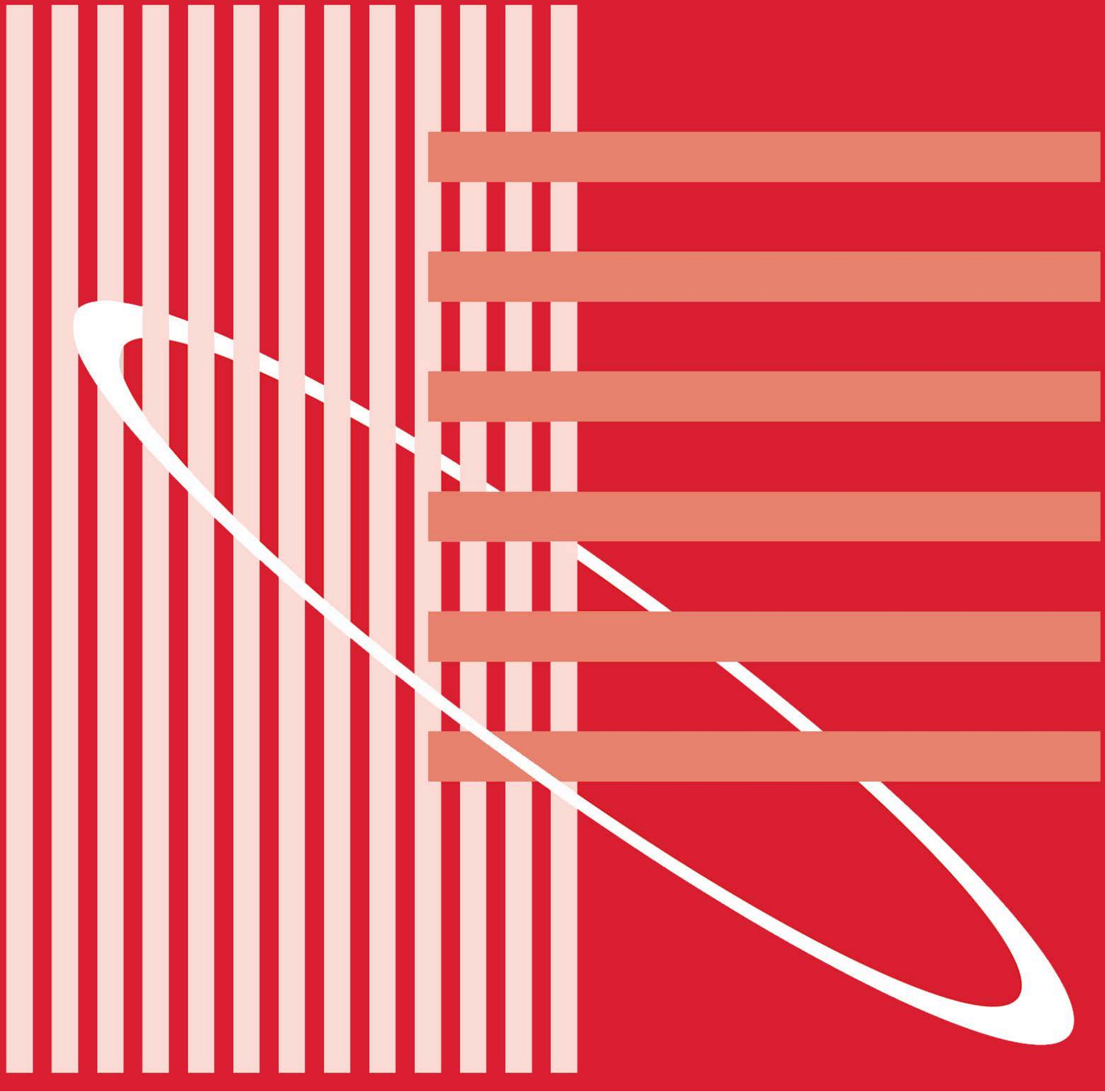
International Conference Organized by IBPSA-Nordic
13th-14th October 2020, Oslo

Book of Abstracts

BuildSim Nordic 2020



Contents

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Welcome to BSN2020 !

You are cordially invited to join the *BuildSim Nordic 2020* conference, to be held on the **13th & 14th October 2020**, organized in cooperation between the Nordic chapter of IBPSA, and hosted as a virtual conference by OsloMet.

The purpose of the event is to create a platform for exchanging ideas, issues and research findings, in the field of building performance simulation. It facilities national & international collaboration, and the meeting of minds between practitioners, researchers and students.

Participants

The conference will appeal to all who are interested in state-of-the-art in building simulation, including system design, HVAC, energy production/use, indoor climate and environmental issues. We have developed a programme covers a wide range of topics and workshops of relevance not only to building simulation researchers but also practitioners in the building industry.

Topics

The conference includes workshops papers on topics involving the use for integration of modeling tools for better building design, performance, and operation. The topics for the conference include (but are not limited to)

- Building acoustics
- Building Information Modelling (BIM)
- Building physics
- CFD and air flow
- Commissioning and control
- Daylighting and lighting
- Developments in simulation
- Education in building performance simulation
- Energy storage
- Heating, Ventilation and Air Conditioning (HVAC)
- Human behavior in simulation
- Indoor Environmental Quality (IEQ) New software developments
- Optimization
- Simulation at urban scale
- Simulation to support regulations
- Simulation vs reality
- Solar energy systems
- Validation, calibration and uncertainty
- Weather data & Climate adaptation
- Fenestration (windows & shading)
- Zero Energy Buildings (ZEB)
- Emissions and Life Cycle Analysis

How to join the virtual conference

Register on the following website. The fee is only approx. € 50. The website gives full access to full papers and events (Zoom sessions/workshops, and Wonder social events):

https://www.conftool.org/buildsim-nordic-2020/sessions.php

Organizing Committee

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- Mandana Sarey Khanie, DTU

International Scientific Committee

We are grateful to the scientific committee their help in reviewing. Their names are listed in the Proceedings.

Conference sponsor

We are very grateful for financial support of EQUA.

Programme overview

Monday 12/Oct/2020, evening

7:00pm - 8:45pm	**Welcome reception on Wonder (a.k.a. YoTribe)** *Chairs: Jørgen E. Christensen, Heidi Liavåg, Matthias Haase* **We have created a virtual lounge for the welcome reception, with a greeting by the President, and information by the organizers. The lounge has many different topic-areas, for you to informally mingle, and make new acquaintances with common interests!**

Tuesday, 13/Oct/2020, morning

9:00am - 10:30am	**Opening Session: BSN2020 Opening Session and Keynote Lecture** *Chairs: Matthias Haase, Peter G. Schild, Vojislav Novakovic* Keynote lecture: **The Great Energy Predictor III Kaggle Competition - How can we bridge physics-based and data-driven modeling?** *Speaker: Clayton MILLER, Department of Building, School of Design and Environment, National University of Singapore*
10:30am - 12:00pm	**Session 1: UBEM, District Heating and Large Buildings** *Chairs: Santeri Siren, Chair: Matthias Haase* **A top-down digital mapping of spatial energy use for municipality-owned buildings: a case study in Borlänge, Sweden** *Samer Quintana, Pei Huang, Mengjie Han, Xingxing Zhang* **Requirements for representative models for comfort and energy simulations in districts** *Matthias Haase* **Planning a low carbon urban area in Helsinki with dynamic energy simulations** *Santeri Siren* **Integration of a high-temperature borehole thermal energy storage in a local heating grid for a neighborhood** *Michael Jokiel, Daniel Rohde, Hanne Kauko, Harald Taxt Walnum* **A novel modelling approach of ground source heat pump application for district heating and cooling, developed for a case study of an urban district in Finland** *Oleg Todorov, Kari Alanne, Markku Virtanen, Risto Kosonen* **Clustering and classification of building structures and their construction years with respect to monthly electricity consumption** *Mengjie Han, Mohsin Raza, Xingxing Zhang, Samer Quintana* **Validation of Norwegian Residential Building Archetypes Based on Empirical Data and Numerical Simulations** *Kamilla Heimar Andersen, Synne Krekling Lien, Hanne Liland Bottolfsen, Aksel Garvik Fagerheim, Igor Sartori* **Numerical Simulations in Transient Condition of a University Building with Complex Topology Equipped with Greenhouses in Winter Conditions** *Eusébio Z. E. Conceição, Mª Manuela Lúcio, Hazim Awbi*

Tuesday, 13/Oct/2020, afternoon

1:00pm - 2:30pm	**Workshop 1: IDA-ICE workshop** *Chair: Mika Vuolle* **IDA Indoor Climate and Energy 5.0 - New features**	
2:30pm - 4:00pm	**Session 2: Airflows and Computational Fluid Dynamics (CFD)** *Chairs: Eusébio Z. E. Conceição, Peter G. Schild* **Calculation of airflow rate with displacement ventilation in dynamic conditions** *Natalia Lastovets, Risto Kosonen, Juha Jokisalo* **POD-interpolation based prediction of indoor airflows** *Mats Kluftødegård, Arnab Chaudhuri* **Analysis of the interfacial mixing in the gravity-driven counterflow through a large vertical opening using Large Eddy Simulation** *Elyas Larkermani, Laurent Georges* **Simulation study on the influence of urban street intersection greening on ventilation performance** *Xin Guo, Zhi Gao* **CFD Simulation Delivered as SaaS for Building and HVAC Design Testing** *Jon Wilde* **Application of Coupling of CFD and Human and Clothing Thermal Response in Ceiling Mounted Localized Air Distribution Systems in Winter Conditions** *Eusébio Z. E. Conceição, Mª Manuela Lúcio, Mª Inês Conceição, Hazim Awbi*	**Session 3: Energy Flexibility, Control and Energy Storage** *Chairs: Igor Sartori, Kim B Wittchen* **A coordinated control to improve energy performance for a building cluster with energy storage, EVs, and energy sharing** *Pei Huang, Xingxing Zhang, Chris Bales, Tomas Persson* **Virtual testbed of the KTH Live-In Lab: development and validation** *Marco Molinari, Davide Rolando* **Influence of space heating distribution systems on the energy flexibility of Norwegian residential buildings** *Christoph Nickl, John Clauß, Laurent Georges* **Model predictive control of District Heating substations for flexible heating of buildings** *Harald Taxt Walnum, Igor Sartori, Marius Bagle* **Analyses of thermal storage capacity and smart grid flexibility in Danish single-family houses** *Kim B. Wittchen, Ole Michael Jensen, Jaume Palmer, Henrik Madsen* **Insight on a local energy community: Agent based model of a peer to peer (P2P) interaction for a group of prosumers** *Marco Lovati, Carl Olsmats, Xingxing Zhang*

