sonderegger and Modera (1979) be repeated in two consecutive nights to form the so-called *"flip-flop-protocol"*: each night the building is heated consecutively with the heating system and the electric co-heaters, with the order of heating reversed one night to the other Andrews (1995). The authors warn about one night influencing the next in case of considerable thermal mass. In those cases, they advise to plan sufficient time in between consecutive test nights.

More recently, the co-heating test has been applied by (non-limitative): Masy (2004), Francisco et al. (2006), Lowe et al. (2007), Bell et al. (2010), Palmer et al. (2011), Stamp (2011), Bauwens et al. (2012), Deconinck and Leunis (2012). Aside from holding the promise of a quantitative assessment, the co-heating test method is often combined with empirical investigations into possible heat loss mechanisms which would otherwise not be as apparent. For instance, local infiltration losses and cold bridges can be depicted through infrared imagery during a combined co-heating test/blowerdoor test. A striking result of such investigative work is the identification of the *party wall thermal bypass*, specific to building typologies and detailing in UK (Lowe et al. (2007)). Recent overviews of the co-heating test method are provided in Johnston et al. (2013) and Stamp (2013).

Since its conception, many short-term and dynamic assessment methodologies have been developed from and as possible alternatives for the co-heating test: Short Term Energy Monitoring (STEM) using the Primary and Secondary Terms Analysis and Renormalisation (PSTAR) Subbarao et al. (1988); Palmer et al. (2011), Measured Performance Rating (MPR) Howard and Saunders (1989); Andrews (1995), Princeton Scorekeeping Method (PRISM) Fels (1986); Kissock et al. (2003) and more recently Quick measurements of energy efficiency of building (QUB) Mangematin et al. (2012). This is a non-limitative list and includes methods that incorporate system efficiency and user behaviour with various degree of detail. Although they will not be discussed in this paper, they take considerable input from a co-heating test part. For instance, a STEM/PSTAR test includes a nighttime co-heating test to evaluate envelope heat loss, as well as a daytime co-heating part to quantify the effect of solar gains.

3. Co-heating test method

In this section we give a short overview of the standard co-heating test. Subsequent sections serve to discuss the commonly used data analysis methods.

The co-heating test procedure comprises a quasi-stationary heating experiment and subsequent data analysis. It assumes an unoccupied dwelling. During the test, the indoor air of the investigated dwelling is homogeneously heated to an elevated steady-state temperature, e.g. $25°C$, using electric heaters and ventilators. As such, the co-heating test essentially consists of a thermostatic heating procedure extended over a longer period of time. The effect of charging and discharging the thermal mass of the building is thereby diminished. Nonetheless, transient effects can take place due to dynamic weather conditions, e.g. heat absorption by irradiated indoor and outdoor wall and floor surfaces.

The electrical energy use necessary to retain this elevated temperature, the indoor and outdoor air temperatures, indoor and outdoor relative humidities, wind speed and direction, precipitation and finally solar radiation are monitored throughout the test.
At the onset, data is sampled at a short time interval, e.g. every 5 minutes. This allows to grasp the building dynamics that play during the experiment and to correctly interpret the *aggregated data points*. As a basis for analysis, the measurement data is aggregated over a sufficient time span (e.g. 1 day, 2 days, 1 week, ...), thereby assuming suitable start times (e.g. midnight to midnight or 8:00 to 8:00 in the case of 1 day time spans). Possible aggregation methods include averaging, resampling and decimating. Combined with the effort made during the experiment to diminish thermal charging and discharging of the buildings' thermal mass, this serves to fulfil the quasi-stationary nature of the co-heating test methodology.

During the test, indoor air temperatures are measured throughout the dwelling. Doors are opened to facilitate homogeneous temperature distribution. As such, the dwelling is regarded as constituting one zone at temperature T_i. A representative indoor air temperature signal T_i is deduced using e.g. principal component analysis or plain averaging.

In order to undertake a succesful co-heating measurement campaign, tailored equipment is indispensable. Figure 1 illustrates the co-heating experimental setup inside a dwelling. Figure 2 shows the tracer gas test and blowerdoor test equipment. Figure 3 depicts the weather station placed in the garden of the investigated dwelling. The basic co-heating test equipment has been extensively described by Leeds Metropolitan University (Johnston et al. (2013)).

As mentioned in the previous section, the overall heat loss coefficient HLC comprises both transmission and ventilation heat loss. Ventilation, on its turn, can comprise both *natural* and *forced* parts. During a co-heating test, the latter is diminished as part of the test, i.e. ducts and other purposefully placed channels are taped. Nonetheless, significant heat losses can still occur due to air infiltration and exfiltration. To decouple HLC into its transmission $\sum UA$ and ventilation c_aG_a parts, the actual *natural* background air change rate n_{actual}, occuring during the experiment, needs to be assessed. Knowledge of n_{actual} allows to calculate c_aG_a:

$$c_aG_a = \frac{1}{3600} c_a \rho_a n_{actual} V \tag{7}$$

where ρ_a density of air $[\frac{kg}{m^3}]$; n_{actual} the actual air change rate $[h^{-1}]$; V air volume of dwelling $[m^3]$.

Two procedures are generally used: (1) tracer gas tests and (2) blowerdoor tests. The former can take place whilst the co-heating test is running, whereas the latter can be performed before and after.

During a tracer gas test, a certain gas is injected into the investigated building. Two options can be discerned here: (1) the gas flow necessary to sustain a constant gas pressure is monitored or (2) the gas pressure decay following a gas injection is monitored. This test yields an estimate of the actual air change rate n_{actual} occuring as the experiment unfolds. In other words, measurements are performed whilst realistic boundary conditions take place and this in a continuous fashion. It is associated with a high measurement accuracy, which, however, comes at considerable cost and complexity.

A pressurisation test or blowerdoor test involves imposing a range of pressure differences over the investigated building fabric, i.e. 10 to $100 P_a$ in steps of 10 P_a. It can be performed just before and right after the test. It results in an estimate of the air change rate occuring at a pressure difference inside-outside of 50 P_a, i.e. n_{50}-value. Evidently, this pressure difference is not representative for real scenarios. Also, as the test is performed only momentarily before and after the co-heating test, only discrete air change rate estimates are within reach. It can be performed at low cost, which, however, comes with low accuracy and *no insight into the evolution in time of the actual air change rate.*

Nonetheless, using a rule of thumb, proposed by Kronvall (1978): $n_{actual} = \frac{n_{50}}{20}$, the n_{50}-value resulting from a blowerdoor test can be related to an average actual air change rate taking place under real pressure difference scenarios. As such, Eq. 7 can be rewritten:

$$c_a G_a \approx \frac{n_{50}}{60} V \tag{8}$$

Figure 1: Co-heating test equipment: heat sources controlled by thermostats, ventilators, temperature sensor and pulse meters spread throughout the different zones of the investigated dwelling.

Figure 2: Blowerdoor and tracer gas test performed to estimate actual air change rates.

Figure 3: Monitoring outside weather conditions: weather station (left) and weather station mast (right).

4. Stationary modeling of a dynamic system

Performing a co-heating experiment is just a first step. In order to reliably quantify the building's thermal performance, the acquired measurement data needs a tailored data analysis. The equations mentioned earlier stem from simplified stationary heat balances of a dwelling: one thermostatically controlled zone sheltered from outside weather conditions by a building fabric. In this section, we identify the physical phenomena working behind the scenes, to come to an extended heat balance equation. Subsequently, taking into account the statistics of the problem, we distill from this a simplified version that is assumed in the actual co-heating data analysis. As such, the different assumptions hidden in the simplified heat balance can easily be retraced.

Buildings essentially constitute thermal dynamic systems, that are effectively modelled as lumped state space models, or equivalently as a system stochastic differential equations: SDEs (Andersen et al. (2000)). As such, the building is modelled as a series of thermal nodes, which can represent an indoor air temperature or a temperature inside in the capacitive building fabric, among others. They are generally referred to as *system states*, bear a certain capacity (C) to charge or discharge heat and are linked through thermal resistances (R). Assuming we distinguish k states, the buildings heat balance can be written as:

$$\sum \mathbf{Q_k} + \mathbf{c_k} = \mathbf{C_k}\frac{\mathbf{dT_k}}{\mathbf{dt}} \tag{9}$$

where $\sum \mathbf{Q_k}$ is a vector representing the sum of heat flows towards states $\mathbf{k}$, $\mathbf{c_k}$ encapsulates the system and measurement noise and $\mathbf{C_k}$ heat capacities and $\mathbf{T_k}$ temperatures of states $\mathbf{k}$.

Assuming that the *whole building acts as one zone* and only considering the indoor air temperature T_i as a state, the building heat balance can be written as one SDE:

$$\sum Q_i + c = C_i\frac{dT_i}{dt} \tag{10}$$

Given a thermostatically controlled indoor air temperature T_i, given appropriately aggregated performance data and given efforts made during the experiment to diminish thermal charging and discharging of the buildings' thermal mass, $\frac{dT_i}{dt}$ in Eq. 10 can be assumed to be zero. Accordingly, the heat balance is simplified to its stationary form:

$$\sum Q_i + c = 0 \tag{11}$$

This *stationary heat balance* represents only a crude modeling of the actual dynamic building response. For instance, the heating power Q_h is assumed to go straight to T_i. An assumption that only holds in the stationary case, i.e. when the thermal mass is charged to a certain equilibrium level, or equivalently when no heat is being charged/discharged by building components. In reality,

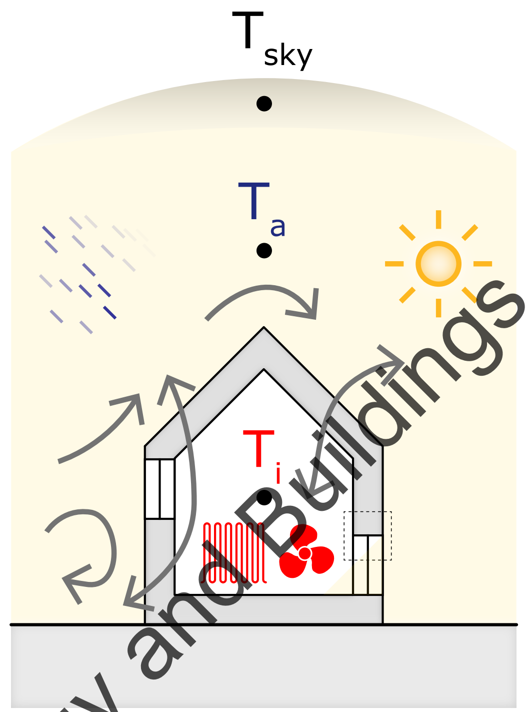


Figure 4: Building heat balance: heat loss and gain terms illustrated.

this situation is never fully reached: partly due to limited control of the indoor environment, but mostly due to dynamic weather conditions, e.g. solar gains charging the buildings' thermal mass. The considered heat loss and heat gain mechanisms $\sum Q_i$ are illustrated in Figure 4 and collected in Eq. 12:

$$Q_h + Q_{sw} - Q_{tr,eq} - Q_v - Q_{latent} + c = 0 \tag{12}$$

where Q_h is the energy supplied by heaters and dissipated by ventilators; Q_{sw} solar gains through transparant fabric parts; $Q_{tr,eq}$ equivalent transmission heat loss through building fabric, taking into account indirect heat gains attributable to short-wave solar irradiation of opaque fabric surfaces and heat gains/losses attributable to long-wave radiative heat exchange at fabric surfaces with sky and environment; Q_v ventilation heat loss through building fabric; Q_{latent} latent heat due to hygroscopic loading and unloading of building parts. A typical example of the latter is drying out of moisture encapsulated in building fabric. All units are in $[W]$. In what follows, we will rewrite the heat loss and heat gain terms in Eq. 12 as a function of the corresponding driving forces, e.g. *temperature differential inside-outside* ΔT. The first term, Q_h is thermostatically controlled. It is not modelled as a function of a driving force, as aggregated measurement data is considered. It is, however, directly available through monitoring.
Throughout the day, the sun travels along a certain trajectory through the celestial sphere, viewing the investigated building from a different angle along the way. The

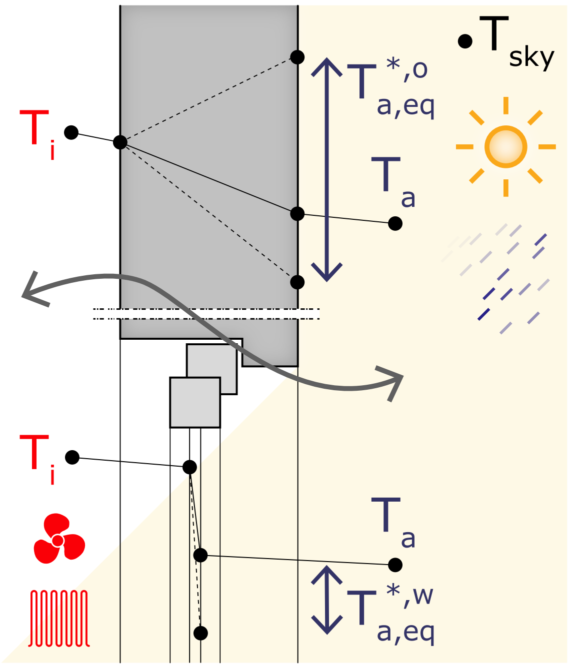


Figure 5: Component heat balance: solar radiation and long-wave radiative heat exchange with sky pushing surface temperatures $T^{*,o}_{a,eq}$ and $T^{*,w}_{a,eq}$ above or below outdoor air temperature T_a.

intensity with which the solar radiation strikes the investigated building depends on factors including the sun angle (zenith and azimuth), cloudiness of the sky and shading, among others. The sun vector can be deconstructed into its projections $*$ on the main axes, i.e. north, south, among others. Hence it makes sense to write *direct and indirect solar gains through transparant fabric parts* Q_{sw} as a *proportional sum* of these *solar radiation projections* $q_{sw,*}$: $\sum(A_{sw,*,w} q_{sw,*})$, where $A_{sw,*,w}$ represent solar aperture coefficients related to projection $*$ and transparant fabric part w. For now, they can be understood as *averaged* gA-values of respective transparant fabric parts.

Let us now take a closer look at the equivalent transmission heat loss term $Q_{tr,eq}$. The indoor-outdoor air temperature difference $\Delta T = T_i - T_a$, directly available from measurements, is typically considered as a driving force for transmission heat loss in the co-heating test heat balance equation. This conductive heat flow Q_{tr}, however, depends on the *surface temperature differential*. As illustrated in Figure 4, the outdoor surface temperature of opaque and transparant fabric parts can differ significantly from the outdoor air temperature. Surface temperatures of opaque fabric parts rise when striked by short-wave solar radiation. Similarly, surface temperatures of opaque and transparant parts typically drop at night time due to long-wave solar radiation exchange with sky and environment. On the basis of a simplified heat balance towards the outdoor surface temperature node of an opaque building fabric part, we can rewrite ΔT to incorporate these phenomena Hens (2008):

$$T_i - T^{*,j}_{a,eq} = T_i - (T_a + \frac{\alpha_{sw,j,*} q_{sw,*}}{h_{ce} + h_{re}} - \frac{e_{lw,j} C_b F_{sky,*} F_{T,sky} (T_a - T_{sky})(1-c)}{h_{ce} + h_{re}}) \tag{13}$$

$T^{*,j}_{a,eq}$ in Eq. 13 constitutes an *equivalent outdoor temperature*. $\alpha_{sw,j,*}$ and $e_{lw,j}$ are the absorption factor and the emissivity of the fabric surface material $[-]$, resp.; C_b the black body constant $5.67 \frac{W}{m^2K^4}$; $F_{sky,*}$ and $F_{T,sky}$ angle factor and temperature radiation factor $[-]$, resp.; T_{sky} sky temperature $[K]$; c cloud factor $[-]$; h_{ce} convective surface heat transfer coefficient $\frac{W}{m^2K}$; h_{re} radiative surface heat transfer coefficient $\frac{W}{m^2K}$; j refers to component j and $*$ refers to the component orientation. Notably, Eq. 13 only holds in the assumption that both ground and surrounding buildings exhibit similar temperatures than the outdoor air.

From Eq. 13, we can conclude that the influence of short-wave solar radiation and long-wave radiative heat exchange on conductive heat flow through the building fabric will differ for different fabric components j ($\alpha_{sw,j,*}$ and $e_{lw,j}$) and for different orientations $*$ ($q_{sw,*}$ and $F_{sky,*}$).

During a clear night, the sky temperature lies around $21°C$ below the outdoor air temperature T_a Hens (2008). Hence, optionally, the term $T_a - T_{sky}$ in Eq. 13 can be replaced by this constant. It allows to rewrite it into a simplified form:

$$T_i - T^{*,j}_{a,eq} = T_i - T_a - \frac{\alpha_{sw,j,*}}{h_{ce} + h_{re}} q_{sw,*} + c_{lw,j,*} \tag{14a}$$
$$= \Delta T - \frac{\alpha_{sw,j,*}}{h_{ce} + h_{re}} q_{sw,*} + c_{lw,j,*} \tag{14b}$$

Note that part of the solar radiation that enters the building through its transparant fabric parts, serves to heat indoor surface areas of indoor and outdoor walls, but primarily the ground floor and intermediate floors. This is not modelled explicitly here: no equivalent temperature is defined to describe the indoor environment. Later in this section, however, we discuss how modeling thermal lag effects can help resolve this.

For transparant fabric parts, both direct and indirect solar gains are already included in Q_{sw}. Nonetheless, long-wave radiation still influences the outdoor surface temperature and thus the transmission losses through transparant components. Heat losses through ground floor components present another special case. We will return to this curious heat flow component when we discuss thermal lag effects. In what follows, we distinguish between transmission heat loss through opaque (o) and transparant (w) fabric parts.

Taking Eq. 14b and above considerations into account, the equivalent transmission heat loss term $Q_{tr,eq}$ can be developed as:

$$Q_{tr,eq} = \sum_{*,o} Q_{tr,eq,*,o} + \sum_{*,w} Q_{tr,eq,*,w} \tag{15a}$$

$$= \sum_{*,o} U_o A_{*,o}(T_i - T^{*,o}_{a,eq}) + \sum_{*,w} U_w A_{*,w}(T_i - T^{*,w}_{a,eq}) \tag{15b}$$

$$= \sum_{*,o} U_o A_{*,o}(\Delta T - \frac{\alpha_{sw,o,*}}{h_{ce}+h_{re}} q_{sw,*} + c_{lw,*,o}) + \sum_{*,w} U_w A_{*,w}(\Delta T + c_{lw,o,*}) \tag{15c}$$

$$= \sum_{*,o} U_o A_{*,o}\Delta T + \sum_{*,w} U_w A_{*,w}\Delta T - \sum_{*,o} U_o A_{*,o} \frac{\alpha_{sw,o,*}}{h_{ce}+h_{re}} q_{sw,*} + \sum_{*,o} U_o A_{*,o} c_{lw,*,o} + \sum_{*,w} U_w A_{*,w} c_{lw,w,*} \tag{15d}$$

Two terms in Eq. 12 remain to be discussed: ventilation heat loss Q_v and the latent heat term Q_{latent}.

Aside from heat loss due to transmission through the building fabric, significant heat losses also occur due to *air infiltration and exfiltration.* Two driving forces cause natural airflow, G_a $[\frac{kg}{s}]$, through building envelopes: thermal stack or buoyancy effect, directly proportional to ΔT; and wind-induced pressure differences, with wind velocity w_v and wind direction w_d as driving forces. The associated heat loss $c_a G_a \Delta T$ $[W]$, with c_a the heat capacity of air $[\frac{J}{(kgK)}]$, is referred to here as total ventilation heat loss. $c_a G_a$ $[\frac{W}{K}]$ then represents a *ventilation heat loss coefficient.*

Latent heat demand Q_{latent} arises due to *hygroscopic loading and unloading of building parts.* Examples of this include uptake and evaporation of driving rain by façade cladding and drying out of encapsulated building moisture. The latter often proves to be important for newly built buildings. By neglecting the former, Q_{latent} can be written as $h_w G_{vP}$, where h_w is the latent heat of evaporation of water $[\frac{J}{(kgK)}]$ and G_{vP} the dry-out rate $[\frac{kg}{s}]$. Often, G_{vP} is assumed constant over the testing period. Hence, in the remainder of this paper, $h_w G_{vP}$ will be denoted as a constant: c_{vP} $[W/K]$.

Until this point, $Q_{tr,eq}$ has been considered an instantaneous heat loss between temperature nodes at either side of the different fabric components. It is, however, generally known that capacitive building fabric parts introduce an important *phase shift* between the heating power necessary to sustain a constant, elevated temperature inside and the dynamic weather conditions outside. This essentially means that $Q_h(t)$ will depend not only on $\Delta T(t)$ and $q_{sw,*}(t)$ at current time step t, but also, and perhaps more importantly, on their evolution some time before. To approximate this thermal lag effect, the supplied energy at time t $Q_h(t)$ can be correlated with a weighted average of ΔT at current time step t and previous time step $t-1$: $\Delta T_{avg} = a_1 \Delta T(t) + a_2 \Delta T(t-1)$, with $a_1 + a_2 = 1$. A similar reasoning and corresponding strategy can be adopted with regards to solar radiation: $q_{sw,*,avg} = b_1 q_{sw,*}(t) + b_2 q_{sw,*}(t-1)$. Taking taking into account solar radiation from the previous day, $q_{sw,*}(t-1)$, as a constituent part of the heat input has the important advantage that *solar gains stored in the building fabric layers are effectively accounted for.*
These weighted averages, however, are not suited to describe physical phenomena associated with a very fast response, including transmission heat loss through low-capacitive transparant fabric parts and ventilation heat loss.
Aside from that, most of the fabric components can be expected to introduce thermal lags in the same order of magnitude, e.g. half a day. Only the floor on ground might exhibit very different behaviour: this component can introduce thermal lags up to several weeks, due to the large soil mass underneath the building possibly being excited along with it. Moreover, the ground has a slowly varying temperature, depending on ground material, boundary conditions and possibly ground water flows. Both factors serve to explain that ground floor heat losses are likely to be stable and constant throughout most measurement campaigns, especially when the floor is insulated. In the specific case of a basement or crawl space underneath the ground floor, the ground floor can be considered similar to other parts of the fabric. In any case, heat loss is not uniformly distributed over the ground floor surface, especially in case of perimeter insulation. This, however, holds for most components.

Based on these considerations, the heat balance in Eq. 12 can be rewritten; with heat gain and heat loss terms organised on left and right hand side, resp.:

$$Q_h + \sum_{*,w} A_{sw,*,w} q_{sw,*,avg} + \sum_{*,o} U_o A_{*,o} \frac{\alpha_{sw,*,o}}{h_{ce}+h_{re}} q_{sw,*,avg} = \sum_{*,o} U_o A_{*,o} \Delta T_{avg} + \sum_{*,w} U_w A_{*,w} \Delta T + \sum_{*,o} U_o A_{*,o} c_{lw,*,o} + \sum_{*,w} U_w A_{*,w} c_{lw,*,w} + c_a G_a \Delta T + c_{vP} + c \tag{16}$$

As discussed, thermal lag effects are not considered to affect low-capacitive transmission heat loss through windows (denoted w), nor ventilation heat loss. Hence, these terms are accompanied by ΔT, rather than ΔT_{avg}, in Eq. 16.

Eq. 16 assumes the building thermal parameters of interest to be constant. Hence, the dependence of the fabric thermal characteristics on temperature and moisture content, $\lambda = f(T, w)$, and the dependence of the surface heat transfer coefficients on ΔT, wind speed and direction are not taken into account. Moreover, we also left possible variations of absorption $\alpha_{sw,j,*}$ and emissivity $c_{lw,j,*}$ factors and moisture dry-out rate G_{vP} out of the equation.

5. Estimating parameters using linear regression analysis

The main aim of the co-heating test is to distill stationary thermal performance characteristics of the investigated dwelling, by *fitting a simple stationary heat balance model to aggregated performance data*. The latter is generally done using linear regression techniques. The advantage over plain averaging is that possible outliers can be taken into account in a more sensible way. In any case, the assumptions made during the analysis need to be considered carefully. Practical and statistical issues make Equation 16 challenging to solve. The aggregated co-heating measurement data only allows for a stationary model of limited complexity to be identified. In short, matters need to be greatly simplified. Throughout this section, several simplifications are made to Eq. 16, to finally come to the basic equation that forms the basis of the co-heating test analysis.

5.1. Applied simplications

First, linear regression analysis only allows to uncover as many parameters as there are independent variables, for instance ΔT, sufficiently significant in explaining the dependent variable, in this case Q_h. Hence, factors relating to a certain driving force, e.g. $q_{sw,*,avg}$ in Eq. 16 need to be grouped. Rewriting yields:

$$Q_h + \sum_* A_{sw,*} q_{sw,*,avg} = U_o A_o \Delta T_{avg} + U_w A_w \Delta T + c_a G_a \Delta T + c \tag{17}$$

where factors $A_{sw,*}$ now incorporate eventual indirect solar gains through opaque fabric parts.

Secondly, considering measurement data averaged over a larger time span, e.g. 1 day, the different solar radiation projections naturally exhibit a strong mutual correlation. For instance, on a *sunny* day we will, *on average*, measure a *high* global solar irradiance, regardless of how our pyranometer is oriented. Hence, $q_{sw,*}$, corresponding to different orientations $*$, are linear dependent vectors and factors $A_{sw,*}$ in Eq. 17 cannot be estimated separately. The stationary heat balance equation is simplified by removing the summation $\sum_*$:

$$Q_h + A_{sw,*} q_{sw,*,avg} = U_o A_o \Delta T_{avg} + U_w A_w \Delta T + c_a G_a \Delta T + c \tag{18}$$

At this point, however unfortunate, $A_{sw,*}$ has lost most of its physical relevance and is very dependent on the solar radiation projection $q_{sw,*}$ that is selected as sole independent variable informing heat input due to solar radiation. It can be understood as *a crudely lumped gA-value* of the glazed surface, with g the g-value associated with the glass panes and A its total surface. The term *lumped* needs to be interpreted as incorporating: multiple glass characteristics and angles of incidence, where multiple angles of incidence can easily occur simultaneously due to multiple window orientations; variations in irradiated surface over the day; influence of shading by surrounding environment, by building geometry and due to dirt at the surface. We consider the term *solar aperture coefficient* a suitable term to describe $A_{sw,*}$, grasping all of the above.

A third challenge is posed by the thermal lag induced by the building fabric. ΔT and ΔT_{avg}, and also $q_{sw,*}$ and $q_{sw,*,avg}$, can be expected to be strongly autocorrelated, leaving it impossible to distinguish both when applying linear regression on averaged data. As such, further simplification of Eq. 18, yields:

$$\begin{aligned} Q_h + A_{sw,*} q_{sw,*} &= U_o A_o \Delta T + U_w A_w \Delta T \\ &\quad + c_a G_a \Delta T + c &\text{(19a)} \\ &= \sum UA \Delta T + c_a G_a \Delta T + c &\text{(19b)} \\ &= HLC \Delta T + c &\text{(19c)} \end{aligned}$$

where $\sum UA$ is the overall transmission heat loss coefficient $[W/K]$, HLC the overall heat loss coefficient $[W/K]$.

In other words, $U_o A_o$, $U_w A_w$ and $c_a G_a$, or $\sum UA$ and $c_a G_a$, are difficult to estimate separately. Instead, they are grouped into an overall Heat Loss Coefficient (HLC). As such, this coefficient groups both transmission heat loss and ventilation heat loss, and assumes both are governed by ΔT. Knowledge of $c_a G_a$ allows to decouple them. From Eq. 19a, however, we conclude that U_o and U_w cannot be decoupled, even if in-situ measurements of window surfaces are available. Hence, such measurements should not be considered as part of the co-heating test. For reasons of clarity and to establish a clear link with co-heating test literature (Section 2), ΔT and $q_{sw,*}$ are considered as independent variables in the remainder of this paper. This does not mean, however, that the thermal lag should be discarded: most often, considering ΔT_{avg} and $q_{sw,*,avg}$ instead of ΔT and $q_{sw,*}$ as independent variables results in a more accurate assessment of HLC, despite data points being lost in lagging time series.

Lastly, the influence of long-wave radiative heat exchange with the sky, described by terms $\sum_{*,o} U_o A_{*,o} c_{lw,*,o}$ and $\sum_{*,w} U_w A_{*,w} c_{lw,*,w}$, and the latent heat loss attributable to drying out of building moisture c_{vP} was grouped into one constant heat loss term c from the very beginning of this section (Eq. 17). In some cases, this term will also comprise the constant heat flow through a heavy-weight ground floor, directly on soil and insulated. Often, c is rather small and better regression results might be obtained by setting it to zero.

By this time, the link with the simplified heat balances discussed in the brief history section has become apparent.

5.2. Linear regression analysis

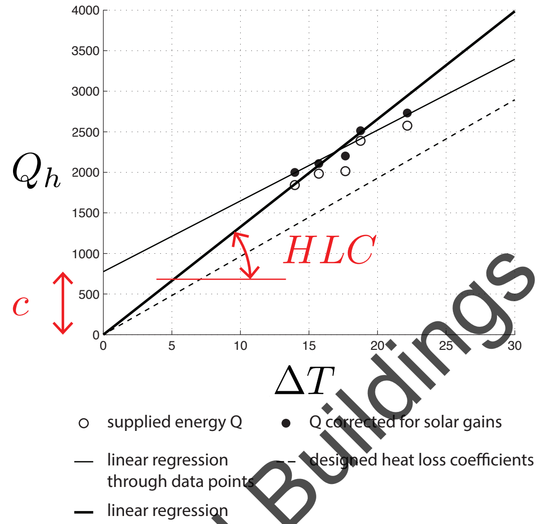
Assuming the heat balance in Equation 19c to hold, the parameters of interest, marked red in Eq. 20, are generally determined by applying simple or multiple linear regression techniques on co-heating measurement data:

$$Q_h = HLC\Delta T - A_{sw,*}q_{sw,*} + c \tag{20}$$

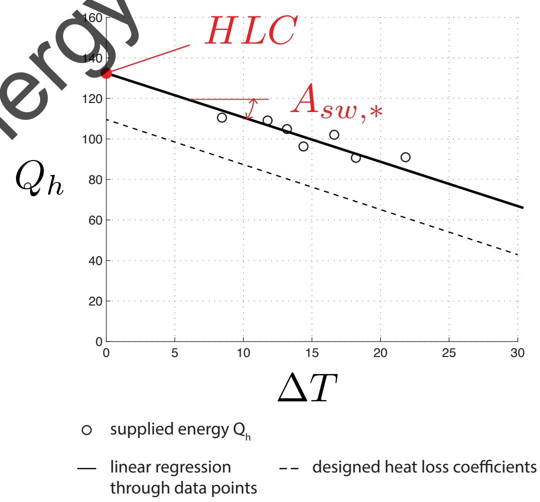
Essentially, three options can be discerned here. First, the energy supplied to the interior under the form of electrical energy can, e.g. on a daily averaged basis, be corrected for solar gains and plotted as a function of ΔT. This correction implies that an assumption is made for the solar aperture parameter $A_{sw,*}$, or that the solar gains $A_{sw,*}q_{sw,*}$ are neglected altogether, by assuming $A_{sw,*} = 0$. As illustrated in Fig. 6(a), *the slope of the regression line* resulting from a simple linear regression on this corrected measurement data set yields an indication of the overall HLC (Bell et al. (2010)).
An alternative method considers $q_{sw,*}$ as an *additional independent variable* aside from ΔT, explaining the variability of Q_h. Multiple linear regression techniques then allow to determine both HLC and $A_{sw,*}$ in Eq. 20 (Lowe et al. (2007), Everett et al. (1985)).
A third method is based on *dividing all terms in Eq. 20 by* ΔT. As such, an equation is obtained on which a simple linear regression can be performed, assuming $\frac{Q_h}{\Delta T}$ as dependent variable and $\frac{q_{sw,*}}{\Delta T}$ as independent or explanatory variable:

$$\frac{Q_h}{\Delta T} = HLC - A_{sw,*}\frac{q_{sw,*}}{\Delta T} \tag{21}$$

As illustrated in Figure 6(b), an estimate of HLC is then given by the intercept. $A_{sw,*}$ represents the downward slope. Hence, this option allows to read both characteristics from a two-dimensional graph. The applied mathematical transformation implicitly forces the above described multiple linear regression through zero: $c = 0$. In both of the earlier discussed options, a non-zero intercept is possible due to discrepancies between the measurement data and the assumed stationary model to which it is fitted.