4:30pm - 6:00pm	**Session 4: Building Envelope, Daylighting and Thermal Design** *Chairs: Steffen Petersen, Petter Wallentén* **Experimental and numerical studies on thermal performance of an office cubicle having gypsum boards coated with PCM-enhanced spackling** *Tor Arvid Vik, Habtamu Bayera Madessa, Arnab Chaudhuri, Andreas Aamodt, Chakkrit Phengphan, Ebenezer Twumasi Afriyie* **Visualizing user perception of daylighting: a comparison between VR and reality** *Muhammad Hegazy, Ken Ichiriyama, Kensuke Yasufuku, Hirokazu Abe* **The Potential of the Multi-Angled Facade System in Improving Natural Ventilation** *Loay Hannoudi, Noha Saleeb* **Adapting to future climate change by integration of Phase Change Materials (PCMs) into the building envelope: a case study in Stockholm, Sweden** *Benedetta Copertaro, Jingchun Shen, Lorenzo Sangelantoni, Pei Huang, Xingxing Zhang* **The Effect of Local Climate Data and Climate Change Scenarios on the Thermal Design of Office Buildings in Denmark** *Steffen Petersen* **Definitions of Floor Area and Evaluating Impacts in Energy Simulation** *Nicholas Frederick Allen-Sandoz* **A parametric tool for combined overheating and daylighting assessments** *Eleni Gkouvelou, Dimitra Moskoveli, Mandana Sarey Khanie*

Tuesday 13/Oct/2020, evening

7:00pm - 9:00pm	**BuildSim Lounge on Wonder (a.k.a. YoTribe)** *Chairs: Jørgen E. Christensen, Heidi Liavåg, Matthias Haase* **We informally meet again in the virtual BuildSim Lounge to relax, mingle and chat about the conference.**

Wednesday, 14/Oct/2020, morning

9:00am - 10:30am	**Session 5: Heat Pumps and Air-Conditioning Systems** *Chairs: Nelson Sommerfeldt, Habtamu Bayera Madessa* **Simulation and parametric study of a building integrated transpired solar collector heat pump system for a multifamily building cluster in Sweden** *Puneet Saini, Frank Fiedler, Emmanouil Psimopoulos, Benedetta Copertaro, Joakim Widén, Xingxing Zhang* **Impact of AC Outdoor Unit Placement on Energy Efficiency** *Krishna Patel, Rajan Rawal* **Energy performance of ground-source heat pump and photovoltaic/thermal (PV/T) in retrofitted and new buildings: Two case studies using simulation and on-site measurements** *Arefeh Hesaraki, Hatef Madani Larijani* **Quasi-Dynamic Modelling of DC operated Ground-Source Heat Pump** *Patrik Anders Ollas, Caroline Markusson, Jörgen Eriksson, Huijuan Chen, Markus Lindahl, Torbjörn Thiringer* **Parametric analysis of ground source heat pump system for heating of office buildings in Nordic climate** *Mehrdad Rabani, Habtamu Bayera Madessa, Jørgen Torgersen, Natasa Nord* **Solar PVT for heat pumps: Collector development, systems integration, and market potential** *Nelson Sommerfeldt, Francisco Beltran, Hatef Madani*	
10:30am - 12:00pm	**Session 6: HVAC general, IEQ and ZEB** *Chairs: Janne Petteri Hirvonen, Jørgen Erik Christensen* **Chilled water temperature control of self-regulating active chilled beams** *Peter Filipsson, Anders Trüschel, Jonas Gräslund, Jan-Olof Dalenbäck* **Energy performance of an office building by using adaptive approach to occupant behaviour and environment control** *Himanshu Patel Tuniki, Andrius Jurelionis, Monika Dobrovolskyte* **Domestic hot water decomposition from measured total heat load in Norwegian buildings** *Synne K. Lien, Dmytro Ivanko, Igor Sartori* **Numerical analysis of heat recovery options in old Finnish apartment buildings** *Janne Petteri Hirvonen, Juha Jokisalo, Risto Kosonen* **Simplified Tool for Pre-Designing Ventilation Air Flow in Greenland** *Jørgen Erik Christensen, William K. K. Vergo, Joan Ferris Gimeno* **From TEK17 to ZEB-O - A case study for a residential building in northern Norway** *John Clauß, Eivind Nygård, Judith Thomsen*	**Session 7: Data-driven Models and BPS education** *Chairs: Hicham Johra, Laurent Georges* **Influence of Data Pre-Processing Techniques and Data Quality for Low-Order Stochastic Grey-Box Models of Residential Buildings** *Xingji Yu, Laurent Georges* **Data-based calibration of physics-based thermal models of single-family houses** *Virginia Amato, Michael Dahl Knudsen, Steffen Petersen* **Datasets for grey-box model identification from representative archetypes of apartment blocks in Norway** *Hanne Liland Bottolfsen, Kamilla Heimar Andersen, John Clauß, Igor Sartori* **Identifying grey-box models of Norwegian apartment block archetypes** *Marius Eide Bagle, Harald Taxt Walnum, Igor Sartori* **Global Marginal Carbon Footprint Evaluation of Internet Services with Building Energy Models** *Eric Mahendra Kumar, Erica Cochran Hameen, Wei Liang* **A Grey Box Model of the Heat Dynamics of a School Building** *Frederik Banis, Christian Anker Hviid, Hjörleifur G. Bergsteinsson, Peder Bacher, Davide Cali, Henrik Madsen, Niels Kjølstad Poulsen* **Video game-based learning for teaching building thermodynamics and control of HVAC systems** *Hicham Johra, Lasse Rohde, Ekaterina Petrova* **Discussing daylight simulations in a proposal for online daylighting education** *Federica Giuliani, Mandana Sarey Khanie, Natalia Sokół, Niko Gentile*

Wednesday, 14/Oct/2020, afternoon

1:00pm - 2:30pm	**Workshop 2: Master-planning based on NZEB for Positive-Energy Districts** *Chair: Matthias Haase* **Master planning based on NZEB for Positive Energy Districts**	**Workshop 3: Building Performance Simulation Accuracy and High-Resolution** *Chairs: Jon William Hand, Petter Wallentén* **Workshop on high resolution modelling**
2:30pm - 4:00pm	**Session 8: Input data workflow, boundary conditions, user interface, BIM** *Chairs: Vojislav Novakovic, Jon William Hand* **Using inference from user attribution of models to support high resolution modelling** *Jon William Hand* **Working with a Small and Predictable Performance Gap** *Marc Azar, Par Carling* **Exploring possibilities to quantify the qualitative description of occupant behavior** *Jakub Wladyslaw Dziedzic, Da Yan, Vojislav Novakovic* **Undefined modelling parameters impact on building simulation results: using IDA ICE according to the Estonian methodology for calculating building performance** *Henri Sarevet, Martin Kiil, Raimo Simson, Martin Thalfeldt, Jarek Kurnitski* **The right way to do building simulations? Using Monte Carlo simulations, sensitivity analysis, and metamodeling on a design case** *Torben Østergård, Lars Broder Nielsen, Rasmus Lund Jensen* **Update of a living building-simulation tool** *Ole Michael Jensen, Kim B. Wittchen, Christian Grau Sørensen, Jesper Kragh, Jørgen Rose, Nanna Dyrup Svane, Karl Grau Sørensen* **Semi-automatic geometry extract from Revit for earlier and faster building performance simulations** *Nanna Dyrup Svane, Artüras Pranskunas, Lars Broder Lindgren, Rasmus Lund Jensen*	
4:00pm - 4:30pm	**Closing Session: BSN2020 Closing Session and Best Paper Awards** *Chairs: Matthias Haase, Peter G. Schild, Vojislav Novakovic*	

Opening Session

Keynote speech: The Great Energy Predictor III Kaggle Competition - How can we bridge physics-based and data-driven modeling?

MILLER, Clayton C.

National University of Singaport (NUS), Singapore

Keywords: Machine learning, Calibration, Energy-use auditing

Dr. Clayton Miller will discuss the machine learning solutions, models, and winning techniques from the Great Energy Predictor III Kaggle Competition (https://www.kaggle.com/c/ashrae-energy-prediction) held in Oct-Dec. 2019. This machine learning competition was hosted by the ASHRAE organization and supported by the SinBerBest2 Lab and the National University of Singapore (NUS). Over 3,600 teams from around the world competed for US$25k in prize money to create the most accurate data-driven hourly building energy models for over 2,300 energy meters collected from 1,448 buildings. Dr. Miller will overview the potential applications of these crowd-sourced winning solutions and discuss their common attributes, such as the use of large ensembles of various types of gradient boosting trees. He will cover the lessons learned from the experience and winning modeling techniques and how these insights can be used to bridge the conceptual and practical gaps between physics-based and data-driven modeling techniques for building performance analysis. He will discuss how and where the top five winging models and two-thirds of the competition data set have been released as an open data set for building energy research and industry professionals to use.

Session 1: UBEM, District Heating and Large Buildings

Paper 1.1: A top-down digital mapping of spatial energy use for municipality-owned buildings: a case study in Borlänge, Sweden

QUINTANA, Samer [1,2]; HUANG, Pei [1]; HAN, Mengjie [1]; ZHANG, Xingxing [1]

[1] Dalarna University, Sweden; [2] Uppsala University, Sweden

Keywords: UBEM, urban, energy

The mapping of urban building energy plays a crucial role in benchmarking energy performance of different districts for various stakeholders. This paper studies a set of buildings owned by the municipality of Borlänge, Sweden, which aims to present a digital spatial mapping of both electricity use and district heating demand. A toolkit for top-down data processing and analysis is considered based on the energy performance database of municipality-owned buildings. The data is initially cleaned and transformed using the Feature Manipulation Engine tool (FME) and then is geocoded using a python script with an application program interface (API) for OpenStreetMap. The final dataset consists of 221 and 89 geocoded addresses for, respectively, electricity and district heating monthly consumption for the year 2018. The electricity use and heating demand in the building samples is about 24.06 kWh/m² and 190.99 kWh/m² respectively, where large potential in saving heating energy is observed. The digital mapping reveals a spatial vision of identifiable hotspots for electricity uses in high-occupancy-dense areas and for district heating needs in districts with buildings mostly constructed before 1980s. This result will provide a comprehensive understanding of the existing energy distributions to stakeholders and energy advisors. It will also facilitate strategy towards future energy planning in the city such as energy benchmarking policies.

Paper 1.2: Requirements for representative models for comfort and energy simulations in districts

HAASE, Matthias

SINTEF Community, Norway

Keywords: districts, parametric, model developments

The development of districts requires a distinct understanding of the situation now as well as a vision of the future district in order to be able develop suitable pathways for this transition. In order to be able to do that a district needs to be modelled that consists of several buildings, sufficiently described so that the future district can actively manage their energy consumption and the energy flow between them and the wider energy system. The energy master planning process requires an analysis of different scenarios, which include new construction to different levels of energy efficiency, major renovation of all or some buildings comprising building stock under consideration with Deep Energy Retrofit of these buildings, minor renovations with energy-related scope of work, or demolition of some old buildings. Such analysis requires building energy modeling. In this research work we collected models of representative buildings from several countries and compared them.

Individual building computer-based energy models that are currently available for general use buildings were collected and can be further customized to function as archetypes to predict energy use in districts and adapted to different climate conditions and energy use requirements. To be used for community planning, all prototype models had to be fully parametrized for common modeling inputs in order to be able to build in energy efficiency measures.

First, a target goal for analysis was defined. Based on the target definition a Baseline was developed. This consists of a snapshot of the current energy use situation. Then Base Cases were developed that extends the baseline into the future and includes already-funded renovation as well as planned construction and demolition activities. Different alternatives – A selected set of scenarios that include different energy measures related to buildings, distribution systems, and generation systems were then developed. These scenarios are compared to the baseline for energy use change and to the Base Case for investment and operational costs.

Different baselines were compared for different countries as Australia, Austria, Canada, Denmark, Finland, Germany, Norway, UK and USA and were put into context (cultural and economic) and pattern were developed. The database of collected models represent their national/agency building stock, that include energy systems specific to their representative climate conditions, and that have representative operation schedules. The next step will be to develop a common approach to calibration of building models to existing energy use data available from metering and sub metering.

Paper 1.3: Planning a low carbon urban area in Helsinki with dynamic energy simulations

SIREN, Santeri

Ramboll Finland Oy

Keywords: urban area, energy simulation, life cycle cost calculation, low carbon solution, energy system

The city of Helsinki has a target to reach carbon neutrality in year 2035.The measures for achieving this target include for example designing new kind of energy systems based on locally produced renewable energy and also the carbon emissions from centralized power plants must be reduced greatly.

The Malmi airport area is the most significant area for upcoming new construction in Helsinki. According to the city land use plan there will be 1.35 million square meters of new construction in that area during 2020s.

The means for achieving the energy and carbon efficiency targets in building energy use in the Malmi airport area were studied. A dynamic urban area energy system simulation was a major part of this study.

The objective was to create a dynamic simulation model of the energy system serving the buildings in Malmi area and use that model to compare different system types to help define the best solution for supporting the carbon neutrality targets. IDA ICE was used as the main simulation engine and other software's were also used to support the process.

The simulated systems consisted of combinations of different technologies such as district heating, local low temperature heat distribution networks, geothermal energy, waste water heat recovery, biogas boilers, deep boreholes (2000 m), district cooling, free cooling, photo voltaic, local CHP power plant, two-way heat trade system and others. Geothermal energy and deep boreholes were also studied as a centralized and decentralized version. Totally 284 different energy systems were simulated in the study.

Energy consumption, life cycle carbon emissions, Investment costs and life cycle costs, were calculated for all the different systems. All the data from the simulations were post possessed in and exported to Tableau, which was used to create an interactive visualization of the results. Visualizations were also transferred to a cloud based service to which the client was able to log in and view the results in an internet browser.

Results indicated that the carbon emissions generated from energy usage of buildings in Malmi area can be greatly reduced compared to the business as usual solution (district heating and district cooling). Also the life cycle costs for the best solutions were lower than in the business as usual scenario.

Paper 1.4: Integration of a high-temperature borehole thermal energy storage in a local heating grid for a neighborhood

JOKIEL, Michael [1]; ROHDE, Daniel [1]; KAUKO, Hanne [1]; WALNUM, Harald Taxt [2]

[1] SINTEF Energy Research, Norway; [2] SINTEF Community, Norway

Keywords: Borehole thermal energy storage, local heating grid, district heating, peak load reduction, excess heat

A new seasonal thermal energy storage will be built in a refurbished residential district in Oslo, Norway. The Furuset district in Oslo consists of 2800 apartments and will be expanded by around 2000 new apartments in the next years. The new heating demand for the whole neighborhood is estimated to be 26 GWh/year, with an anticipated maximum load of 10.1 MW. To partially meet this heating demand, excess heat from a local waste incineration plant will be used. During summer, when waste still needs to be burnt despite the lack of equivalent heating demand, the excess heat is stored in a high-temperature borehole thermal energy storage (HT-BTES). In winter, the stored thermal energy can be used as a heat source. A local heating grid connects the energy storage with a district heating network.

A Modelica model of the HT-BTES system has been created and calibrated using the results from a prestudy. The model was used in combination with aggregated measured heat demand profiles for Furuset to get preliminary evaluations on the efficient integration of a thermal energy storage in a local heating grid. The HT-BTES system performance is highly dependent on the amount of water that is pumped through the borehole park and therefore several possible control strategies and operation modes were taken into consideration.

Several cases were investigated where the use of the HT-BTES was limited to periods with peaked heating demand. Fluctuating seasonal district heating prices were considered to highlight the economical benefits when thermal energy storages are used during peak periods. The district heating price tends to be highest during peaked heat demand and it was shown that the utilization of stored heat during these periods provide great potential to reduce the import of expensive heat from the district heating network.

Paper 1.5: A novel modelling approach of ground source heat pump application for district heating and cooling, developed for a case study of an urban district in Finland

TODOROV, Oleg [1]; ALANNE, Kari [1]; VIRTANEN, Markku [1]; KOSONEN, Risto [1,2]

[1] Aalto University, Department of Mechanical Engineering, Finland; [2] Nanjing Tech University, Nanjing, China

Keywords: Ground-source heat pump (GSHP), district heating and cooling, ATES integration, mathematical and groundwater modeling, nonlinear optimization

The world impact of fossil fuels on air pollution is responsible for several millions premature deaths every year. The present study analyses the decarbonization of district heating (DH) and cooling (DC) networks by the integration of ground source heat pump (GSHP) within an urban district in south-western Finland, in terms of techno-economic feasibility, efficiency and environmental impact. A novel mathematical modelling for GSHP operation and energy system management is proposed and demonstrated, using hourly-based data for heating and cooling demand. Hydrogeological and geographic data from different Finnish data sources is retrieved in order to calibrate and validate a groundwater model. Three different scenarios for GSHP operation are investigated, limited by the maximum pumping flow rate of the groundwater area. The additional pre-cooling exchanger in scenario 2 and 3 resulted in an important advantage, since it increased the heating and cooling demand covered by GSHP by 15% and 16% respectively as well as decreased the energy production cost by 4%. Moreover, scenario 3 was solved as nonlinear optimization problem resulting in 4% lower pumping rate compared to scenario 2. Overall, the annually balanced GSHP management in terms of energy and pumping flows, resulted in low long-term environmental impact and is economically feasible (energy production cost below 30 €/MWh).

Paper 1.6*: Clustering and classification of building structures and their construction years with respect to monthly electricity consumption

HAN, Mengjie; RAZA, Mohsin; ZHANG, Xingxing; QUINTANA, Samer

School of Technology and Business Studies, Dalarna University, Sweden

Keywords: clustering, electricity consumption, principal component analysis

Urban planning and city energy management are interconnected to buildings, their construction materials structures and built years, as these parameters directly affect the energy demand. Data-driven approaches for classifying buildings according to their energy performance may help urban management to make sustainable decisions. The aim of this study is to adopt monthly electricity consumption of different buildings to extract those with similar features in terms of monthly electricity consumption. This study then examines different categories of building structures and their construction years for understanding the influence on their consumption patterns. Monthly electricity data for the year 2018 was collected from a locally owned housing company in Borlänge, Sweden. Based on the electricity consumption data, a dimension reduction is used before implementing clustering analysis. Buildings were categorized in three groups: high, medium and low electricity consumption. The results show that a multi-family house built in 1950s and 1970s are the most representative building structure consuming lowest electricity. On the other hand, apartment buildings built in the period of 1950s to 1970s are the most common buildings and could indicate high electricity consumption. However, the cluster with highest electricity consumption does not have sufficient observations and each individual feature needs to be examined by adding more variables in the future.

* **Extended abstract** for paper Paper 1.6 is available at the end of this book.

Paper 1.7*: Validation of Norwegian Residential Building Archetypes Based on Empirical Data and Numerical Simulations

ANDERSEN, Kamilla Heimar [1]; LIEN, Synne Krekling [1]; BOTTOLFSEN, Hanne Liland [1]; FAGERHEIM, Aksel Garvik [2]; SARTORI, Igor [1]

[1] SINTEF Community, Architectural Engineering, Norway; [2] Aalborg University, Civil Engineering Department, Denmark

Keywords: residential archetypes, energy use, validation, measurements, building performance simulations

Building performance simulations (BPS) are often used to describe the characteristics of building stock and to assess the potential benefits of building and renovating to different levels of building standards. Recently, increasing attention is devoted to peak loads and hourly energy use profiles, on top of annual performance figures. However, many previous studies have shown that a significant deviation exists between simulation results and actual performance of the real buildings, especially for low-energy ones, for both annual energy use and typical hourly profiles. Therefore, the validation and calibration of numerical models are essential to ensure meaningful predictability of estimated energy use and load profiles.