(a) Simple linear regression



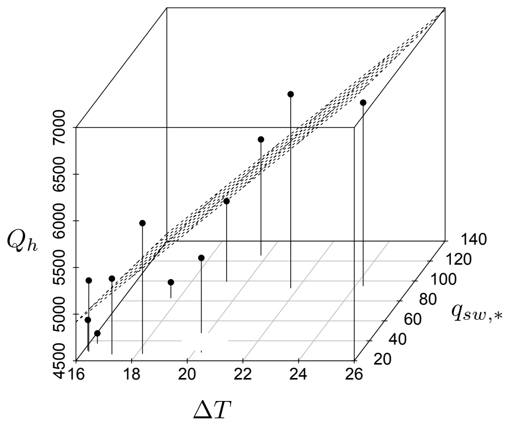
(b) Simple linear regression transformed equation

Figure 6: Estimation of HLC and $A_{sw,*}$ by applying simple linear regression. The curved arrows indicate the *slope of the regression line.*

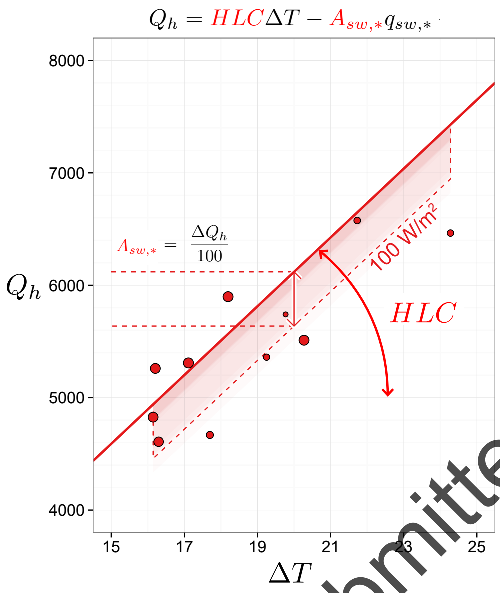
5.3. One graph to rule them all

Regardless of its visualisation advantage, the single linear regression based on the mathematical transformation presented in Eq. 21 needs to be applied with caution: it can be shown that it is unstable when ΔT hovers around 0, causing $\frac{q_{sw,*}}{\Delta T}$ and $\frac{Q_h}{\Delta T}$ to take on extreme values (towards $+-\infty$). Therefore, we advise to apply multiple linear regression.

Multiple linear regression is not regularly adopted in literature, mainly because it does not allow for a very intuitive visualisation, as illustrated in Figure 7(a). However, by considering both ΔT and $q_{sw,*}$ as independent variables and projecting the fitted regression surface to the $(Q_h, \Delta T)$ surface, a two-dimensional representation lies within reach.
Figure 7(b) illustrates this: the red thick upward sloped line represents the intersection of the regression surface with the $(Q_h, \Delta T)$ surface, where $q_{sw,*} = 0$. From this line, a layered flag is hanging downwards, showing contour lines corresponding to the discrete, averaged $q_{sw,*}$ observed during the experiment period. Additionally, the width of the flag illustrates the spread of aggregated ΔT.



(a)



(b)

Figure 7: Three-dimensional (a) and alternative two-dimensional (b) representation of multiple linear regression analysis of co-heating measurement data.

Also here the HLC is determined as the slope of the regression line. Additionally, by drawing a vertical line connecting one contour line with another, the solar aperture coefficient $A_{sw,*}$ can be determined as a fraction of the traversed Q_h and $q_{sw,*}$ (Eq. 23a). As depicted in Figure 7(b) and described by Eq. 22, the contour lines are parallel translations of the regression surface intercept. We propose to complement them with one more, corresponding to an aggregated value for $q_{sw,*}$ of $100\frac{W}{m^2}$. As such, $A_{sw,*}$ can be deduced from Eq. 23b.

$$Q_{h,i} = HLC\Delta T + (A_{sw,*}q_{sw,*,i} + c) \tag{22}$$

$$A_{sw,*} = \frac{\Delta Q_h}{\Delta q_{sw,*}} \tag{23a}$$

$$A_{sw,*} = \frac{\Delta Q_h}{100} \tag{23b}$$

Evidently, the same graph can be used to visualise single linear regression, for instance in case $q_{sw,*}$ proves not to be significant. As such, it effectively visualises whether single or multiple linear regression is applied. More generally, it facilitates comparison between different co-heating test results, regardless of regression models that were assumed.

6. Conclusions

We started this paper with a review: the co-heating test has been around for more than three decades, serving many purposes. More recently, it has primarily been used to assess stationary fabric performance characteristics of dwellings. As such, it consists of a quasi-stationary homogeneous heating experiment performed on an unoccupied dwelling, stretching over an extended period of time. The building performance parameters of interest, under the form of the overall heat loss coefficient (HLC) and the global solar aperture coefficient ($A_{sw,*}$), are then determined by applying linear regression analysis, assuming a simplified heat balance and aggregated performance data.

We uncovered the physical phenomena that are lumped into the simplified heat balance. We defined an equivalent transmission heat loss to include influence of short-wave and long-wave radiative heat exchange at the building fabric surface. By correlating the heating power Q_h with the independent driving forces ΔT and $q_{sw,*}$ averaged over the current and previous days, we take into account thermal lags induced by the building fabric.

Using aggregated performance data comes with statistical constraints. Linear regression only allows to identify as many parameters as there are independent variables after this pre-processing. As such, we naturally evolved back to the well-known simplified heat balance. Transmission heat loss through transparant and opaque fabric parts are grouped together with ventilation heat loss in the HLC. We showed that the *global solar aperture coefficient* has lost much of its physical relevance. It is, however, important to quantify this coefficient in those cases where solar radiation is significant during the experiment. We could also conclude that an in-situ survey of window and opaque surface areas does not hold the promise of a better building performance assessment, nor does it allow to decouple transmission heat loss through transparant and opaque fabric parts. We strongly advise not to *calculate* $A_{sw,*}$ on the basis of geometric and physical assumptions, as the phenomena involved are complex and inextricably lumped into this coefficient. The according assumptions generally made in literature are very difficult to justify. The influence of long-wave radiative heat exchange at the fabric surface, latent heat loss and possibly ground floor heat loss are grouped into a constant heat loss term c. Often, more reliable assessment results are obtained when c is neglected altogether.

A transformed regression model, dividing all terms of the simplified heat balance by ΔT, allows to determine both HLC and $A_{sw,*}$ on the basis of measurement data, whilst still allowing for a two-dimensional representation. However, in cases where ΔT approaches 0, the assessment results can be heavily disturbed. Therefore, we propose multiple linear regression as an alternative. Also here, two building performance coefficients are determined, but it is much more stable in cases of low ΔT. To depict co-heating test results, we suggest an outline plot of the actual three-dimensional regression plane. Not only does this allow for an intuitive way to deduct HLC and A_{sw} visually, it also allows to compare co-heating test results from different test cases, under different weather conditions and assuming different regression models as a basis for analysis.

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ANNEX 58 SEMINAR – REAL BUILDING ENERGY PERFORMANCE ASSESSMENT

Experiences with in situ measurements

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ABSTRACT

As reducing energy from the built environment becomes a priority and governing bodies enact regulations and programmes to make this happen, it has become critical to ensure that the measures undertaken to make buildings more energy efficient lead to real energy and carbon savings. Unfortunately, recent studies indicate that large gaps exist between the theoretical and actual thermal performance of buildings.

To fill this gap, leaders from all sectors of the building industry must work together with regulators and academia to understand why buildings are not always performing as well as expected. This requires the development of robust standardized and shared and neutral in-situ test methods to build knowledge within the sector of real performance and drive improvements in the design and assembly of building components as well as complete buildings. Having these tools and data will enable building product and system manufacturers to deliver solutions and provide installation guidance to support the building chain with their responsibility to deliver buildings that deliver real performance.

For the past 3 years Knauf Insulation has been working with leading building scientists, architects and policy makers to work with on the development of a new and effective knowledge base for real-world building energy performance. The programme aims to understand how to ensure that the thermal envelope of buildings performs as designed, to develop systems and solutions that can support the building chain to deliver buildings that perform for real and to define the regulatory tools needed to deliver such solutions in practice. As part of this work we have been working on a number of co-heating tests (whole-house heat loss test) as we believe that they provide a robust basis for measuring and comparing the real thermal performance of the fabric of a building. The presentation will present some of these tests.

KEYWORDS

Real performance. Co-heating tests. In-situ test methods. Building envelope.

One of the greatest obstacles to delivering a low-energy and sustainable built environment is ensuring that buildings perform as expected in reality and not simply in design. Current regulations and standards that govern thermal performance in buildings are mostly based on models of how buildings perform and laboratory testing of products. Taken together, this means that sometimes the real thermal performance of a building can be significantly worse than expected. There is a performance gap to close.

Unfortunately, due to a lack of coordinated research to-date, a “knowledge gap” also exists that is making this worse. The limited studies that do exist paint a worrying picture: not only do some buildings perform significantly worse than expected, but the variation in performance is also significant.

To fill this gap, leaders from all sectors of the building industry must work together to understand why buildings are not always performing as well as expected and take up the challenge of developing systems and solutions that can support the building chain with their responsibility to deliver buildings that deliver real performance.

Knauf Insulation understands the magnitude of this challenge and is preparing for it. We have been working closely with leading building scientists from KU Leuven and Leeds Metropolitan, architects and policy makers to build an effective knowledge base for real-world building energy performance.

The programme aims to:

- understand what is causing the differences between intended and actual design and look at what can be done to both reduce the gap in real performance as well as the variability of performance,
- develop new insulation solutions that can support the building chain to deliver buildings that perform for real and to define the regulatory tools needed to deliver such solutions in practice,
- define the regulatory tools needed to deliver these solutions in practice, both in existing schemes (such as the UK Green Deal) and in future schemes and programmes.

The development of an effective knowledge base for real-world building energy performance requires more than just data generation. It also requires testing and measurement protocols and standards that can be applied consistently across the industry regardless of building geography or environment. Only by developing repeatable and sensible protocols for gathering and analysing data can the industry hope to use the data to its fullest effect and to create models that can generate accurate and reasonable expectations of real-world performance for insulation products. One test that may serve as model for the development of robust protocols is the “co-heating” test, in which the dwelling to be tested is homogeneously heated to an elevated interior temperature.

As with current standards that provide a robust basis for comparing the thermal performance of insulation products, it’s important to develop agreed and common standards for measuring the real thermal performance of the fabric of a building. The co-heating test could be the basis for such a standard, as such Knauf Insulation has been working on a number of co-heating tests as we believe that they provide a robust basis for measuring and comparing the real thermal performance of the fabric of a building. Co-heating testing not only provides a consistent and repeatable means to test the real-world effects of a given type of insulating product, it also helps us identify and understand the discrepancy between real and expected performance. Our most recent test using our Supafil blown insulation has shown that insulating cavity walls, party-wall cavities (partition between two adjoining buildings), and the roof slab with Supafil insulation reduced heat loss through the building envelope by 50%.

RELIABILITY OF CHARACTERIZATION MODELS AND METHODS: A ROUND ROBIN EXPERIMENT ON A TEST BOX

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ABSTRACT

IEA EBC Annex 58-project 'Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements' tries to develop the necessary knowledge, tools and networks to achieve reliable in-situ dynamic testing and data analysis methods that can be used to characterise the actual thermal performance and energy efficiency of building components and whole buildings. The research within this project is driven by case studies. As a first simple case, an experiment on testing and data analysis is performed on a round robin test box. This test box can be seen as a scale model of a building, built by one of the participants, with fabric properties unknown to all other participants. Full scale measurements have been performed on the test box in different countries under real climatic conditions. The obtained dynamic data are distributed to all participants who tried to characterise the thermal performance of the test box's fabric based on the provided data. It is shown how different techniques can be used to characterise the thermal performance of the test box, ranging from a simple stationary analysis to advanced dynamic data analysis methods.

KEYWORDS

Building energy performance, performance assessment, in situ characterisation, dynamic data analysis, system identification.

1 INTRODUCTION

To determine the state of the art on full scale measurements and dynamic data analysis a round robin experiment has been set up in the framework of Subtask 3 of Annex 58. The global objective of the round robin experiment is to perform a well-controlled comparative experiment on testing and data analysis. To this extent, a test box (a scale model of a simplified building) has been built by KU Leuven. KU Leuven is the only partner within the Annex 58-project aware of the exact composition of the test box. After construction the box has been shipped to different partners (different climatic conditions and different acquisition equipment) with the aim to perform a full scale measurement of the test box under real climatic conditions. The obtained dynamic data is distributed to different institutes who have to try to characterize the test box based on the provided experimental data.

2 DESCRIPTION OF THE EXPERIMENT

The investigated test box has a cubic form, with exterior dimensions of 120x120x120 cm³. Figure 1 gives an overall schematic view of the round robin test box. The floor, roof and wall components of the box are all identical and have a thickness of 12cm, resulting in an inner volume of 96x96x96cm³. One wall contains an operable wooden window with overall dimensions of 71x71 cm² and a glazed part of 52x52 cm². A structure is provided around the box, so that the box remains free from the thermal influence of the ground. Hence, the box can be considered as floating in free air.

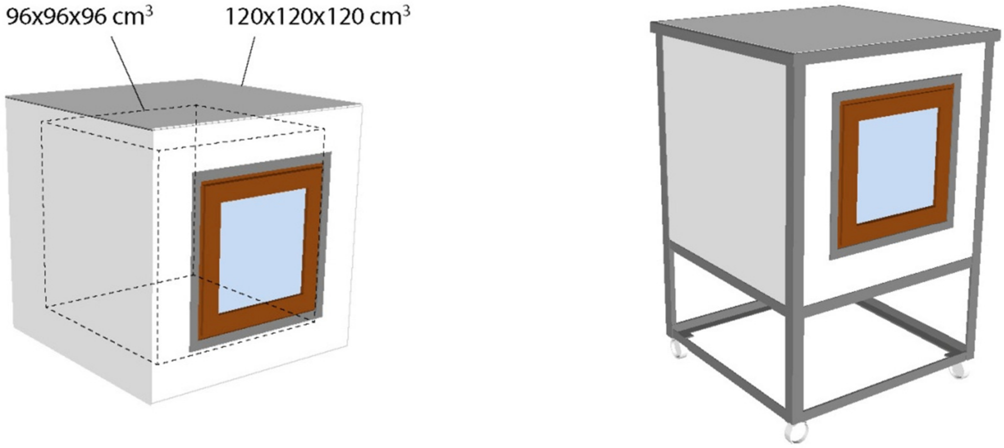

Figure 1: Overall schematic view of the round robin test box

Winter 2012-2013 the test box has been tested at the premises of the Belgian Building Research Institute in Limelette, Belgium (50°41' N, 4°31' E). Afterwards the box has been shipped to Spain, where it was measured under summer conditions in Almeria (37.1° N, 2.4° W). In general, the weather conditions in Belgium are temperate, with a mild, but rainy, humid and cloudy winter. The weather at Almeria on the other hand is dry and extremely hot in summer, with large temperature amplitudes between day and night. During day time, solar radiation is very high on horizontal surfaces and the sky is usually very clear. Figure 2 shows the test box at both sites.

Figure 2: Test box during winter at the measuring site at BBRI. Belgium (left) and during summer at the Plataforma Solar de Almeria, Spain (right).

At both sites, different experiments have been performed, ranging from co-heating tests with constant indoor temperature, over free floating temperature runs, to imposed dynamic heating sequences (ROLBS-signals). During the experiments, heat fluxes on all internal surfaces, together with internal and external surface temperatures, indoor temperature and delivered heating energy within the box have been measured. In addition, both test sites are equipped with an outdoor weather station, measuring all relevant boundary conditions (temperature, relative humidity, wind direction and speed, diffuse and direct solar radiation, long wave radiation,…). Figures 3 and 4 show the measurement devices in the experiment set up in Almería. The measured data has been provided to all participants in the Annex 58-project. They are requested to characterise the thermal performance of the round robin test box as good as possible based on the provided dynamic data. Both stationary properties, e.g. the overall heat loss coefficient, and dynamic properties of the test box are aimed for. For more detail about each of these experiments and exercises the reader is referred to Jiménez et al. 2013a and Jiménez et al. 2013b.

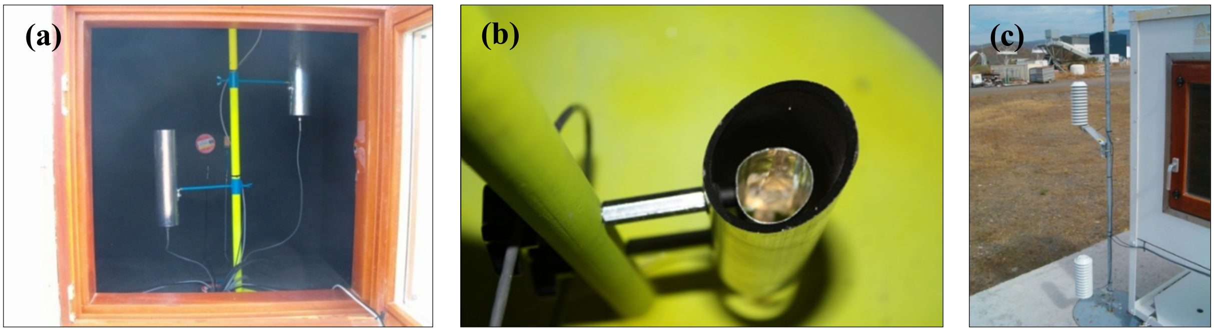

Figure 3: Test set up in Almería. Temperature measurement devices: (a) Indoor air temperature, (b) detail of indoors shielding devices, (c) outdoor air temperature.

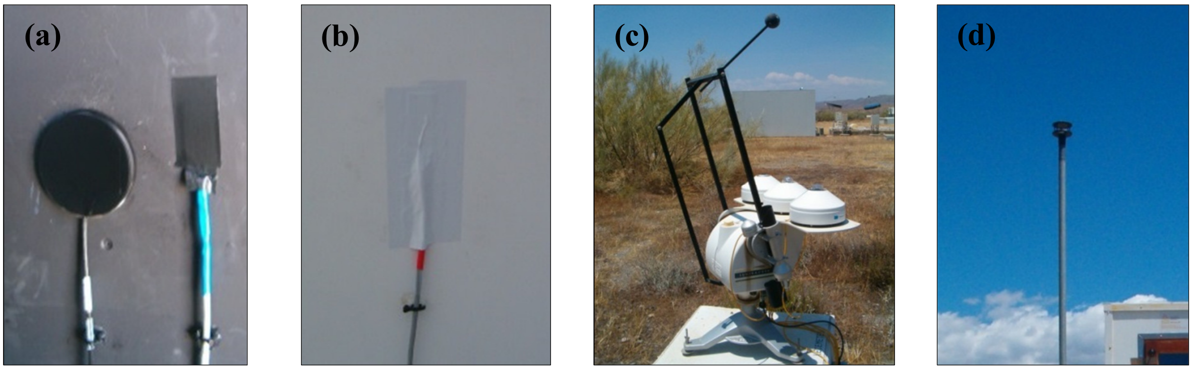

Figure 4: Test set up in Almería. Other measurement devices: (a) heat flux and internal surface temperature, (b) external surface temperature, (c) beam, diffuse and global solar radiation, (d) wind speed and direction.

3 DATA ANALYSIS METHODS

Based on the provided dynamic data, different analysis methods have been used by the participants of Annex 58 to characterise the thermal performance of the test box. The techniques vary from simple stationary methods to advanced dynamic data analysis methods. In the next paragraphs a short description of the most important characterisation methods is given together with their main possibilities and limitations.

3.1 Averaging method

Averaging methods are typically used in winter conditions to estimate the thermal resistance of building elements from in situ surface temperature and heat flux measurements (ISO 9869, 1994). The method assumes that the (average) heat flow rate and temperatures over a sufficient long period of time give a good estimate of the values in stationary conditions. By averaging the (dynamic) measured data the steady state values are calculated. This way, making use of the measured heat input and indoor/outdoor temperature difference, the overall (stationary) heat loss coefficient of the box can be determined. The method is only valid if the thermal properties and heat transfer coefficients can be treated constant over the test period and if the effect of heat storage is negligible. As a result, it is clear that the method can be of use for the parts of the data measured during winter conditions in Belgium (when also the indoor temperature is kept constant and solar gains are negligible), but that the method loses his applicability for the Almeria data. Furthermore, only the stationary thermal properties of the box can be determined.

3.2 Single and multiple linear regression

Apart from the averaging method, linear regression techniques are typically used to determine the stationary thermal properties. By fitting the linear correlation between the heat input and indoor/outdoor temperature difference, the overall heat loss coefficient can be determined. But where in the averaging method detailed (short interval data) can be used and the stationary values follow from the averaging technique, the linear regression typically makes use of daily averaged values, to cancel out short-term effects of thermal mass (Bauwens et al., 2012). Applying multiple linear regression, allows to determine not only the overall heat loss coefficient, but to gain also some information on the solar transmittance. Major drawback is again that only the stationary properties can be determined and no characterisation of the dynamic thermal behaviour of the box can be made.

3.3 ARX-models and ARMAX-models

Compared to the previous methods, ARX and ARMAX -models allow to include the dynamics of the system. In the abbreviation AR stands for AutoRegressive: the current output is related to the previous values of the output; MA (Moving Average) refers to the noise model used and X for the fact that eXternal inputs are used: the system relies not only on the current input value, but also on the history of the input. For identifying generic systems AR(MA)X-models are the standard methodology. The most used ARX model structure is the simple linear difference equation which relates the current output at time t to a finite number of past outputs and inputs.

ARX and ARMAX models have among others been applied by Jimenez and Heras (2005) and Jimenez et al. (2008b) for modelling the heat dynamics of buildings and building components. One of the main problems when applying AR(MA)X-models on the data of the round robin box is first of all the selection and validation of the model, but then also how to interpret the model to get information on the thermal characteristics of the test box. Steady-state physical parameters are usually obtained by comparing the steady-state energy balance equation of the considered system and the AR(MA)X model obtained, particularised to the case with all its input and output constants, that must be coincident. An important step in this process is to select inputs and outputs that make this comparison possible. Bacher and Delff (2013) show that by stepwise increasing the model order until most significant autocorrelation and crosscorrelation is removed, a reliable modelling of both stationary and dynamic properties of the box is feasible.

3.4 Stochastic state space or so-called grey box models

A final methodology to characterise the round robin box is making use of stochastic state space models. The distinctive characteristics of these models are to be stochastic and to be based on differential equations. Differential equations give high flexibility and wide possibilities to the analysis. The stochastic features help to achieve a good accuracy with relatively short test periods.

Some participants made use of simple state space models based on resistance/capacitance schemes to simulate the dynamic behaviour of the box. Mostly a forward selection approach is used. In this approach the analysis starts with fitting a very simple model, which is then stepwise extended until the loglikelihood no longer increases significantly compared to the previous model and the model validation shows that the residuals (the difference between the measured and predicted output) correspond to white noise. As both the initial model as well as all possible extensions are expected to represent a simplified version of the round robin test box, this requires some prior physical knowledge. Figure 5 shows as an example a two-state model for the round robin test box, taking into account heat input by heater and solar radiation, capacity of the interior and walls of the box and (conductive) heat flow through the walls of the box. To identify all relevant dynamic characteristics of the box, preferably a predetermined heating power signal (e.g. ROLBS- or PRBS-signal) is imposed to excite the box around its expected time constants, whilst remaining uncorrelated with outdoor weather conditions.

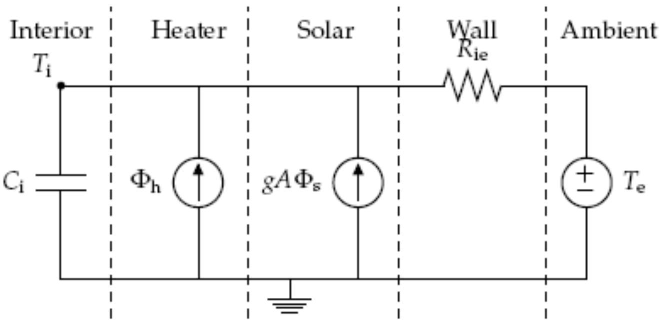

Figure 5: Example of a two-state grey box model applied by one of the participants (Bacher and Delff, 2013).

4 CHARACTERISATION OF THE TEST BOX – DISCUSSION OF THE RESULTS

Tables 1-2 and Figures 6-8, summarise the results received since July 2013 till April 2014. As some of the methods are only able to determine the stationary properties of the box, Table 1 compares the obtained overall heat loss coefficient as determined by different participants.

Considering the heat loss coefficient (Figures 6 and 7), some spread is observed in the results based on each data set. Note that some of the participants used different methods to determine the overall heat loss coefficient.

Comparing the results, it can be seen that most methods result in an overall heat loss coefficient around 4 W/K. Observing all reported results, the most deviating ones (assumed more inaccurate) are those given by models not considering dynamics, or just applying formulas which are far from accomplishing their hypotheses of validity.

Results following the average tendency, have been reported using different methods such as stochastic state space, ARX, ARMAX, linear regression models, and average methods. Differences are observed not only in the mathematical modelling approach but also in the physical assumptions used to build the models and concerning pre-processing issues. So, some of the differences can be attributed to the different level in analysis skills of participants.

Most participants that have analysed both cases, give slightly higher values of the heat loss coefficient for the data recorded in Spain (Figure 7). This increasing tendency can be qualitatively explained taking into account the different temperatures of the building fabric along both tests and the temperature dependency of its thermal conductivity. However, taking into account that the values obtained overlap if their uncertainty is taken into account, it is difficult to discern if these differences correspond to a typical experimental spread around the true value, or if it is following a systematic tendency.

Some participants have detected problems modelling the effect of solar radiation and have studied different models considering different assumptions and approximations aiming to improve models. Different physical and statistical approaches have been studied but no clear improvement has been demonstrated yet, although this is an interesting topic for consideration in further works.

Some participants using models apparently logical from a physical point of view present results which are far from the average tendency. This behaviour is for instance observed when participants are trying to identify purely deterministic models using short testing periods. The outcome change radically when stochastic models are considered, incorporating the possibility of modelling errors giving more accurate parameter estimates.

Although state space models have a very high potential to represent a wide variety of physical systems governed by more general differential equations, all reported grey box state space models are relatively simple. Most applied models are limited to the RC-type, but do produce acceptable results.

Table 1: Determined overall heat loss coefficient (W/K) of the round robin test box by different modelling teams and making use of different data analysis methods.

Team		Winter data Belgium	Summer data Spain
1	Averaging method	3.77-3.92	
	State space model (RC using LORD)	3.07-3.42	
2	Averaging method	2.86-4.15	
	Linear regression (5’-data)	2.84-4.11	
	Linear regression (daily averaged data)	3.68-4.12	4.32-4.48
	AR(MA)X-models	3.79-4.06	4.07-4.20
	State space models (RC using LORD)	3.93	4.23
3	Multiple linear regression (hourly data)	4.77-5.24	
	Multiple linear regression (daily data)	3.73-4.39	
4	State space models	4.27-4.56	
5	Linear regression (daily averaged data)	3.99-4.08	
	State space models (RC using CTSM-R)	3.99	
6	State space models (RC using Matlab)	3.97	4.1-4.46
7	ARX-models	3.95	4.05-4.10
	State space models (RC using CTSM-R)	3.84	3.96
8	Averaging method	3.72-3.99	
	Linear regression (5’-data)	2.98-3.94	
	AR(MA)X-models	4.01-4.08	
	State space models (RC using CTSM-R)	4.48	

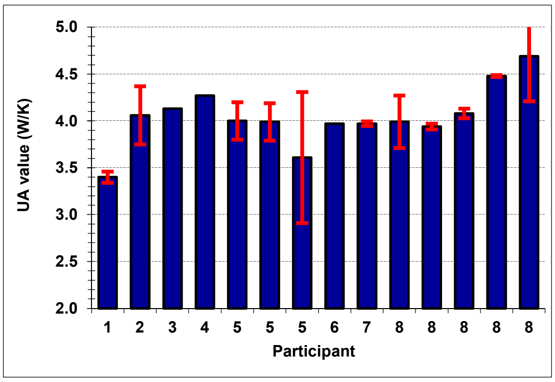

Figure 6: Summary of results from all participants using Winter Belgian data.

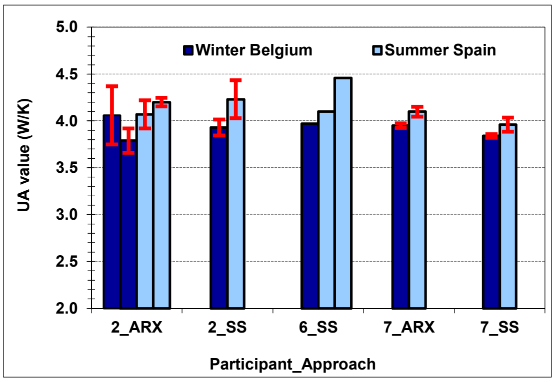

Figure 7: Results from participants that have applied dynamic models to winter and summer data.