This study aims to validate a set of BPS models representing the Norwegian stock of apartment blocks, previously developed in the TABULA/EPISCOPE project, against a large dataset of measured buildings. The models consist of ca. 20 archetypes, each

representing a segment of the stock, and modeled with the building simulation software IDA ICE. The archetypes reflect a combination of different age groups and renovation levels. In particular, we investigate four archetypes corresponding to the national Norwegian building standards of the periods 1971-1980, 2001-2010, 2011-2020 and after 2020 (passive house standard), respectively. Measurement data are available for ca. 50 different sources (from a single building to large housing cooperatives), representing ca. 180 000 m² of heated floor area, from the years 2015 to 2018 in Trondheim and Oslo. To validate the archetypes, we compare the difference between the archetypes and the energy measurements in terms of annual energy performance, load duration curve and typical daily load profiles. The measurement data from the same age group, location and year are aggregated to minimize the variance due to different user behaviors. Typical daily load profiles are considered for the four different seasons, plus an additional period representing the coldest weeks in winter. The validation focuses on the heating demand, and special attention is devoted to assessing the archetype's ability to estimate the peak load and its timing during a day since this information is crucial for the impact that energy use in buildings have on the energy system and the flexibility they could provide.

*** Extended abstract** for paper Paper 1.7 is available at the end of this book.

Paper 1.8*: Numerical Simulation in Transient Conditions of a University Building with Complex Topology Equipped with Greenhouses in Winter Conditions

CONCEIÇÃO, Eusébio Z.E. (1); LÚCIO, Mª Manuela J.R. (1); AWBI, Hazim B. (2)

[1] University of Algarve, Portugal; [2] University of Reading

Keywords: Solar Radiation, Building Simulation, Greenhouse, Thermal Comfort, IAQ

In the present paper a numerical model, developed by the authors in the last years, which incorporate the building thermal behaviour, with complex topology, with the human thermal-physiology is applied. The building numerical model uses a multi-nodal equation system, developed through a virtual building with complex topology, using a Computational Aid Design, and resolved with a Runge–Kutta–Felberg method with error control. All coefficients are calculated using sub-models developed, also, by the authors.

In this numerical study, made in winter conditions, with transient conditions, a university building with complex topology, is used. The thermal comfort, using the PMV index, and the air quality, using the carbon dioxide concentration, are evaluated. The building, with 319 compartments and with four floors, are equipped with two warm internal greenhouses in each floor of three levels.

In accordance with the obtained results, the internal greenhouse contribute to increase the comfort levels.

*** Extended abstract** for paper Paper 1.8 is available at the end of this book.

Session 2: Airflows and Computational Fluid Dynamics (CFD)

Paper 2.1: Calculation of airflow rate with displacement ventilation in dynamic conditions

LASTOVETS, Natalia (1); KOSONEN, Risto (1,2); JOKISALO, Juha (1)

[1] Aalto University, Department of Mechanical Engineering, Espoo, Finland; [2] College of Urban Construction, Nanjing Tech University, Nanjing, China

Keywords: Displacement ventilation design, airflow rate, temperature gradient, dynamic model

Design of displacement ventilation (DV) is usually based on a heat balance method when overheating is the primary indoor climate concern. Various models for calculating airflow rate have been developed for several decades. Commonly used models are based only on steady-state models. However, in practical applications, the performance of DV depends on potentially dynamic parameters, such as strength, type and location of heat gains and changing heat gain schedule. Besides, thermal mass affects dynamically changing room air temperature. The study presents case studies of dynamic DV design in a few typical applications. The difference in the designed airflow rate was studied with various models in both dynamic and steady-state conditions. The presented dynamic DV model demonstrated a capability to take into account the combination of dynamic parameters in typical applications of DV. In the cases analysed, the airflow rate calculated with the dynamic model is significantly lower than the one calculated with the steady-state models.

Paper 2.2: POD-interpolation based prediction of indoor airflows

KLUFTØDEGÅRD, Mats; **CHAUDHURI, Arnab**

Oslo Metropolitan University, Norway

Keywords: CFD, POD, Interpolation, Indoor airflows, data-driven

Fundamentally, air flow, heat and mass transfer phenomena govern the indoor air quality, thermal comfort and energy usage in buildings. Air change rate, pollutant removal, heat removal, exposure and air distribution are the key features to assess the performance of a heating, ventilating and air-conditioning (HVAC) system. Ventilation systems can be classified into various types depending upon the concentration distribution, location of the air supply/exhaust device and the use of natural and mechanical forces (Cao et al. [1]). For several decades, a substantial scientific research focus has prevailed achieving design of energy efficient, effective airflow distribution and thermal comfort in buildings.

Apart from the advanced experimental measurements, computational fluid dynamics (CFD) is widely used as a reliable numerical tool to predict a wide range of ventilation problems with detailed spatiotemporal distributions of flow-field variables. In CFD, the governing non-linear coupled partial differential equations are solved with a suitable discretization and solution procedure. However, high-fidelity CFD-simulations for design and optimization is indeed costly both in terms of necessary computer resource and CPU time. In this regard, proper orthogonal decomposition (POD) based interpolation can be used, exploiting the CFD results with varying one or many parameters (e.g. relevant non-dimensional numbers involved in the governing phenomena) of interest to produce desired predictions in an efficient and cost effective manner. For example, considering a set of steady-state CFD solutions as “snapshots” the dominant POD coefficients/modal amplitudes and POD modes have to be estimated first. These intern can be used with a suitable interpolation of the coefficients to generate desired solution(s) for particular values of the parameter(s) of interest without performing costly CFD simulations.

This work aims to predict complex flow physics involved in indoor environments using CFD snapshots and POD-interpolation method. We made the validation of the implemented methodology related to a 2D mixed convection problem similar to that presented in Selimefendigil [2], involving a horizontal channel with cavity heated from below for a range of Richardson and Reynolds numbers. A cubic spline interpolation of the POD coefficients is used to compute the solution. A preliminary CFD solution of indoor airflow with thermal stratification is performed. Detailed flow-analysis and POD-interpolated predictions will be presented in the final manuscript.

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Paper 2.3: Analysis of the interfacial mixing in the gravity-driven counterflow through a large vertical opening using Large Eddy Simulation

LARKERMANI, Elyas ✉; GEORGES, Laurent

Norwegian University of Science and Technology, NTNU

Keywords: Computational Fluid Dynamics, Large Eddy Simulation, Large Vertical Opening, Open Doorway, Natural Convection, Bulk Flow Regime, Interfacial Mixing, Indoor Airflow

The study of natural convection flows in multi-zone enclosures is a topic of great importance due to its direct influence on room air circulation patterns, distribution of indoor air contaminants, and thermal comfort inside buildings. The flow in a large vertical opening is intrinsically more complex than forced convection flows. It may be driven by density differences, wind, occupant motion, or door motion. In the past, many researches on the natural convection flow through a large vertical opening between two enclosures have been done. However, they paid less attention to the unsteady flow structures generated by the sophisticated bidirectional flow, especially in the middle of the doorway. In past investigations, Computational Fluid Dynamics (CFD) simulations of this flow have been performed, but mostly using RANS, and/or two-dimensional assumption, and/or what can be considered today as very coarse grids. This made the unsteady flow structures impossible to capture. From the experimental side, several past studies reported on the flows in differently heated enclosures with a partition wall. While these studies analyzed the flow inside these enclosures, the flow within the doorway itself was measured for a limited number of locations. In conclusion, the CFD standards of today enable to better investigate the unsteady nature of the bidirectional flow inside the vertical opening.

In this research, the ANSYS Fluent is used to investigate the density-driven bidirectional flow through a large vertical opening connecting two isothermal reservoirs (with different air temperatures), the so-called bulk flow regime. The boundary conditions and the enclosure geometries have been designed in order to be as close as possible to isothermal reservoirs without leading to a prohibitive computational time. The geometry of a door (2m×1m) is considered with a temperature difference of 5°C on both sides. CFD results are obtained using a fine structured mesh at the level of the doorway. The flow is assumed incompressible and buoyancy effects integrated using the Boussinesq approximation. The simulation is unsteady and turbulence is modelling using Large Eddy Simulation (LES). Simulation results show the development of unsteady flow structures in the middle of the doorway, a phenomenon called "interfacial mixing". This phenomenon has been hardly documented in the literature and only using experiments.

Paper 2.4: Simulation study on the influence of urban street intersection greening on ventilation performance

GUO, Xin ✉; GAO, Zhi

School of Architecture and Urban Planning, Nanjing University

Keywords: Urban intersection, ventilation, greening form, numerical simulation

The purpose of this study is to explore the impact of greening forms on street intersections on ventilation performance. Starting from common greening forms, the study focuses on road intersections surrounded by surrounding buildings. By simplifying the shape of the intersection, an ideal city is established. Models of street intersections and numerical simulation software FLUENT was used to simulate airflow and pollutant distribution in the area. Based on the simulation results of the wind speed and pollutant distribution at the pedestrian height, find out the internal flow field and pollutant diffusion law at the street intersection, and use the ventilation index to compare the greening arrangement on the street with the intersection, especially the pedestrian activity at the bottom Ventilation effects of the space. This paper first analyzes the influence of single vegetation type greening on the ventilation performance of the intersection and then analyzes the influence of structural greening on the street intersection. The wind direction is 0 ° and 45 °. The first step is to analyze the effects of shrubs and trees on the velocity of the flow field and the concentration of pollutants by analyzing the velocity clouds and pollutant clouds on three height sections (0.5m, 1.5m, and 5m). Analyze and compare the changes in the average speed, average concentration, and maximum concentration in the intersection area at the vertical height, and study the situation where streets in different directions in the intersection with greenery are affected by different wind directions. The second step is to study the influence degree of different greening forms on different types of intersections from the common greening forms of Arbor and shrub combination. After analyzing the impact of common greening forms on the intersection, the degree of influence of the greening form on each intersection was evaluated through ventilation indicators. The general influence of plant layout on ventilation was obtained through research, and design methods and strategies for improving the air quality environment at street intersections were obtained.

Paper 2.5: CFD Simulation Delivered as SaaS for Building and HVAC Design Testing

WILDE, Jon

SimScale GmbH, Germany

Keywords: simulation, HVAC, energy efficiency, thermal comfort, SaaS

With increasingly high demands for indoor air quality, thermal comfort, and energy efficiency, engineers and architects have an increasing amount of factors to account for in the building design process. Furthermore, in complying with industry standards—such as ASHRAE 55, ISO 7730, EN 16798-1:2019, and more—all of these areas need to be assessed long before the construction phase is started.