Apart from the overall heat loss coefficient, also the indoor air temperature has been predicted. Models identified on the basis of data corresponding to different test periods in Belgium and Spain have been used. Indoor temperature are predicted for a test carried out in Spain in Summer, which is different from the one used for identification. Note, that the measured indoor air temperatures in the predicted period was not available for the participants. The agreement between measured and predicted values is presented in Figure 8.
Taking into account the tendencies shown in Figure 8 and the average and standard deviations of the differences between predicted and measured values summarised in Table 2, it can be concluded that models identified using summer data perform better for the current case. This is attributed to the improved time resolution and accuracy on the measurement of heating power in the data used to identify this model.

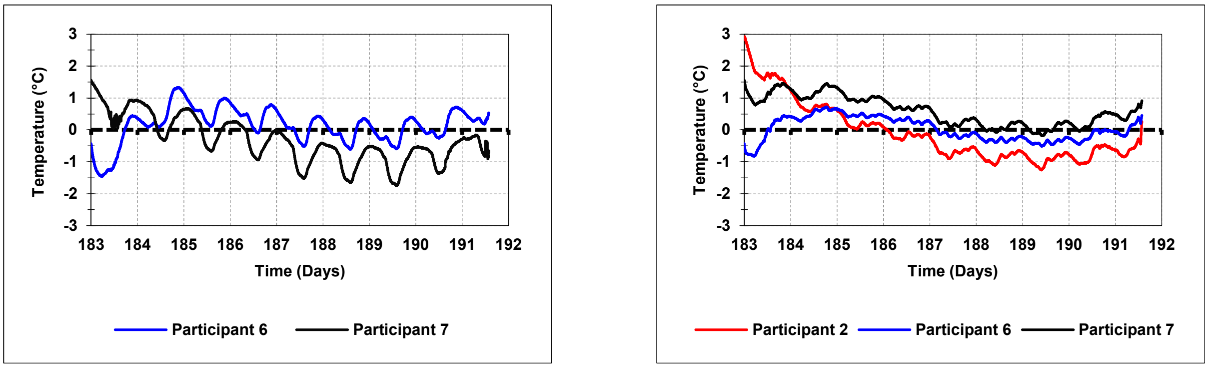

Figure 8: Difference between predicted and measured indoor air temperature, reported by participants. Left, using models based on Winter data. Right, using models based on Summer data. Predicted indoors temperature corresponds to a test carried out in Spain in Summer, which is different from the one used for identification.

Table 2: Summary of averages and standard deviations of the difference between measured and predicted indoor air temperature reported by participants, using models based on Belgian and Spanish data. Predicted indoors temperature corresponds to a test carried out in Spain in Summer.

	Model based on Summer Spanish data		Model based on Winter Belgian data	
Participant	Mean (°C)	Stdv (°C)	Mean (°C)	Stdv (°C)
2	-0.108	0.896		
2	-0.435	0.471		
6	0.025	0.372	0.149	0.549
7	0.590	0.458	-0317	0.712

5 CONCLUSIONS

A round robin test box experiment has been performed within the framework of Annex 58. The global objective of the round robin experiment was to perform a well-controlled comparative experiment on testing and data analysis. It is shown how different techniques can be applied to characterise the thermal performance of the test box ranging from (quasi)stationary techniques towards dynamic system identification. Where the first ones are only able to estimate the steady state properties of the box (e.g. overall heat loss coefficient), the latter can give additional information on the dynamic behaviour of the box and can be used to simulate the dynamic response of the box in a simplified way. In a next step the investigated methods will be applied to characterise real buildings.

6 ACKNOWLEDGEMENTS

The construction of the IEA EBC Annex 58 round robin test box was financially supported by Knauf Insulation. This as well as the input from the different Annex 58 members who participated in the common exercises is greatly acknowledged.

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Dynamic building envelopes; testing, analysis and simulation

Hans Bloem

INTRODUCTION

The EPBD (2010) mentions for the energy performance, assessment by measurement or calculation. A key item here is verification of the calculation rules, validation of the applied parameters and the CEN energy standards that are presently reviewed.

An important aspect becomes the assessment of real energy performance of buildings when it concerns renovation issues and the related financial investments. A proper evaluation of the energy performance of the building starts from on-site measurement and monitoring using intelligent metering environments. Key issue is to identify the part that is linked to the building fabric (climate and geo-position related), building systems (climate, energy mix and efficiency) and the usage of the building (energy consumed by appliances and gains from metabolism and appliances).
Apart from passive design for new buildings, renewable energy technologies for heating, cooling, domestic hot water, daylight for the design of nearly-zero energy buildings have to be incorporated

Energy performance assessment of buildings under realistic conditions can be categorized in two areas, each with characteristic features.

- Test buildings, erected for the purpose of studying detailed processes of energy flows, experimental work on innovative materials, products and components
- Real and existing buildings for living or working in which occupancy may influence the performance assessment.

Innovative materials and application in building components require improved assessment of the thermal processes in the building envelope. Often the specific features of the fore mentioned technologies are the result of construction as a pre-fabricated building element or on-site by installers. It is therefore to be considered in most cases as a unique system and quality is therefore an important issue. It should be noted also that the sum of product performances is not representing the energy performance of the overall building element and is often influenced by quality of workmanship, in particular when it concerns the creation of air gaps for air flow management.
Testing under real climatic conditions requires knowledge about the variability of certain processes the influence the energy performance of the building. A proper experimental set-up can optimize the analysis process and hence can contribute to improved simulation work.
Experimental work is required to give input to simulation work which might range from verifying calculation models used for predicting the energy consumption, up to validating specific parameters in the calculation rules.

The energy performance assessment of dynamic building envelope elements, have to be based on more complex performance values that may include dynamic relations and importantly be verified by in-situ measurements. In order to give reliable input for building designers, a common approach for testing, analysis and simulation of dynamic building envelopes is required.

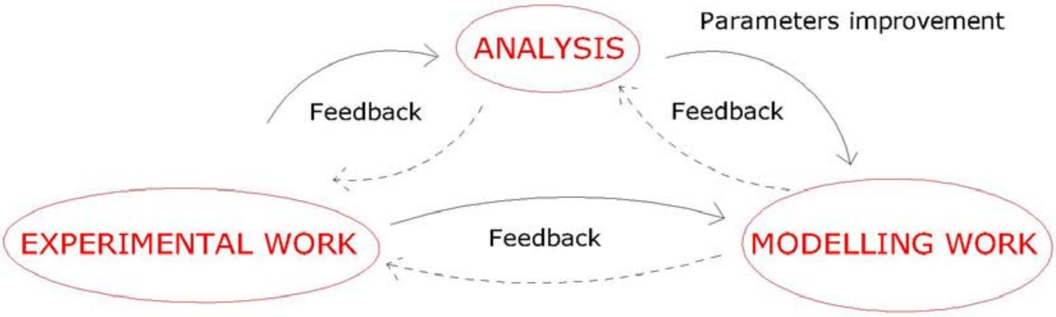

Figure 1. Schematic representation of the relation between testing, evaluation and simulation

Recent developments in industry show increased interest for new building products and elements that are more related to reducing energy consumption in the building sector. These expressions require a closer look, in particular in relation to definitions, common test and evaluation methodology as well as a calculation method for design purposes.
Some examples of known technologies (these are often non-linear due to air flow and variable by solar control system):

- Trombe wall, ventilated roof or wall, curtain wall
- Multi-functional wall
- Solar wall and solar chimney
- Building integrated PV roof and facade

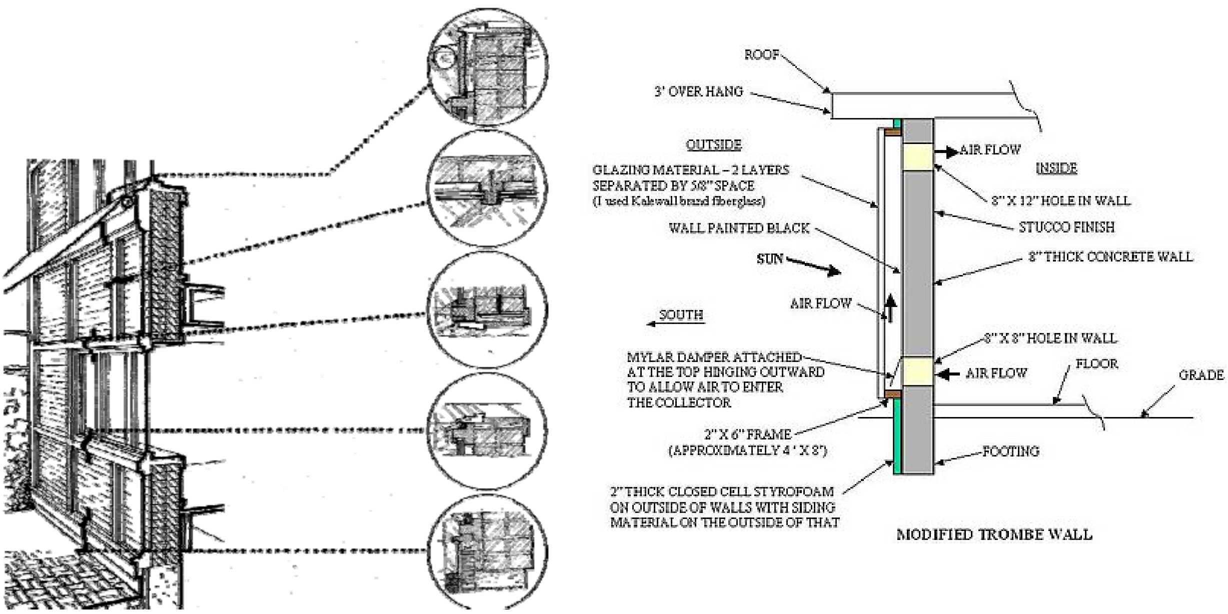

Figure 2. Trombe wall is used to describe a passive solar building technique

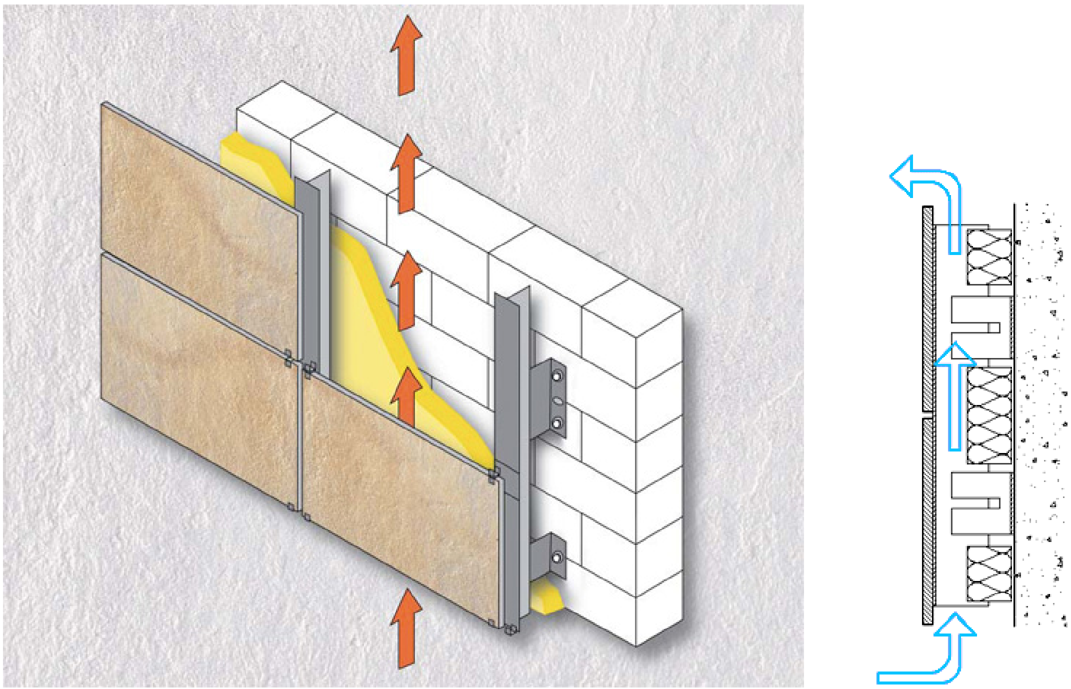

Figure 3. Curtain wall or ventilated wall may use natural or forced air flow

In situ tests are by definition unique and have to deal with dynamic boundary conditions (not necessarily steady-state). To be more precise; *in situ* measurements are made on-site which compasses experimental test facilities, specific test houses and well-controlled real buildings and hence are unique experiments for a given location and object. The object could be a whole building, a part of it (building unit) or a building element.

Often the specific features of the fore mentioned technologies are the result of construction as a pre-fabricated building element or on-site by installers. It is therefore to be considered in most cases as a unique system and quality is therefore an important issue. It should be noted also that the sum of product performances is not representing the energy performance of the overall building element and is often influenced by quality of workmanship, in particular when it concerns the creation of air gaps for air flow management.
Very useful would be that test facilities would carry out field testing of innovative building envelop components and elements for the production of tabulated performance values for specific boundary conditions, e.g. applications of construction products and/or building components. This would provide useful data for the assessment of the energy performance of buildings the verification of building design calculations

Therefore the energy performance assessment of Advanced Building Skin elements, have to be based on declared and designed performance values and importantly be verified by in-situ measurements.

For a common approach (at the level of standardisation) one has to consider:

- A common **Calculation Method** for design purposes
- A common and generalised **Test Method** for energy performance assessment
- A related **Evaluation Methodology** for assessment of characteristic parameters
- An in-situ **Verification Methodology**

Note that many research projects and papers are available but a lack of a common approach for testing, analysis and simulation of dynamic building envelopes is notified.

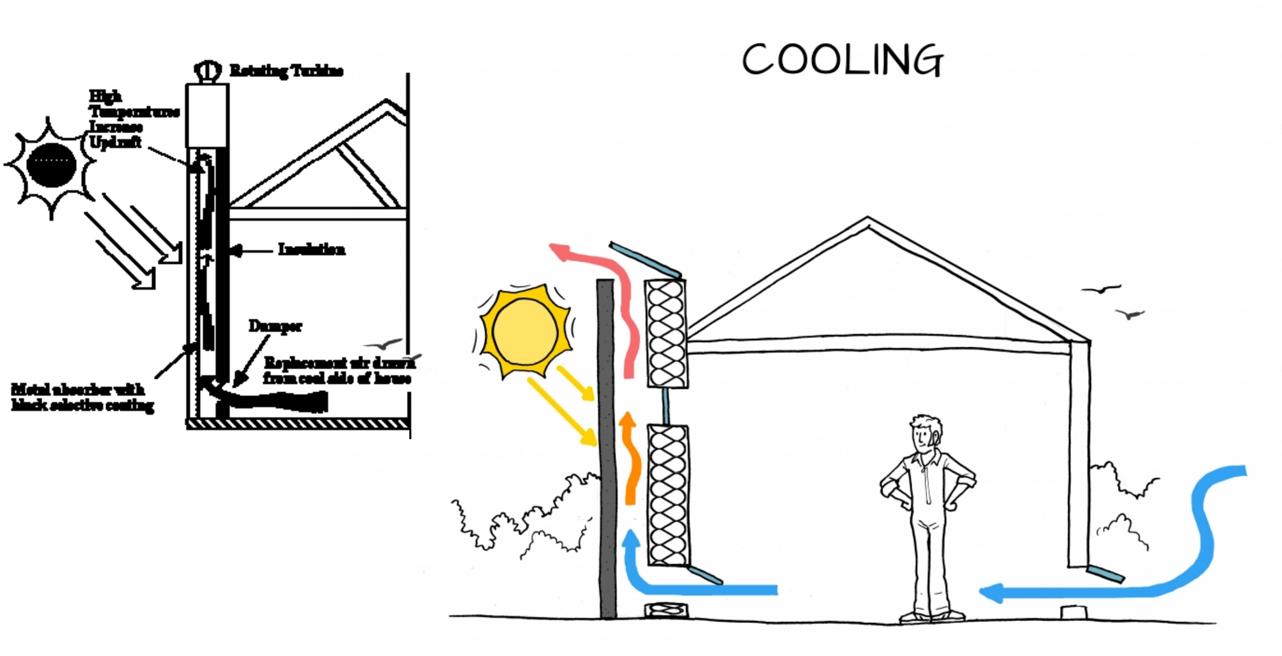

Figure 4. Bernoulli and stack effect ventilation

Some of the important characteristics are:

- Dynamic and able to deal with variable climatic conditions (in particular solar and wind)
- Intended for optimisation of the overall building performance (balance of demand, supply and storage)
- Dealing at energy balance level with all physical processes of energy transfer (thermal and electrical!)
- Heat transfer is NOT to be considered as one-directional (traditional insulation technology is considered as one-directional)
- Beside conductive, also convective and irradiative transfer has to be taken into account
- Energy balance approach for performance characterisation

Keywords are:

- Dynamic assessment, eg. the inclusion of the aspect of time in different time frames (τ_1 …. $\tau_{4;}$ hourly, daily, monthly and yearly)
- Energy Balance: the balance between energy demand, supply and storage
- Thermal mass: a passive technology regaining interest from building designers
- Control technology for optimisation of energy usage.

Physics	Mathematics
Physical Object, Processes, Parameters	
Feedback	General mathematical description of methodology for object, processes, etc.
Experimental set-up Data information required Data collection	
Data pre-processing	Mathematical method, model and parameters analysis techniques
Parameter conversion	Parameter identification and Mathematical assessment
Physical parameters and performance expression	
	Reporting of performance value and estimated uncertainty

Figure 5. Overview of process steps in testing and evaluation.

Applying system identification techniques on physical systems requires at all stages knowledge of the physical system. For buildings it is important to know what the impact is of cold-bridges, corner effects, etc. The researchers goal is to estimate physical parameters by using mathematical models.

To identify physical parameters of a system the following procedure is applied:

1. An experiment is performed by exciting the system and regular observing its input and output signals over a specific time interval.
2. These signals are recorded for subsequent "information processing".
3. A parametric model is developed to process the recorded input and output sequences. Several models can be applied.
4. An appropriate form of the model is determined (typically a linear differential equation of a certain order).
5. A statistically based method is used to estimate the unknown parameters of the model.

In most cases the calculation from mathematical parameters, which are derived from the chosen model, to physical parameters, in this case the heat resistance and solar aperture, introduces another point for discussion between physicists and mathematicians. Physicists like to compare the obtained values of the estimates from different methods, however they do not always realise that the way they are obtained from mathematic procedures might be different.

The particular case of BIPV

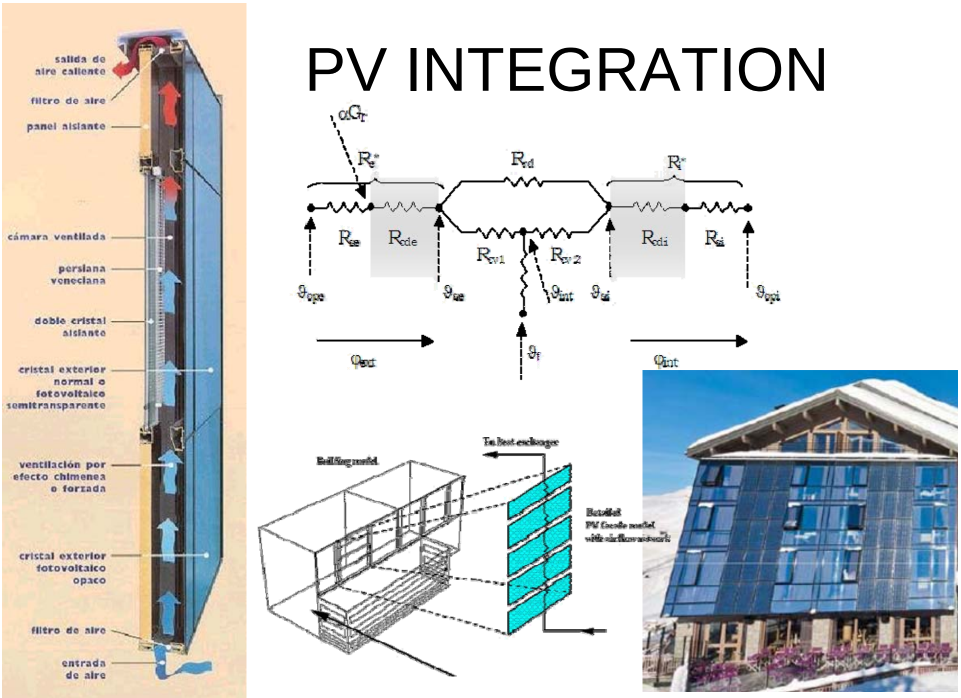

Figure 6. Energy producing technologies in the building envelope.

Building integrated applications are critical area for standards, in view of the requirements of the EPD Directive. However the various stakeholders (constructors, installers, PV industry and building designers) have different perspectives and priorities. Similarly the existing standards address different requirements:

- CENELEC/IEC standards for electrical performance and safety
- CEN/ISO on building energy performance and energy related standards(as required under the Energy Performance of Buildings Directive)
- EuroCodes for the mechanical/construction part (as required under the Construction Products Directive and Regulation)

Currently most BIPV manufacturers deliver products with mechanical and electrical specifications, which are for almost all cases well defined. It would also be desirable for the development of the market that thermal performance characteristics as well as well as optical data such as transmittance and reflectance be included.

The situation is further complicated by the need to assess how electrical and thermal performance contributes to the whole building performance (related to EPBD requirements). The module temperature depends importantly on the boundary conditions such as the convective heat exchange at the rear side (material and air flow depended) and the radiative exchange with the boundary (emissivity and absorbance of long wave radiation).

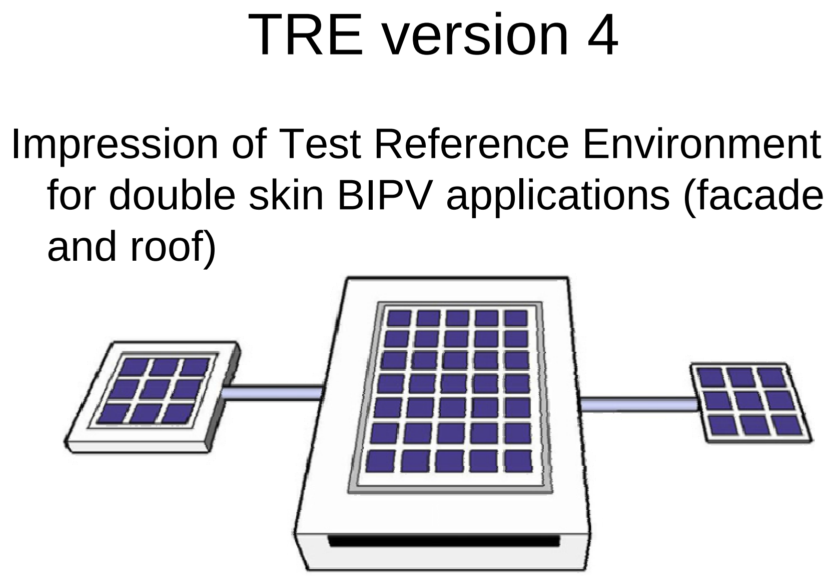

Figure 7. A proposal for a Test Reference Environment for PV roof or façade systems

Conclusion

To assess the energy performance of dynamic building envelope elements, the relation between testing on site (under real and variable weather conditions), a proper evaluation method (based on dynamic calculation technique) and prediction of energy consumption of buildings by means of simulation, is evident. Verification of simulation models by in situ measurements is essential to predict more accurate the performance of the building or building element.

A View on the Future; Characterization based on Smart Metering Data

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Abstract

This article focus on data-driven statistical methods for assessment of thermal performance of buildings and the presented methods can be used to extract valuable information from smart meter readings. Examples of such valuable information are an automatic and objective energy labelling and scanning of large amounts of buildings to find the poorest performing buildings and thus enabling more focused energy refurbishment efforts. Considerations on the choice of modelling method are given. Selecting the methods which can be successfully applied depends on the characteristics of the available data, regarding sampling frequency and accuracy. A method for separating the total heating into heating for domestic hot water (DHW) and space heating is presented first and followed by a method for estimation thermal performance based on daily values. Smart meter data from single family houses in Denmark is used together with local climate measurements.

Keywords

Smart meters, statistical models, time series analysis, buildings, energy performance

1 Introduction

This article focus on data-driven statistical modelling for assessment of thermal performance of buildings and the presented methods can be used to extract valuable information from smart meter readings. For example an automatic and objective energy labelling of buildings[Mortensen and Nielsen, 2011], and scanning of large amounts of buildings to find the poorest performing buildings and thus enabling more focused energy refurbishment efforts.

Considerations on the choice of modelling method is given. Selecting the methods which can be successfully applied depends on the characteristics of the available data, regarding sampling frequency and accuracy. A method for separating the total heating into heating for domestic hot water (DHW) and space heating is presented first and followed by a method for estimation thermal performance based on daily values.

The first method for separating the total heating is based on robust kernel smoothing techniques with which the spikes of the heating signal (in the presented case 10 minutes values are used) is filtered from the total heating signal and represents the DHW heating. The remaining signal represents the space heating. Using an automatic separation can avoid the need for installing separate flow meters for DHW and space heating, and thereby decrease system costs. The method can for example be applied to provide information to the users about their usage patterns and create a better foundation for thermal performance assessment of the building.

The second method for describing the main energy performance characteristics of a building is based on daily readings from smart meters in single family houses, and a climate station located within a few kilometers from the buildings. The main thermal performance characteristics estimated are the response of a building to changes in ambient temperature (UA-value), solar radiation (gA-value), and wind (wA-value). The effect of the wind could be characterized both in terms of the wind speed and the wind direction, implying that wA-values are estimated for different wind directions. Especially, the UA- and wA-values are directly related to the insulation and air sealing of the house. The gA-values are related to the ability of the house to passively use solar heating.

The methods can be used to supply users with valuable information about the thermal performance of their house, which they can use for achieving energy savings. The thermal characteristics can be presented via web pages or smart phone apps. In addition the methods can be used by e.g. district heating companies in order to screen for households with an unusual high consumption. In Denmark this is of interest to district heating companies since they are obliged to implement energy savings.

The outline of the article is as follows. In Section 2 the perspectives of application of data-driven modelling methods are discussed. In Section 3 the choices of modelling method are discussed. In Section 4 the first study in which a method for separating 10 minutes readings of total heating into DHW and space heating is presented and finally in Section 7 a study in which daily average values are analyzed for estimating the thermal performance of many buildings is presented.

2 Perspectives

The perspectives of the work presented in this article point towards an automatic characterization of the main thermal characteristics of a building. Such calculations can be used to supply users with valuable information about their house via web pages or smart phones or to help e.g. district heating or energy retrofit companies determining house owners who might be worth-while contacting for informing about potentials for energy savings.

First, consider interactive services where measurements of heat consumption is available from smart meters. The results presented in this article show that daily values of heat consumption are sufficient for estimating the non-dynamic thermal characteristics, which are the most important ones with relation to the overall energy consumption of the building.

Based on measurements from the heating season **2009/2010** your typical indoor temperature during the heating season has been estimated to **24** ^oC. If this is not correct you can change it here $\boxed{24}$ ^oC.

If your house has been left empty in longer periods with a partly reduced heat supply you have the possibility of specifying the periods in this $\boxed{\text{calendar}}$.

According to BBR the area of your house is **155** m^2 and from **1971**.

Based on BBR information it is assumed that **you do not use any supplementary heat supply**. If this is not correct you can specify the type and frequency of use here:

- Wood burning stove used $\boxed{0}$ times per week in cold periods.
- Solar heating $\boxed{\text{y/n}}$, approximate size of solar panel $\boxed{0} \times \boxed{0}$ meters.

Based on the indoor temperature **24** ^oC, the use of a wood burning stove **0** times per week, and **no** solar heating installed, the response of your house to climate is estimated as:

- The response to outdoor temperature is estimated to **200** $W/^oC$ **which given the size and age of your house is expectable**[a].
- On a windy day the above value is estimated to increase with **60** $W/^oC$ **when the wind blows from easterly directions. This response to wind is relatively high and indicates a problem related to the air sealing on the eastern side of the house.**
- On a sunny day during the heating season the house is estimated to receive **800** W as an average over 24 hours. **This value is quite expectable.**

[a]Many kind of different recommendations can be given here.

Figure 1: Main elements in a possible user interaction. **Bold** entries indicate information specific for the user and $\boxed{\text{boxed}}$ fields indicate information which the user has the ability to enter. Assuming measurements are available on a time scale of 4 hours the above could be supplemented with the dynamic characteristics of the response, see more in the Report [ENFOR, 2010b].

The information to the user could be extended with behavioral information. The *actual* heating season can be detected and if this is unreasonable long the user can be advised to turn of the heating system during e.g. summer periods. Also, if the user specifies the overall indoor temperature and if data from the summer period is used the consumption profile for hot tab water can be estimated.

Figure 1 shows a text-based sketch of the main elements in a user interface of a possible application based on the work presented in this article. As indicated such a user interaction should indicate clearly the interpretation of the estimated values in terms which can be understood by a non-technical user. Several approaches can be possible in this aspect:

(i) The values are related to a database of expert knowledge regarding what energy class the building belongs to.

(ii) The values are related to values estimated for other users and the system can automatically inform the user about the thermal performance of the particular house compared to other houses.

As the number of users increases the information sharing ability of the application will be increasingly valuable.

3 Considerations on modelling method

A wide range of methods exists for thermal characterisation of buildings based on measured data. Naturally the choice of method depends on the purpose of the modelling, but generally speaking two important factors determines which methods can be applied with success:

- Frequency of data: The resolution is both a matter of accuracy of the measurement equipment and sampling frequency of the measurements. Most installed energy meters measure accumulated values with a resolution which is apllicape for modelling with daily values. Modelling with daily values requires minor inclusion of dynamical effects [Mortensen and Nielsen, 2011], whereas modelling with a higher sampling frequency requires dynamical methods, as the second method presented in this paper. Smart meters typically measure with a time resolution between ten minutes and one day.
- The available variables: As a minimum the energy consumption for heating and the outdoor temperature is needed. Preferably also solar radiation. Other important climate variables are wind speed and direction. More variables are: separate heat consumption for heating and hot tab water

(which can be derived from the total heating as described in Section 4), electricity consumption, indoor temperature.

The method needs to account for uncertainty caused by several other effects, such as, the distance from where the climate measurements are recorded to the building, since this distance will have an effect on the accuracy. Clearly one other challenge is dealing with measurements from inhabitet buildings, where the effects from users in the building can influence the results and should be accounted for by the models. This could be opening of windows, changes of control settings and similar changes to the system.