Facilitated by the emergence of cloud computing, computer-aided engineering (CAE) technology is now being delivered by different providers as software as a service (SaaS) solutions, which increases its accessibility and ease of use. Online CAE or engineering simulation has become part of the design testing process, as engineers virtually test the indoor climate, measure air quality, ensure thermal comfort, and assess energy efficiency in industrial, residential, and commercial buildings.

This paper illustrates how a particular type of simulation, computational fluid dynamics (CFD), can be used to investigate the complex airflow patterns under different scenarios—by testing different air supply outlets, their placement or number, and evaluating the temperature gradients, air distribution or velocity plots—in order to achieve healthy indoor environment conditions. The research assesses the capabilities of CFD simulations for preliminary design and testing of traditional, as well as innovative designs, crucial for the advancement of sustainable ventilation systems and high-performance buildings.

The investigation is supported by case study examples of CFD simulations of different indoor spaces—including a data center and an office, located in different climates (Europe and Middle East)—for which several iterations of HVAC system designs were tested with the goal of achieving superior efficiency results.

Paper 2.6: Application of Coupling of CFD and Human and Clothing Thermal Response in Ceiling Mounted Localized Air Distribution Systems in Winter Conditions

CONCEIÇÃO, Eusébio Z.E. (1); CONCEIÇÃO, Mª Inês L. (2); LÚCIO, Mª Manuela J.R. (1); AWBI, Hazim B. (3)

[1] University of Algarve, Portugal; [2] Instituto Superior Técnico, University of Lisbon, Portugal; [3] School of Construction Management & Engineering, University of Reading, Reading, RG6, 6AW, United Kingdom

Keywords: Building Simulation, CFD, Thermal Comfort, IAQ

This work presents and applies a numerical model, developed by the authors in the last years, that considers the coupling of the CFD (Computational Fluids Dynamics) and HCTS (Human and Clothing Thermal System). The coupling system, itself, generates the occupation presence and transfers the inputs/output between the CFD and HCTS numerical models.

The input of the compartment, using the Computational Aid Design, the location of the occupants and the external environmental variables are introduced in the software, while the occupant geometry is generated by empirical equations, based in height and weight.

The study is made in a virtual chamber occupied by twelve virtual manikins, six desks and twelve seats and equipped with a new ceiling mounted localized air distribution systems. The ventilated system is equipped with an inlet system built with two horizontal ducts and an extraction system, built with six ducts. The inlet horizontal ducts consider twelve jets located above the head and in front to the occupant level and twelve jets located above desk area.

In the present study thermal comfort level, the air quality level and the ADI (Air Distribution Index) are calculated, for an inlet air velocity of 1, 3 and 5 m/s, in winter conditions. In accordance with the obtained results the ADI index is highest for highest inlet air velocity.

Session 3: Energy Flexibility, Control and Energy Storage

Paper 3.1: A coordinated control to improve energy performance for a building cluster with energy storage, EVs, and energy sharing

HUANG, Pei ; ZHANG, Xingxing ; BALES, Chris; PERSSON, Tomas

Department of Energy and Built Environment, Dalarna University, Falun, 79188, Sweden

Keywords: PV, electric vehicle, energy sharing, building cluster, control

Many countries and associations have established laws or targets to promote the deployment of renewable energy. For instance, the E.U. set a target of 32% of energy coming from renewables by 2030. In response to such renewable energy target, distributed renewable energy systems are now widely installed in many buildings, forming the new type of buildings known as 'electricity prosumers'. Existing studies have developed some advanced controls for energy storage system charging/discharging in a building cluster (enabling renewable energy sharing among different buildings), which can effectively improve the aggregated performances of the building cluster. However, in the existing controls, the flexible demand shifting ability of electric vehicles (EVs) are rarely considered, leading to limited performance improvements at building cluster level. For instance, in practice the EV charging will start once they are plugged into charging stations. However, in such charging period the renewable generation may be insufficient to cover the EV charging load, leading to grid electricity imports. On the other hand, when there is surplus renewable generation, the EVs cannot be used as electricity storage if they have already been fully charged, leading to the surplus renewable energy exports. As a result, the overall building-cluster-level performance is not optimized.

Therefore, this study proposes a coordinated control of building cluster with both energy sharing and the EV charging considered, with the purpose of improving the cluster-level performance by taking advantage of energy sharing and storage capability of electricity batteries in both buildings and EVs. An EV charging/discharging model is first developed. Then, a coordinated control is developed for building cluster with the energy storage, EVs and energy sharing considered. Based on the predicted future 24h electricity demand and renewable generation data, the coordinated control first considers the whole building cluster as one 'integrated' building and optimizes its operation as well as the EV charging/discharging using genetic algorithm. Then, the operation of individual buildings in the future 24h is coordinated using nonlinear programming. For validation purpose, the developed control has been tested using the energy demand and supply data on a real buildings cluster (with three EVs considered) in Ludvika, Sweden. The study results show that the developed coordinated control can increase the cluster-level daily renewable self-consumption rate by 40% and meanwhile reduce the daily electricity bills (due to grid power purchase) of the building cluster by as much as 20% under the same fixed electricity price compared with conventional controls.

Paper 3.2: Virtual testbed of the KTH Live-In Lab: development and validation

MOLINARI, Marco ; ROLANDO, Davide

KTH, Royal Institute of Technology, Sweden

Keywords: Building ICT, Smart Building, NZEB, virtual testbed, Building automation

In the last decade, the development of Information and Communication Technology (ICT) has enabled unprecedented possibilities to tackle worldwide ambitious sustainability targets. Digitalization plays a pivotal role in fostering energy efficiency to meet the increasing demand of more sustainable buildings.

Demonstration facilities are fundamental for the adoption of ICT solutions for energy efficiency and sustainability in buildings. KTH Live-In Lab infrastructure is a platform of testbeds designed to promote research and innovation in real case scenarios. The testbeds include residential and non-residential buildings instrumented with state-of-the-art monitoring capabilities, including high-resolution sensor networks for indoor environmental parameters and energy flows. The main residential facility within KTH Live-In Lab is a new building designed to be a NZEB (Nearly Zero Energy Building) equipped with ground source heat pumps, local renewable capabilities (solar PV system) and Thermally Activated Building Systems (TABS). Data collected will be used to systematically assess the energy performance and the indoor comfort of the building and to showcase cost-effective solutions for monitoring, control and fault detection.

In parallel to real demonstrators, virtual building testbeds, acting as digital-twins, facilitates a cost effective development, test and implementation of advanced control and fault detection strategies.

In this paper, the development and validation of a virtual testbed are described. First the indoor environmental quality and energy flows in the KTH Live-In Lab residential testbed is investigated. Subsequently, the creation process of a virtual testbed is described. The virtual testbed consists in a simulation model of the KTH Live-In LAB developed in IDA-ICE. The paper includes the description of the validation process against the complex sensor network of measured data. The results of this

paper will be instrumental to the improvement of control systems and it will facilitate the study of behavioral aspects of the energy use.

Paper 3.3: Influence of space heating distribution systems on the energy flexibility of Norwegian residential buildings

NICKL, Christoph [1,2]; **CLAUß, John** [2,3]; GEORGES, Laurent [2]

[1] Team für Technik GmbH, Munich, Germany; [2] Norwegian University of Science and Technology, Norway; [3] SINTEF Community, Norway

Keywords: Energy flexibility, Heat pump system, Heat distribution system, Zero emission building

This study aims at evaluating the influence of the heating distribution system on the energy flexibility of residential buildings. Detailed building performance simulations of a zero-emission residential building were performed using the software IDA ICE Version 4.7.1. Three different heat-distribution systems, (1) air heating, (2) water-based radiators, and (3) floor heating, were investigated. The building energy system consists in each case of a heat pump, a domestic hot water and space heating tank, as well as solar thermal collectors and photovoltaic panels.

To evaluate the influence of the space heating distribution system on the energy flexibility of residential buildings, detailed dynamic simulations were carried out. Firstly, the ventilation system was designed according to plans of the case building, the living laboratory in Trondheim, and the current building regulation. Secondly, a heat load simulation was carried out for the design outdoor temperature and the calculated airflow rates. The results were then used to size the heat generation system (heat pump and tanks) as well as the three heat distribution systems. For each of the heat distribution systems simulation models were created.

The behaviour of the different systems was assessed for a rule-based control using a schedule to shift electricity to off-peak hours as well as using a price-based signal which uses data from the day-head spot market. The controls affect firstly the heating set point in the rooms and are then extended to the space heating and domestic hot water tank. Results are evaluated based on the key performance indicators energy use, operational costs, self-consumption and load shifting.

For the radiator system the energy use during peak hours was decreased up to 20%. For the floor heating system, the energy use during peak hours did not decrease or even increased. The air heating cases showed little to no shifting potential. The total energy use and operational costs increased in each case, most pronounced with the schedule-based set point variations for hot water and space heating tank. It was found that the building was not suitable for air heating. The heat loss through the building envelope can be considered too high. The ventilation rates had to be increased significantly (up to 0.9 ACH) in times of cold outdoor temperatures to ensure thermal comfort.

Paper 3.4: Model predictive control of District Heating substations for flexible heating of buildings

WALNUM, Harald Taxt; SARTORI, Igor; BAGLE, Marius

SINTEF Community, Norway

Keywords: Control of hydronic heating systems, District Heating, MPC

District heating can exploit several sources of energy, thus serving as a source of flexibility for the electric grid. Heat supply usually consists of several production units, from base to peak load units, with different sources and operational costs; their operation is prioritized in order to minimize the total system cost. Heat demand is mainly dependent on outdoor temperature, although factors related to user behaviour also influence the demand. To minimize the total production cost it is usually desirable to minimize the peaks in demand. Several studies have shown that utilisation of the building thermal inertia has a large potential for peak reduction.

A common way of controlling buildings with district heating is through an outdoor temperature compensation curve, that decreases the supply temperature to the radiators as the outdoor temperature gets milder than the design conditions. This is called weather compensated control (WCC). In many buildings, especially older ones, the radiators are only equipped with manually adjustable valves, so that WCC is the only automated control for the heat supply and works as a feed-forward controller. Thus, the indoor temperatures fluctuate somewhat in the various rooms, given that occupants only marginally adjust the radiator valves. In other words, WCC relies on the users' tolerance, presuming – without feedback knowledge – that indoor temperatures fluctuate within a limited and still comfortable range. Such buildings present an opportunity for simple and cost-efficient introduction of model predictive controls (MPC) of the heating system, with the potential to both improve indoor climate and reduce peak loads.