3.1 Time series modelling

Modelling of time series data from dynamical systems requires proper use of statistical modelling techniques as for example presented by Madsen [2007]. The available methods are ranging from simple linear regression models where no dynamics are included, over classical linear time series models (ARMAX type of models), to grey-box models based on stochastic differential equations. Furthermore a set of measures for evaluating model performance and providing insights into un-modelled features, should be taken into account.

3.1.1 Linear regression models

The most fundamental and widespread statistical models are based on linear regression. An output variable is modelled as a linear function of some input variables and the coefficients are estimated by minimizing the squared errors. By using lagged values of input variables this type of models is perfectly suited for modelling physical phenomenons, for example the response in energy consumption to the ambient temperature and other climate variables as carried out in the second study presented in Section 7. The linear regression techniques can applied and extended in many ways, for example by time-varying estimation of the coefficients, inclusion of dynamical effects and non-linear dependencies, which is also important parts of the modelling in such a study. The application of linear regression models, only including the dynamics of a system in a very crude manner, is useful for daily or lower time resolution values.

3.1.2 Linear time series models

ARMAX models can be applied for modelling dynamical systems and can be very useful for modelling heat dynamics of buildings. ARMAX models include a linear transfer functions for modelling dynamical effects and the coefficients can be estimated using maximum likelihood techniques. If the models are restricted to ARX models, they can be fitted as simple linear regression models, making robust and fast parameter estimation possible. Furthermore, these models can also be made time adaptive and non-linear, making them very useful also for modelling complicated effects, such as solar gains in buildings. The steady-state properties, e.g. the UA- and gA-value can be estimated with this type of models, together with the time constants of the system. It is noted that important statistical time series techniques can be used in the model evaluation and selection, such as the auto-correlation and cross-correlation functions, see for example [Madsen, 2007] for more details. For examples of applying ARMAX type of models see [Jiménez and Madsen, 2008], [Jiménez et al., 2008] and [Bacher et al., 2013].

3.1.3 Grey-box models of a dynamic system

A grey-box model is established using a combination of prior physical knowledge and statistics, i.e. information embedded in data. The prior physical knowledge is formulated by a set of stochastic differential equations formulated on state space form. The equations describe a lumped model of the heat dynamics of the building. The physical model is coupled with a data-driven part in which the information embedded in observed data is used for parameter estimation. The data-driven part is represented by a discrete time measurement equation. Tests of the performance of the model can be performed using white noise tests of the residuals of one-step predictions, since if the assumption is not contradicted it is an indication that the physical model is consistent with the observed heat dynamics of the building. For more on grey-box modelling see for example [Madsen and Holst, 1995], [Kristensen et al., 2004] and [Bacher and Madsen, 2011].

4 Separating into domestic hot water heating and space heating

In this section a method for separating the total heat load into domestic hot water (DHW) heating and space heating is presented. Data from an individual residential building located in Denmark is used. It consists of a time series of 10 minute values of total heat load, which is the sum of DHW and space heating. The DHW heating is seen as spikes on top of the space heating. This is due to the fact that showering use intense amount of heating in a short period. The commercial opportunities for this study is that the number of sensors needed can be minimized, since the DHW and space heating doesn't need to be measured separately, hence the system costs can be decreased. The described method for separating the total heat load is quite generic and can therefore easily be used for other applications, where spikes need to be separated from other signals. The separation can be useful for building energy performance estimation based on data ([Rabl, 1988] and [Jiménez et al., 2008]) and for load forecasting where the presented method was actually used [Bacher et al., 2013]. The separated DHW consumption can be used for example for constructing load profiles for DHW ([Widén et al., 2009] and [Andersen et al., 2013]), the latter using in-homogeneous Markov chain models providing a fully data-driven stochastic modelling approach. Other important applications are control for heating systems enabling demand response for integration of renewables, for example by using a hot water tank [Halvgaard et al., 2012] or the building structures [Prívara et al., 2013] for energy storage.

Separating consumption signals into sub-components has been studied quite intensively the last decades, mainly for electrical appliance load monitoring ([Hart, 1992] and [Farinaccio and Zmeureanu, 1999]), where the electrical load is dis-aggregated into event categories. Also residential water consumption dis-aggregation into end-use categories has been studied [Nguyen et al., 2013], where high resolution readings (5 sec.) were used.

In the present study a statistical time series approach [Madsen, 2007] based on kernel smoothing techniques for time series ([Epanechnikov, 1969] and [Robinson, 1983]) is applied. These are combined with robust estimation (see [Huber, 2003] and [Rousseeuw and Leroy, 2005]) enabling the separation of the very high spikes to be carried out without interfering with the remaining signal. The basis of the method is to use a non-parametric function to estimate the space heating. The space heating changes during the day and is a low-pass filtered response of mainly the outdoor temperature and the solar radiation. Consequently, the heating changes over time at frequencies related to those variables and the method is therefore designed such that the non-parametric estimate follows these changes, without being influenced by the spikes, which are significantly higher than this estimate and therefore can be separated as DHW heating.

4.1 Data

The data used in the study consists of the total heat load of a single-family freestanding residential building with two occupants. The total heat load is the sum of DHW heating used for heating water for showering, dish washing, etc., and space heating used for heating the building. Sønderborg District Heating Company located in Southern Denmark delivered the data. The period used is covering one month from 1$^{\text{st}}$ of March to 1$^{\text{st}}$ of April 2010. The data was logged approximately every 10$^{\text{th}}$ minute. The unit of the heating is MJ/h. The total heat load is represented with the time series

$$\Big\{Q_t, \quad t = 1, \ldots, N\Big\} \tag{1}$$

where Q_t is the value at time t and $N = 4607$ is the number of observations in the times series, i.e. equidistant sample points. Figure 2 shows the raw data from this period. Some of the spikes are as high as 160MJ/h and have been cut off by the frame in order to make the lower variations visible. The figure shows that in a two weeks period from Friday 12$^{\text{th}}$ until Friday 26$^{\text{th}}$ there are no spikes and the total heat load has very little variation. It is assumed that the inhabitants were on holidays and left the house during these two weeks. Including the holiday period in the evaluation provides an opportunity to see the performance of the models in separating the DHW heating from the space heating, since the models should predict that no DHW heating is used in the period.

5 Kernel smoother

In this section a simple zero order kernel smoother is presented. It is assumed that the spikes represent DHW heating and the remaining signal represents space heating, therefore spikes significantly higher than the kernel smoother estimate needs to be identified.

A kernel smoother is a method to estimate the underlying function of some given noisy measurements. Kernel estimation is a non-parametric estimation technique, where no explicit description of the true function is needed and only a bandwidth parameter needs to be set [Robinson, 1983]. The kernel smoother is

$$\hat{g}(t) = \sum_{i=1}^{N} \frac{Q_i k\{\frac{t-i}{h}\}}{\sum_{i=1}^{N} k\{\frac{t-i}{h}\}} \tag{2}$$

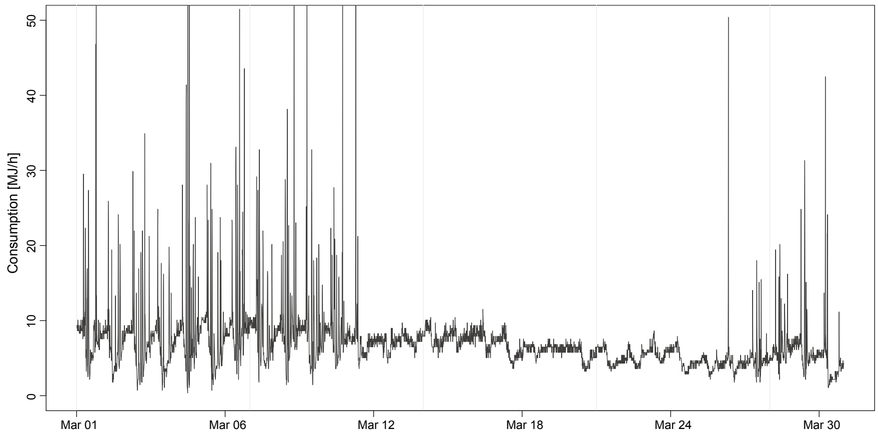

Figure 2: Total energy consumption for March 2010.

where $\hat{g}(t)$ is the kernel estimate for a given time t and h is the bandwidth parameter. From the formula it is seen that the kernel smoother is a local weighted average around the given time t, hence a zero order local estimate. The function $k(\cdot)$ is the kernel, which determines how the weight should be put on the neighboring data points. The Gaussian kernel $k(u) = \frac{1}{2\pi}\exp\{-\frac{u^2}{2}\}$ is chosen. The bandwidth h is a smoothing parameter which determine the width of the kernel. As $h \to \infty$ the estimate will go towards the overall mean value $\hat{g}(x) = \bar{Y}$. Therefore for large values of h the kernel estimate will be biased. As $h \to 0$ the kernel estimate would just be equal to the nearest data points and there will be no bias, but a large variance. Hence the bandwidth needs to be tuned for the particular data and the present case a bandwidth equal to $h = 12$ (which is 2 hours) is found adequate. This results in the kernel seen in Figure 3. The kernel smoother estimate is used to separate the DHW and space heating in the total heat load. The DHW heating is found by

$$\hat{Q}_t^{\text{water}} = I\left(Q_t > q_{\text{thres}}\,\hat{g}(t)\right)\ \left(Q_t - \hat{g}(t)\right) \tag{3}$$

where $I(\cdot)$ is the indicator function. Hence spikes above "q_{thres} · kernel estimate" are identified as DHW heating and the value of them are found by subtracting the kernel estimate. The separation threshold q_{thres} needs to be tuned and it should be set related to the local variance of noise in the space heating signal, such that the spikes are significantly higher than this noise level. In the present case it was set to the factor 1.3. Since only one time series is available a scheme for tuning of q_{thres} is left for future studies where many different series are included. The space heating is found simply by subtracting DHW heating from the total heat load

$$\hat{Q}_t^{\text{space}} = Q_t - \hat{Q}_t^{\text{water}} \tag{4}$$

In the following section a robust kernel smoother is presented.

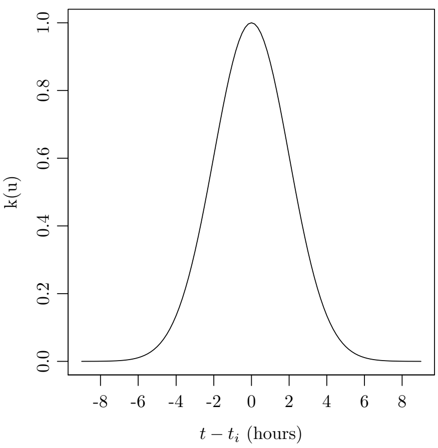

Figure 3: The Gaussian kernel with $h = 5$ used for the smoothing.

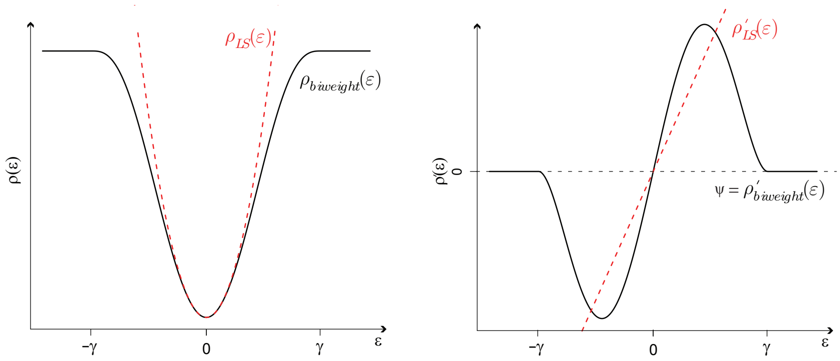

Figure 4: Left: Tukey's biweight and a square function. Right: The derivatives also known as the influence function.

6 Robust zero order kernel smoother

The robust zero order kernel smoother applied for the separation is described in this section. The idea behind robust estimation is to make the estimation method robust against outliers or extremes. Optimization methods generally try to minimize some function $\rho(\varepsilon)$ of the residuals ε. In this case the kernel estimator in (2) is a zero order local regression model [Friedman et al., 2001] and can be formulated as

$$\hat{g}(t) = \arg\min_{\theta} \frac{1}{N} \sum_{i=1}^{N} w_i(t) \left(Q_i - \theta\right)^2 \tag{5}$$

where the residuals are $\varepsilon_i = Q_i - \theta$. The estimation is made robust by replacing the quadratic function with Tukey's biweight function, see [Huber, 2003]. Tukey's biweight function is also known as the bisquare function. The biweight estimation minimizes the following function

$$\rho_{\text{biweight}}(\varepsilon) = \begin{cases} \frac{1}{6} \frac{\varepsilon^2\left(\varepsilon^4 - 3\,\varepsilon^2\gamma^2 + 3\,\gamma^4\right)}{\gamma^4} & \text{if } |\varepsilon| \leq \gamma \\ \frac{1}{6}\,\gamma^2 & \text{if } |\varepsilon| > \gamma \end{cases} \tag{6}$$

The biweight function is approximately quadratic for small residuals and constant for residuals larger than γ. A plot of $\rho_{\text{biweight}}(\varepsilon)$ and a scaled version of $\rho_{LS}(\varepsilon)$, together with their derivatives is shown in Figure 4. The derivative is also also known as the influence function. The biweight function induces that outliers do not cause displacement of the resulting estimate. For residuals further away than the γ limit the influence function $\rho'(\varepsilon) = 0$, hence they do not affect the estimate. The parameter γ is a selected threshold for the biweight function, determining when residuals are large. For the actual heating data a reasonable value found to be $\gamma = 7$ Mj/h. For a given time t the robust kernel estimate is found by solving the optimization problem

$$\hat{g}(t) = \arg\min_{\theta} \frac{1}{N} \sum_{i=1}^{N} w_i(t)\, \rho_{\text{biweight}}\left(Q_i - \theta\right) \tag{7}$$

The result of the kernel estimation with a biweight function is shown in Figure 5. It is seen that almost all of the spikes in the heating are removed compared to the original kernel estimate. So using the robust kernel solves the problem that the kernel estimate was too affected by the large spikes.

6.1 Discussion

A scheme for automatically tuning the parameters: the kernel bandwidth h, the separation threshold q_{thres} and the γ threshold for the biweight function in the robust estimation scheme, should be developed in further work. Furthermore, for the present heating series a relative value of kernel estimate instead of fixed value as the separation threshold instead was used. However, how this threshold is constructed should be studied in further details. Finally, the use of additional explanatory variables, e.g. electrical load, ambient temperature, solar radiation, should be studied for possible improvements of the method.

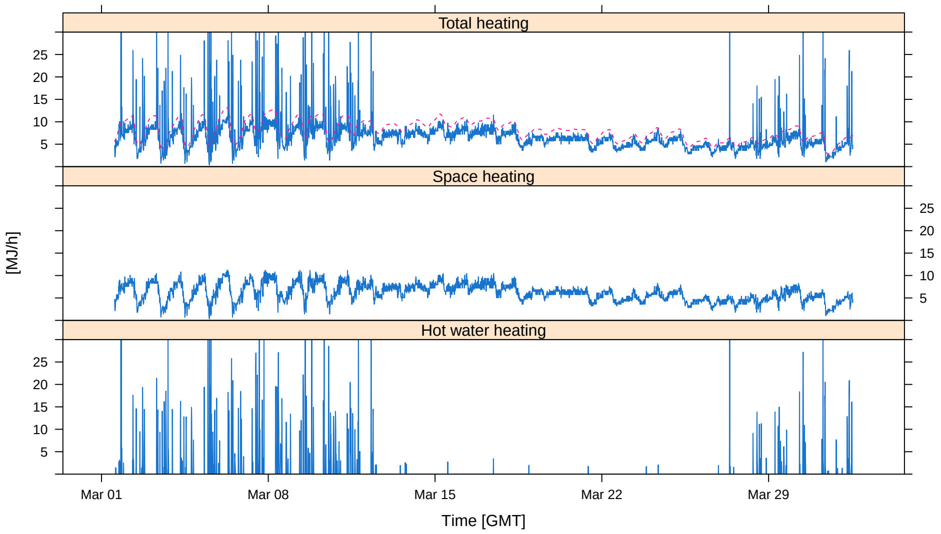

Figure 5: Separating with robust kernel smoother. The red dashed line is 1.3 · kernel estimate.

7 Thermal characterisation of buildings using data from smart meters

The next session is concerned with estimating thermal characteristics of single family houses based on measurements of energy consumption and climate. The main thermal characteristics describe how the building respond to: temperature differences between indoor and outdoor environment (UA-value), solar radiation (gA-value), and wind (wA-value). The effect of the wind can be characterized both in terms of the wind speed and the wind direction, implying that wA-values are estimated for different wind directions. Especially, the UA and wA-values are directly related to the insulation and air sealing of the building. The gA-values are related to the ability of the building to passively use solar heating. The estimated thermal characteristics have been analyzed with respect to background information regarding the households. The information is obtained via questionnaires and via the Danish Building Register (BBR). The significant effects are the ground area of the building, the year of construction, and the number of times per week a wood burning stove is used. This analysis is found in the Report [ENFOR, 2010b].

Further characterization of the building is the dynamic response to changes in climate variables. This is carried out as described by ENFOR [2010b], where the dynamic response is characterized by time constants of the response to temperature and solar radiation.

The data used in this section consists of heat and electricity consumption data for the period from ultimo September 2008 to primo December 2009 from 56 households connected to the district heating system in Sønderborg, Denmark. Also climate data obtained at a local weather station within a few kilometers from the buildings. The energy consumption data is described in detail in the Report [ENFOR, 2010a]. For 26 of the 56 households the electricity data is available, they are considered in this article. In the Report [ENFOR, 2010b] it is shown that the thermal characteristics of the building can often be well estimated based on measurements of the heat consumption alone. This is the case when the electricity consumption is not too large as it would be if for example electrical floor heating is used.

7.1 Daily sampling

The analysis is carried out using daily power consumption values, i.e. using a sampling period of 1 day. With a unit resolution of 0.01 GJ this gives the daily consumption a unit resolution of 2.78 kWh/day, which is found to be sufficient for the analysis of daily values. Heat consumption is estimated based on the difference in the accumulated consumption from midnight to midnight. The electricity consumption is treated in the same way. Climate data are available in the period from 2008-10-06 to 2009-11-18 with a 10 minute sampling interval. The available variables are ambient air temperature T_a in °C, solar radiation R_0 in lux, wind speed w in m/s and wind direction θ in degrees. All climate data are down sampled to diurnal averages. The measurement of solar radiation is assumed to be dominated by direct sunlight and thus to be proportional with the effect of the direct sunlight.

The stationary heat transfer for a building is for the main part assumed to be comprised by three ways of heat transfer, namely through walls, windows, and by ventilation. Here heat transfer through

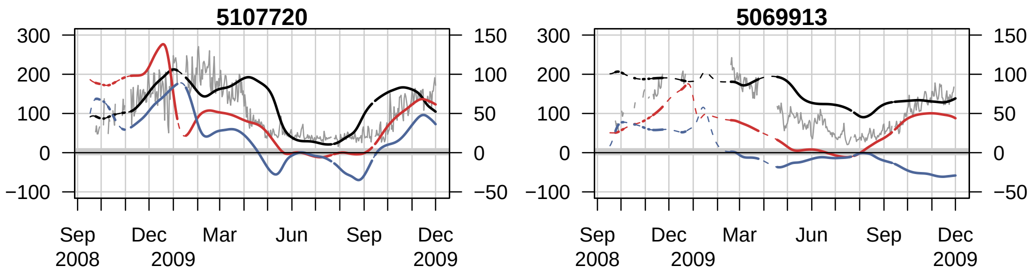

Figure 6: Time varying estimates of coefficients in (2). Black is UA [°C], red is gA [W/kLux] and blue is b1 [W/m/s] all measured on the left side axis. The underlying gray curve is daily total energy consumption in kWh measured on the right side axis.

the roof is assumed to be included as part of the model for the walls. By considering stationary models for heat transfer trough walls and windows and via ventilation a model with the following characteristics is derived:

- Responses on the temperature are collected into one term for which the coefficient is the UA-value.
- Responses on the solar radiation are collected into one term for which the coefficient is the gA-value.
- Responses on the product of the temperature and the wind speed are collected into one term for which the coefficient is the wA-value.

The model can only be used during the time period where the building is heated to maintain a constant indoor temperature, such that the heat transfer from the building can be measured based on the amount of energy supplied to the household. In the following it is shown how this period is estimated.

7.1.1 Analysis of daily values of power consumption

The estimation of UA and gA values and wind dependence is based on the assumptions outlined in the previous section. Unknown parameters in the model are UA, gA, $v(\theta)$. The function $v(\theta)$ is modelled either as a constant $v(\theta) = c_w$ or as piecewise constant for the major wind directions. There are only three days with an average wind direction from the northern quarter, and hence it is chosen to keep only three major wind segments, namely east (E) 0-135 deg., south (S) 135-225 deg., and west (W) 225-360 deg. The piecewise constant approximation to $v(\theta)$ is given as

$$v(\theta) = \sum_{j=E,S,W} I(\theta \in j) c_{wj} \tag{8}$$

where I is an indicator function equal to 1 when the argument is true and otherwise 0. The three coefficients c_{wj} gives wind dependence in the model and is interpreted as 'wA' values such that $\mathrm{wA}_j = c_{wj}$.

7.1.2 Time varying estimates

Initial investigation of the energy consumption data is done by estimating the time variations of the coefficients in a linearized and simplified version of the model outlined above. To reduce the number of parameters to be estimated the interaction between wind speed and air temperature, is not included giving the model

$$Q_t = b_0 - \mathrm{UA} \cdot T_{a,t} - \mathrm{gA} \cdot R_{0,t} + b_1 w_t + e_t \tag{9}$$

where b_0 and b_1 are constants, $T_{a,t}$ is the ambient air temperature, $R_{0,t}$ is the solar radiation, and w_t is the wind speed. The coefficient b_1 cannot be interpreted in relation to the physical model, but it still gives an indication of wind speed dependence in the energy consumption.

The time variations are estimated using locally weighted estimation of the linear model. The method is described by Nielsen [1997] and gives local estimates in time of the model coefficients by only considering observations within a limited time window. This makes it possible to see if they are constant over time, e.g. to look for variations during the heating season and how they change during the summer period. Figure 6 shows these time varying estimates for two households. For most of the households the estimates of UA, gA and b_1 are relatively stable during the winter period which is also seen for these two households.

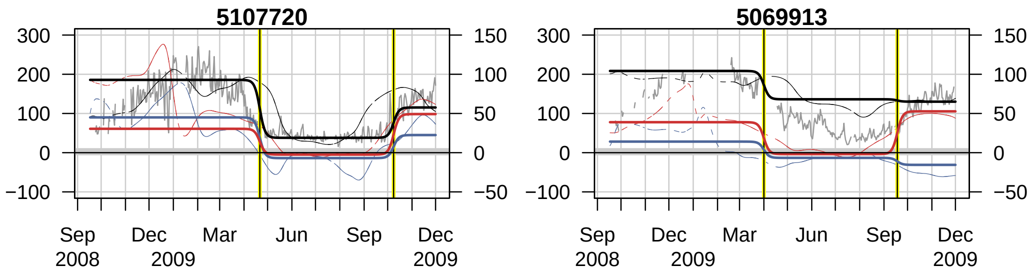

Figure 7: Thick lines are estimates of parametric models for time varying coefficients in (2). Black is UA [W/ °C], red is gA [W/klux] and blue is b1 [W/m/s] all measured on the left side axis. Thin lines are estimates based on local regression from Figure 7. Vertical black-yellow lines are estimated time point of change. The underlying gray curve is daily total energy consumption in kWh measured on the right side axis.

7.1.3 Parametric modelling of time-variations

Based on the estimates of time variations of the coefficients in the model in (9) it seems reasonable to assume that the coefficients can be modelled with a constant level for each of the two winter and one summer periods, giving three levels in total. Estimating when the changes in level occur will indicate the exact extent of the heating season for each individual building and this information can then be used to select the longest possible period of the actual heating season for further analysis. The model is estimated by means of partial linear estimation techniques and results are shown for the two selected households in Figure 7.

In previous work for estimation of UA-values alone based on daily averages of energy consumption [Nielsen, 2008] it has been found that there is significant dependence on the ambient temperature one day back for the heat consumption. This dynamic effect is also included here. In order to be able to get a good estimate of the effect of the solar radiation the heating season must comprise into the spring, where there is a significant contribution from the sun.

7.1.4 Results

The method has been applied for the 26 households and the results are shown in Table 1. To aid the interpretation of the estimated gA are multiplied by the 99% quantile of observed daily average of solar radiation and denoted $\hat{\mathrm{gA}}^{\mathrm{max}}$. This parameter determines the average effect in W which is absorbed on a day with maximal average solar radiation. Similarly the direction dependent estimates of the wind $\hat{c}_{wj}$ are multiplied by the 99% quantile of observed daily average wind speed and denoted $\hat{\mathrm{wA}}_E^{\mathrm{max}}$, $\hat{\mathrm{wA}}_S^{\mathrm{max}}$, and $\hat{\mathrm{wA}}_W^{\mathrm{max}}$. One can interpret these parameters such that they can determine the absolute change in UA value in W/°C due to ventilation for a day with a maximal average wind from the particular direction. As an example, House 6 has an estimated UA value of 155W/°C and during a very windy day with wind coming from east the UA value is increased by 40W/°C.

In the table the estimated UA values ($\hat{\mathrm{UA}}$) and indoor temperatures ($\hat{T}_i$) are shown together with their estimated standard error ($\hat{\sigma}_{\mathrm{UA}}$ and $\hat{\sigma}_{T_i}$). The $\hat{\mathrm{gA}}^{\mathrm{max}}$ and $\hat{\mathrm{wA}}_*^{\mathrm{max}}$ are not always statistically significant, for more details see the report ENFOR [2010b].

Most of the estimated values are within realistic physical values, some are not, however this will (nearly) always be the case when analyzing this type of data, where unknown effects can influence the results. Using proper statistical techniques the quality of the results can be assessed, e.g. with estimation of the uncertainty of the parameters and with statistical testing. All details and a more thorough analysis of the results, including a proper statistical analysis of the residuals, can be found in the report [ENFOR, 2010b]. The estimates of the UA values are all positive and their standard deviance indicates that they are relatively accurately determined (95% confidence intervals are approximately the estimate $\pm 2\hat{\sigma}$). The $\hat{\mathrm{gA}}^{\mathrm{max}}$ values are all positive as they are expected to be except for one case. The estimates of the $\mathrm{wA}_*^{\mathrm{max}}$ values are mostly positive, although there are some negative estimates indicating a reduced UA value for these wind directions. However, overall the estimates of the $\mathrm{wA}_*^{\mathrm{max}}$ values gives a picture of the wind dependence for each house, and it is seen that some are clearly more wind sensitive than others. Finally, it is noted that the estimates of the indoor temperature are here based on the intercept in the linear model, which implies that all heat losses which in average are different from zero, will influence these estimates. For example a leak which is not dependent on the other inputs will increase the indoor temperature estimate, this could for example explain that the estimates generally seems slightly too high and the very high value for House 21.

House	$\hat{UA}$ (W/°C)	$\hat{\sigma}_{UA}$ (W)	$\hat{gA}^{max}$	$\hat{wA}_E^{max}$ (W/°C)	$\hat{wA}_S^{max}$ (W/°C)	$\hat{wA}_W^{max}$ (W/°C)	$\hat{T}_i$ (°C)	$\hat{\sigma}_{T_i}$
1	212	10	597	11	3	9	24	1.10
2	99	11	-96	24	10	13	22	2.30
3	228	13	1012	30	43	40	0.00	1.00
4	155	6	519	14	4	9	0.03	0.90
5	178	7	800	2	-8	8	0.00	1.00
6	155	8	591	40	28	21	0.00	1.10
7	236	18	1578	4	3	19	0.06	1.60
8	160	11	716	10	8	7	0.68	1.40
9	145	10	88	4	2	17	0.03	1.50
10	208	9	962	4	9	11	0.01	0.90
11	189	15	658	41	29	16	0.08	1.60
12	265	17	1364	18	-10	-20	0.00	1.70
13	205	6	614	-2	-3	4	0.01	0.70
14	173	14	68	8	8	-5	0.33	1.80
15	196	7	931	15	24	31	0.00	0.80
16	148	8	758	-7	1	7	0.03	1.40
17	170	8	554	26	8	2	0.00	0.90
18	178	14	429	-4	-26	6	0.00	1.70
19	209	8	725	23	19	32	0.00	0.70
20	129	15	609	18	2	8	0.42	2.70
21	63	5	187	0	-1	0	0.56	4.20
22	222	13	246	8	2	30	0.04	1.00
23	132	10	408	-7	-2	7	0.02	1.90
24	182	14	1039	32	20	24	0.00	1.80
25	206	18	841	6	-42	-9	0.00	2.30
26	171	15	522	3	-6	13	0.06	1.90

Table 1: Estimates obtained with the model which includes sensitivity to wind direction.

7.1.5 Discussion on the estimation of energy performance of single family houses

A fundamental assumption of the presented method is that measurements with a time resolution of one day are available. During the recent years such measurements has started to appear, both for electricity, district heating, and natural gas consumption. Obviously, measurements performed with a high frequency imply higher demands for bandwidth and data storage. Maybe less obviously high frequency measurements also require better resolution of the basic measurement equipment. The resolution of the measuring equipment compared with the time resolution can have an important effect on information embedded in the data. In the present study a unit resolution of 2.78 kWh/day has proved to be sufficient for estimation of the energy performance of single family houses. For energy optimization by load-shifting using dynamical methods a higher time resolution is needed.

8 Conclusion

The presented methods for separating total heating into DHW heating and space heating, and estimation of the thermal characteristics of single family houses enables the use of smart meter readings to provide valuable information about the energy consumption in buildings. Most importantly an objective description of the energy performance of individual buildings can be obtained and the methods can be applied to analyze very large amounts of buildings. It is possible to assess how well a building is insulated, combined with its wind sensitivity for the prevailing wind directions and its ability to passively use solar heating. This implies estimation of the coefficients characterizing the response of the building to differences in temperature (UA-value), solar radiation (gA-value), and wind (wA-value). Such methods based on measurements from smart meters, can enable ICT-facilitated improvements of building energy efficiency by means such as: providing objective methodologies to calculate the thermal performance of buildings for implementation of policy and in measuring its effectiveness, providing advises on the best ways of improving the energy performance of a building, and enhancing the energy awareness of users via interactive web sites or smart phones.

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