In this work we demonstrate how such MPC applications could work. The demonstration will be performed in a co-simulation framework utilizing the Functional Mock-up Interface (FMI) standard; where a building and its district heating substation are modelled in Modelica and used as the emulator, while the MPC algorithm is programmed in python. Based on weather forecast

and indoor temperatures feedback from the emulated building, the algorithm optimizes the heat demand. The heat demand is then translated into a corresponding radiator supply temperature that is sent to the substation emulator as a control signal, thus realizing a closed loop predictive controller.

The results will be a comparison between the WCC and MPC controllers and show how the MPC controller can respond to different objective functions, such as minimizing peak loads, energy consumption or energy cost, given a variable price from the district heating system.

Paper 3.5: Analyses of thermal storage capacity and smart grid flexibility in Danish single-family houses

WITTCHEN, Kim B. [(1)]; JENSEN, Ole Michael [(1)]; REAL, Jaume Palmer [(2)]; MADSEN, Henrik [(2)]

[1] Aalborg University, Denmark; [2] Dept of Appl. Math. and Comp. Sci., Danish Technical University (DTU), Lyngby, Denmark

Keywords: energy flexibility, thermal storage

Six archetype models of Danish single-family houses, representing most of the Danish housing stock of this type, have been set up to analyse the potential energy flexibility if heat pumps heated these houses. The archetypes represents differences in building tradition and historical changes in energy requirements in shifting Danish Building regulations, covering the following age categories:

1850-1930, 1931-1950, 1951-1960, 1961-1972, 1973-1978 and 1979-1998

The reasoning for not having houses older than 1850 is that these houses are normally poorly insulated, leaky and represent a very small share of the total housing stock. In the other end of the age scale, houses constructed after 1998 have been excluded as these houses are normally made of light constructions (little thermal energy storage possibility) and are highly insulated and airtight. They do thus not offer a large absolute amount of energy storage.

Analyses showed that up to 99% of the energy demand for space heating within peak hours can be moved to outside peak hours, without compromising the indoor climate.

Analyses carried out assumed that the peak hours are fixed in time to two hours in the morning (breakfast peak) and three hours in the evening (cooking peak) and indoor temperatures were controlled to reduce energy demand for space heating during these peak-hours.

The next step will step will be inclusion of a model predictive control in the dynamic simulation tool used for the analyses. The model predictive control will enable control of the houses heating systems and indoor climate based on the availability of wind- and/or solar-power in the grid.

Controlling houses or buildings in this way will make it possible to have a better utilization of varying renewable energy sources in future energy grids.

The paper describes the simulation approach and the results for different archetype houses as well as upscaling to nation-wide energy flexibility potential.

Paper 3.6: Insight on a local energy community: Agent based model of a peer to peer (P2P) interaction for a group of prosumers

LOVATI, Marco; OLSMATS, Carl; ZHANG, Xingxing

Dalarna University, Sweden

Keywords: energy community, high renewables penetration, techno-economic modelling, agent based modelling, low carbon systems.

Photovoltaic (PV) technology has became a cheap and abundant source of electricity that can be produced locally where it is consumed. One of the major drawbacks of the use of PV is its intermittency due to day night cycle: a huge body of research and attention goes to the electric storage technologies as it is a perceived bottleneck to the installation of large quantities of PV. It is easy to forget that even in countries that have been upbeat for many years on PV (i.e. Germany and Italy), the PV fraction of the energy mix still stops short of 10% of the energy mix. Numerous studies have shown that without storage the economic hosting capacity of the energy mix would easily go beyond 20%. The PV market for household electricity is still based on a single pro-sumer household paradigm and, as such paradigm cannot be profitable with high capacities, heavily reliant on public incentives (i.e. tax cuts or Net-metering for the over-production). In this study a different approach is offered: a high penetration scenario (> 20% of the mix) without necessity of use of storage technology can be achieved while generating revenues in an unincentivized self-consumption oriented framework. The result can be achieved by locally balancing production and demand to guarantee grid stability, it is demonstrated by means of an agent-based model of a community of prosumers. The focus is on the techno-economic framework of the electricity exchange between the different agents interacting within the grid.

Session 4: Building Envelope, Daylighting and Thermal Design

Paper 4.1: Experimental and numerical studies on thermal performance of an office cubicle having gypsum boards coated with PCM-enhanced spackling

VIK, Tor Arvid (1) ; MADESSA, Habtamu Bayera (1) ; CHAUDHURI, Arnab (1) ; AAMODT, Andreas (1); PHENGPHAN, Chakkrit (1); TWUMASI AFRIYIE, Ebenezer (2)

[1] Dept. of Civil Eng. & Energy Tech., OsloMet, Norway; [2] Saint-Gobain Sweden AB, Bålsta, Sweden

Keywords: PCM, passive cooling, thermal comfort, office cubicle

The building industry has gained worldwide attention towards improvement of energy efficiency and innovation during the recent years. In this perspective, improvement of energy performance and reduction of carbon emission of buildings requires strategic development of smart building materials. Incorporation of phase change materials (PCMs) in building elements essentially increases the thermal mass when used in latent thermal energy storage systems and thermal management systems. PCMs are used in construction materials e.g. HVAC systems, passive heating/cooling systems, floors, ceilings, roofs, concrete, drywalls, coating plaster, blends etc. Among these, PCM enhanced wallboards on internal surfaces of building spaces can be an attractive solution.

In this work a novel spackling compound used as a primer coating material will be investigated for passive cooling and thermal comfort management. The spackling compound contains heavy fillers, lightweight fillers, rheological additives and binding agents together with micro-encapsulated PCM. To the best of our knowledge, there is no literature about the micro-encapsulated PCM enhanced spackling material and its usage for thermal management in building applications.

The study is based on experimental work of an office cubicle having 15 m2 floor area. PCM enhanced spackling has been applied on the internal walls and ceiling surface (about 2-3 mm thickness). Indoor air temperature in the occupied zone as well as the surface temperatures in the room were recorded. The room was investigated with and without PCM enhanced spackling on the wall and ceiling surfaces.

The preliminary result shows that a significant cooling effect could be achieved when covering walls and ceiling with PCM enhanced spackling directly exposed to the occupied zone. The PCM could therefore, to a certain extent, reduce the need of mechanical cooling and thus save costs for installation, energy use and maintenance.

Paper 4.2: Visualizing user perception of daylighting: a comparison between VR and reality

HEGAZY, Muhammad (1) ; ICHIRIYAMA, Ken (1); YASUFUKU, Kensuke (2); ABE, Hirokazu (2)

[1] Graduate School of Engineering, Osaka University, Japan; [2] Cybermedia Center, Osaka University, Japan

Keywords: immersive virtual environment, daylighting; game engine, human perception, building performance

Daylighting is a core element of building design, where it has an extensive role in shaping both building performance and aesthetics. Although the advancements in lighting research and the emergence of Building Performance Simulation (BPS) have introduced various accurate and validated metrics of daylight performance considering user comfort, an adequate establishment of the correlation between these indicators and occupants' actual daylight perception and preferences still lacks. Virtual reality (VR) has been utilized in numerous studies to investigate various subjective aspects of daylighting within a human centric approach. However, they have shown limitations regarding built model complexity, environment customization, and feedback methodology. While utilizing game engines can overcome those limitations, due to their ability to transit game-principles into research applications for a more interactive and rich user experience inside VR, a significant barrier in the acceptance of game engines as a light simulation tool is the lack of validation studies on their accuracy in representing luminous values compared to real life scenarios.

This study introduces an exploratory method using game-engine real time rendering, and VR headset to investigate human perception of daylight in an interactive and immersive way. The proposed method produces highly realistic, physically-based renderings in real time that users can explore and walkthrough freely and report their perception on daylight quality using ranked snapshots. A perceptual light heat maps (PLM) are generated based on user feedback inside VR and validated through comparison of resultant heat maps in an identical real environment. This approach has a potential to overcome some of the challenges facing current light simulation tools, regarding rendering speed and interactivity, as well as visualizing daylight perception into a more readable format. It also opens the door for more validation studies to game-engines light simulation accuracy and its adoption as an established light simulation tool.

Paper 4.3: The Potential of the Multi-Angled Facade System in Improving Natural Ventilation

HANNOUDI, Loay; SALEEB, Noha

Middlesex University, London, United Kingdom

Keywords: Indoor climate, Natural ventilation, overheating hours, facade orientation, air draught

The research study focuses on the potentials of Multi-Angled facade system in improving natural ventilation inside the office room leading to a better indoor climate for the employees inside it. The design concept of Multi-Angled facade is a three-dimensional façade that is extended outward somewhere in the middle and connected from the sides to the original building flat façade. There are two different orientations of windows in each Multi-Angled facade: a larger window on one of the two parts oriented more to the north to optimize the use of daylight, and a smaller window on the second part oriented more to the south to optimize the solar radiation penetrating through the façades. This is combined with using appropriate window properties and the solar shading control system. The principle of natural ventilation inside the office rooms is one side ventilation depending on the area and the orientation of the openings. The design of the intake and the outtake areas is achieved through a sequence of calculations depending on the formulas from By og Byg Anvisning 202 (Natural ventilation in commercial buildings. 1st edition). The criteria that are used in this building depend on EN 15251 and CEN CR 1752. The calculations of the number of overheating hours (max 100 h above 26°C, and 25 h above 27°C per year) in addition to the RH and CO2 evaluations are made by the program IDA ICE. The simulation of airflow through the office room in addition to the room air temperature and the air velocity is achieved by the program CFD (Computational Fluid Dynamic). The two oriented facade parts will help to have better air penetration through the facade compared to a flat facade leading to a better air exchange inside the office room. In addition to that, the draught problems in the Multi-Angled facade are less compared to a flat facade which has its impact on the comfort of the employees inside the office room.

Paper 4.4: Adapting to future climate change by integration of Phase Change Materials (PCMs) into the building envelope: a case study in Stockholm, Sweden

COPERTARO, Benedetta [(1)]; SHEN, Jingchun [(1)]; SANGELANTONI, Lorenzo [(2)]; HUANG, Pei [(1)]; ZHANG, Xingxing [(1)]

[1] Department of Energy and Built Environments, Dalarna University, Falun, Sweden; [2] CETEMPS, Center of Excellence, Department of Physical and Chemical Sciences, University of L'Aquila, Italy

Keywords: PCM in building envelopes; Future climate scenarios; PCM optimization

Climate change is considered as one of the biggest threats that humankind is facing nowadays, with environmental, social and economic consequences. In itself, the building sector is facing multiple climate change impacts, becoming more and more vulnerable. By this way, as the replacement of new buildings in Europe is low and the lifetime of buildings is estimated to be in a range of 50-100 years, it is expected that much of the existing building stock will be affected by several climate change impacts in near future. Specifically, from the building point of view, these impacts can range from a slight rise in the average environmental temperature and humidity levels to extreme and severe events (such as strong wind and floods), changing in most cases, the building performance and thermal behavior. Among the adaptation strategies to climate change, the envelope optimization, whichever climate type, is the most effective way to reduce the building dependency from heating and cooling energy while maintaining the proper indoor thermal comfort. In this regard, the integration of Phase Change Materials into the building envelope can produce a sort of extra thermal capacity to the building, enhancing its overall energy efficiency. Specifically, when PCM is used without any control systems, it means that they are passively contributing to the building thermal comfort, stabilizing the indoor temperature and reducing both cooling and heating demands. In this regard, considering that the effectiveness of PCM application over the building envelope is mostly associated with the selection of the appropriate melting temperature and thickness, in the context of climate change, it is expected that the optimal PCM melting point and amount for the present period, will not be optimal for future period and vice versa. Therefore, in the present study dynamic thermal simulations by using IDA ICE software were performed in order to evaluate the passive effect, under future climate scenario, of PCM used to fully refurbish a single zone house in a typical Nordic city, Stockholm. Moreover, a parametric study aimed at defining, for each future climate scenario, the optimum PCM melting temperature and amount has been carried out. The aim is to show that the use of an "optimized PCM" can lead to a reduction of the heating demand and to an increase of the building thermal comfort not only in the present period but also in the future in one, becoming a good adaptation strategy towards climate change.

Paper 4.5: The Effect of Local Climate Data and Climate Change Scenarios on the Thermal Design of Office Buildings in Denmark

PETERSEN, Steffen

Associate professor, Aarhus Universitet, Denmark

Keywords: Thermal simulation, Weather data, Climate change

Building thermal simulation is a powerful tool to predict the annual thermal performance of buildings in the design stage. For this purpose, it is common to use national or regional standardized hourly weather data sets such as Test Reference Years (TRYs), Design Reference Years (DRYs), Typical Meteorological Years (TMY or TMY2), weather year for energy calculations (WYEC), etc. The common approach for establishing these weather data files is to identify so-called 'typical' weather either a full year from a multi-year real weather data set (CIBSE example weather year method) or by constructing an artificial year consisting of 12 individual months selected from the months of a multi-year real weather data set using one of the several methods described in existing literature. However, recent studies have suggested that simulation for decision-making in building design should be based on weather data sets representing typical and extreme future climate generated by climate models and weather generators so that design decisions makes the building more robust towards future environmental changes.

This study presents the results of a Sobol' sensitivity analysis a range of design variables defining a thermal model of a typical office building in Denmark. The analysis is conducted using the Danish Design Reference Year, which currently is considered the mandatory weather data file for documenting fulfilment of energy and indoor climate requirements during the building design phase. Design variables are ranked with respect to their impact on the variance of the output. The analysis is repeated using weather data sets representing typical and extreme future climate generated by a climate model and a weather generator. The outcome of the two sensitivity analyses is then compared to assess whether there is a shift in the ranking of the design variables. Furthermore, the simulated energy performance of the two analyses are compared. Based on these results, it is discussed whether the Danish building industry should change their current thermal simulation practice.

Paper 4.6*: Definitions of Floor Area and Evaluating Impacts in Energy Simulation

ALLEN-SANDOZ, Nicholas Frederick

Karpman Consulting, United States of America

The modeled conditioned floor area must be the same for the baseline and proposed design, and aligned design documents. Deviations between modeled area and area specified in design documents commonly occur. Narratives are commonly provided to explain the difference. Gross floor area reported in design documents is based on the definition in the 2015 International Building Code (IBC), which differs from the ASHRAE 90.1 definition. Section 11 and Appendix G of 90.1 do not explicitly specify how building area should be inputted into the model.

FLOOR AREA, GROSS (IBC). The floor area within the inside perimeter of the exterior walls of the building under consideration; exclusive of vent shafts and courts, without deductions for corridors, stairways, ramps, closets, the thickness of interior walls, columns or other features. The floor area of a building, or portion thereof, not provided with surrounding exterior walls shall be the usable area under the horizontal projection of the roof of floor above. The gross floor area shall not include shafts with no openings or interior courts.

Conditioned floor area (90.1): see floor areafloor area, gross: sum of the floor areas of the spaces within the building, including basements, mezzanine and intermediate-floored tiers, and penthouses with a headroom height of 7.5 ft or greater. It is measured from the exterior faces of walls or from the centerline of walls separating buildings, but excluding covered walkways, open roofed-over areas, porches and similar spaces, pipe trenches, exterior terraces or steps, chimneys, roof overhangs, and similar features.

Interpretations of floor area definitions can lead to inaccurate performance and challenges with calibration. Interpretations of modeled conditioned floor area can affect the envelope and HVAC performance of both the baseline and proposed models as well as the baseline's window-to-wall ratio and skylight-to-roof ratio allowances. Interpretations of the lighted area affect the baseline interior lighting power density allowance. The table below represents the configurations of floor area definitions used to evaluate the change in performance. The prototype building shall be an academic building containing classrooms, office and labs in Climate Zone 5A. Energy simulations are done in eQUEST software for ease of use and speed of simulations.

* **Extended abstract** for paper Paper 4.6 is available at the end of this book.

Paper 4.7*: A parametric tool for combined overheating and daylighting assessments

GKOUVELOU, Eleni ✉; MOSKOVELI, Dimitra; KHANIE, Mandana Sarey

Technical University of Denmark, Denmark

Keywords: parametric design, grasshopper 3D, overheating, daylighting, facade

With energy efficient strategies focusing on reduction of the heat losses, indoor daylight has been compromised, downgrading the health and comfort needs of their occupants. The paper presents a Grasshopper 3D tool for simultaneous assessment of overheating and daylighting. A parametric analysis of two reference offices in Danish context using the developed tool is presented. The results indicate the challenge of adequate daylight in deep offices and the problem of overheating in shallow ones. Large glazing areas are preferable in deep offices in orientations with low solar radiation, choosing the right window types. Additionally, wider and higher-placed windows benefit daylight access.

* **Extended abstract** for paper Paper 4.7 is available at the end of this book.

Session 5: Heat Pumps and Air-Conditioning Systems

Paper 5.1: Simulation and parametric study of a building integrated transpired solar collector heat pump system for a multifamily building cluster in Sweden

SAINI, Puneet [1,2]; FIEDLER, Frank [1]; PSIMOPOULOS, Emmanouil [1,2]; COPERTARO, Benedetta [1]; WIDÉN, Joakim [2]; ZHANG, Xingxing [1]

[1] Department of Energy and Built Environment, Dalarna University, Sweden; [2] Department of Engineering Sciences, Civil Engineering and Built environment, Uppsala University, Sweden

Keywords: BIPVT, Building Cluster, TRNSYS, Optimization, Sensitivity Analysis

Solar integrated building envelopes represent a significant energy harvesting potential in an era of decentralized building energy systems. This paper aims to simulate an energy system that consists of a transpired air solar collector component for a multifamily building cluster in Sweden. The energy system consists of an unglazed transpired solar collector in conjunction with air ventilation unit and exhaust air heat pump. The hot air from the solar collectors is used to increase the brine temperature at heat pump evaporator inlet to improve its coefficient of performance. The exhaust air heat pump is used to meet space heating and hot water demand for the buildings. The energy system is modelled using TRNSYS simulation program. The associated controls of the energy systems are optimized to increase the seasonal performance factor of the complete system while maintaining the optimal performance of various subsystems. The quantification of the energetic benefits obtained from the proposed energy system is also presented using various key performance indicators. Furthermore, sensitivity analysis of different collector areas and operating variables such as airflow rate of the the collector is conducted. The results show that the seasonal performance of the simulated energy system is 1.43 and the annual collector utilization factor is 0.18. Furthermore, the variation of the collector airflow rate has a positive impact on system performance, with an increase of 2 % in the annual heat pump coefficient of performance.

Paper 5.2: Impact of AC Outdoor Unit Placement on Energy Efficiency

PATEL, Krishna [1]; RAWAL, Rajan [2]

[1] Faculty of Technology, CEPT University, Ahmedabad, India; [2] Centre for Advanced Research in Building Science and Energy, CEPT University, Ahmedabad, India

Keywords: Split Air-Conditioners, CFD, Outdoor unit, Energy Efficiency

India's share in total global primary energy demand is expected to increase from 6% to 11% by 2040. Easy access to electricity and increased prosperity further increases the use of Air Conditioners. Per capita energy use from Room Air Conditioners (RAC) is expected to rise from 72 kWh to 1,140 kWh by 2050. Constant efforts are made to increase the system efficiency of the Air Conditioners. Though, not much care has been taken in the installation practices.

In densely populated areas, the Outdoor Air Conditioner units are stacked very close to each other. These outdoor units dissipate heat in the outdoor environment that increases the ambient temperature around the outdoor unit. Density difference causes upward movement of warm air. As a result, temperature around the topmost unit will be very high compared to the bottom units. The heat rejection capacity of the refrigerant will decrease due to hotter ambient temperatures. Thus, overall efficiency of the Air conditioners go down, eventually increasing the energy consumption of the building.

The measurement and experimentation will be done in Ahmedabad which has Hot and Dry Climate. A six floor building will be taken into consideration. The outdoor units are stacked one above the other at the distance of 3m.

The efficiency of each Air Conditioners will be calculated. Power Factor (PF), electric current (Amp), voltage (V) and electric power consumed (W) will measured at a time interval of 1 minute. Enthalpy difference method will be used to calculate the cooling loads. Energy Efficiency Ratio (Ratio of Watts of Cooling Load to watts of Electricity Consumed) of the system will be calculated as per Equation to determine the efficiency of Air Conditioners. The field study was conducted at six sites having total 30 RAC units over 15 days.

Air movement and temperature variation were studied from CFD analysis done using scStream software. Numerical CFD model was generated using on-field observations. The stacking of outdoor units was optimized which helped the ACs to run at maximum efficiency, reducing the Building energy consumption due to space cooling.

The results could help quantify the impact of hot air plume on operation efficiency of RACs. Guidelines will be prepared to help RAC installers to avoid negative installations impacts.

Paper 5.3: Energy performance of ground-source heat pump and photovoltaic/thermal (PV/T) in retrofitted and new buildings: Two case studies using simulation and on-site measurements

HESARAKI, Arefeh; MADANI LARIJANI, Hatef

KTH Royal Institute of Technology, Sweden

Keywords: Ground-source heat pump, Photovoltaic/thermal (PV/T), IDA ICE, Energy savings

The Sweden national goal is to have 50% more efficient energy use by 2030 compared with 2005, to have 100% renewable electricity production by 2040 and to achieve zero net greenhouse gas emissions by 2045. This paper aims to contribute by presenting calculated and measured energy use in two case studies single-family house during the heating season of 2019-2020 in Stockholm, Sweden. The first case study house was built in 1936 with an oil burner, which was renovated to a ground-source heat pump (GSHP) in 2007, and the second case study was a new building built in 2013 with a ground source heat pump. The application of photovoltaic/thermal (PV/T) systems in combination with GSHP was theoretically investigated for both case studies. Buildings were modelled using the energy simulation tool IDA Indoor Climate and Energy (ICE), and the model was validated against the measured energy consumption. Simulation results revealed that combining GSHP with 5 m² PV/T gave 24% and 50% energy savings for the first and the second case studies, respectively.

Paper 5.4: Quasi-Dynamic Modelling of DC operated Ground-Source Heat Pump

OLLAS, Patrik Anders [1,2]; MARKUSSON, Caroline [1]; ERIKSSON, Jörgen [3]; CHEN, Huijuan [1]; LINDAHL, Markus [1]; THIRINGER, Torbjörn [2]

[1] RISE Research Institutes of Sweden, Built Environment, Sweden; [2] Department of Electrical Engineering, Chalmers University of Technology, Sweden; [3] EQUA Solutions AB, Sweden

Keywords: Quasi-dynamic modelling, direct current, DC, Heat pump, NZEB, photovoltaic, battery

The performance of a conventional ground-source heat pump (GSHP) have been measured in the laboratory with alternating current (AC) and direct current (DC) operation using the standardised points from EN14511:2018. The results from these measurements have been used to modify a variable speed heat pump model in IDA Indoor Climate and Energy (ICE) and the annual performance of AC and DC operation have been simulated for an entire year's operation at two geographical locations in Sweden. Results show that the energy savings with DC operation from laboratory measurements span between 1.4-5.2% and when simulating the performance for an entire year's operation, the energy gains vary between 2.5-3.4%. Furthermore, the energy savings from the simulations have been compared to the bin method described in EN14825:2018.

Paper 5.5: Parametric analysis of ground source heat pump system for heating of office buildings in Nordic climate

RABANI, Mehrdad [1]; MADESSA, Habtamu Bayera [1]; TORGERSEN, Jørgen [2]; NORD, Natasa [3]

[1] Oslo Metropolitan University- Norwegian University of Science and Technology, Norway; [2] Asplan Viak AS; [3] Norwegian University of Science and Technology

Keywords: GSHP, Sensitivity analysis, Optimization process, Borehole, IDA-ICE

In cold climatic countries, ground source heat pump (GSHP) is widely used for heating purposes and thereby enhancing its energy efficiency is necessary. This paper conducted a sensitivity analysis followed by optimization to improve the performance a GSHP system for an office building located in Nordic climatic conditions. The ground source heating model was firstly validated by available measured data. Comparison of measured and simulated results for the outlet temperature from boreholes showed satisfactory correlation between measured and simulated values, with goodness of fit $R^2 = 0.96$. Afterwards, a sensitivity analysis was performed on the effect of different parameters on the energy use for the peak load heating and base load heating. The analyzed parameters included radius of boreholes, length of boreholes, number of boreholes, mass flow rate of the brine water, and conductivity of ground and borehole filling mass. Furthermore, the parameters of building envelope and GSHP system were optimized to minimize the delivered energy to the building. The optimization was conducted by integrating IDA ICE software with GenOpt tool. The sensitivity results showed that the borehole depth was the most effective parameter, so that by varying it by 20% for Tromsø, the energy supply by the peak load heating reduced by 22% and increased by 31% with the corresponding reduction of borehole depth. The optimization results showed that compared to the reference system, the delivered energy was reduced around 22%, 5%, and 12% in Oslo, Stavanger, and Tromsø, respectively.

Paper 5.6: Solar PVT for heat pumps: Collector development, systems integration, and market potential

SOMMERFELDT, Nelson ✉; BELTRAN, Francisco; MADANI, Hatef

KTH Royal Institute of Technology, Sweden

Keywords: electrify everything, sustainable buildings, solar heat pumps, TRNSYS, COMSOL

Building electrification with heat pumps is a promising technique for heating decarbonization, particularly if combined with solar energy. Historically, solar heat pump (SHP) research has focused on solar thermal technologies, however cost reductions in photovoltaics (PV) has led to an increase in PV based SHP research and a renewed interest in PV-thermal (PVT) hybrid collectors. PV installations are rapidly increasing, but while PVT has been researched for decades it has never found success in the market due to a lack of suitable applications and high cost. This paper outlines a research plan for developing novel, low-cost PVT collectors specifically for use in a range of SHP systems toward the increased electrification of buildings and renewable energy adoption.

A recently concluded, three-year project sought to identify market potential for PVT collectors by connecting them in series with ground source heat pumps (GSHP). A complete systems model in TRNSYS was used to model the building, heat pump, and PVT with a primary focus on total system efficiency (i.e. seasonal performance factor) and total life cycle cost. The results show that PVT integrated systems add investment costs that are not returned through reduced electricity use, and the recommended design is PV with a traditionally sized borehole field. However, PVT can reduce borehole field size, saving over 80% of the land area. If the value of land is included or a limiting factor in borehole drilling, as is the case in many existing buildings, then PVT with GSHP can be a cost effective alternative to combustion-based heating. However, cost reductions in PVT are still needed to keep pace with continuously reduced subsidies.

A recently initiated, four-year project seeks to build on this work and deliver PVT-based SHP to a broader market. Large buildings and legacy heat pump systems are targeted as high potential applications for early adoption. Further TRNSYS simulations will be used to refine and optimize the concept for multiple SHP configurations, and a pilot site will be constructed to validate the systems models and identify real-world challenges. At the component level, novel PVT designs will be developed considering cost reductions in materials and manufacturing afforded by heat pump integration. Digital prototyping will be done using COMSOL with physical prototypes tested in an outdoor laboratory for validation. By the end of the study, the goal is to have market-ready component and systems-level solutions that will advance sustainable building energy system adoption.

Session 6: HVAC general, IEQ and ZEB

Paper 6.1: Chilled water temperature control of self-regulating active chilled beams

FILIPSSON, Peter [1,2]; TRÜSCHEL, Anders [1]; GRÄSLUND, Jonas [1,3]; DALENBÄCK, Jan-Olof [1]

[1] Division of Building Services Engineering, Department of Architecture and Civil Engineering, Chalmers University of Technology, 412 96 Gothenburg, Sweden; [2] CIT Energy Management AB, 412 88 Gothenburg, Sweden; [3] Skanska Commercial Development AB, 112 74 Stockholm, Sweden

Keywords: active chilled beams, self-regulation, supply temperature control, simulation, IDA ICE

The flow rate of chilled water in a self-regulating active chilled beam is constant without respect to the actual cooling load. The cooling rate is instead determined by the room temperature, which gives rise to the self-regulating effect, and also by the chilled water supply temperature, which is equal throughout the system and may be controlled centrally. The purpose of the study presented in this paper is to investigate different strategies of central control of the chilled water supply temperature with respect to energy use and thermal climate.

Simulations are carried out in the building performance simulation software IDA ICE. The studied model represents one floor of an office building dominated by open-plan offices, located in Stockholm, Sweden.

Excessive use of energy and too low room temperatures are inherent risks of self-regulating active chilled beams. The results presented in this paper indicate that such overcooling is effectively avoided by increasing the chilled water supply temperature during the heating season. Controlling the chilled water supply temperature as a function of the outdoor air temperature is a simple strategy with performance similar to more advanced strategies. With this simple control, a building equipped with self-regulating active chilled beams does not require more heating and cooling than a conventional system with individually controlled active chilled beams.

Paper 6.2: Energy performance of an office building by using adaptive approach to occupant behaviour and environment control

TUNIKI, Himanshu Patel [1]; JURELIONIS, Andrius [1]; DOBROVOLSKYTE, Monika [2]

[1] Kaunas University of Technology, Lithuania; [2] YIT Lietuva

Keywords: Predicted Percentage of Dissatisfied, Clothing level, Building Occupants, Occupant Behavior, Energy Simulation

The predicted percentage of dissatisfied (PPD) value indicates the percentage of people dissatisfied with thermal environment, as it depends not only on the thermal environment itself, but on physical, psychological or behavioural aspects as well. Flexible and adaptive occupant behaviour provides more opportunities for both reaching higher perceived levels of comfort and energy savings. In this research, the software simulation tool IDA-ICE has been used to analyse the building performance of the office building under two scenarios, an adaptive case and a non-adaptive case. One pattern was based on standard clothing levels, while the other dealt with the possibility for the occupants to make adjustments in terms of clothing and window operation with respect to the air temperature. The analysis was based on the concept that coping with dissatisfaction can be linked to lower PPD values, and adaptive models can be incorporated into dynamic building energy performance simulations. The results show that there are noticeable differences in the energy used per m², cooling and thermal dissatisfaction, upon adopting adaptive approach with respect to clothing, Predicted Mean Vote (PMV) value and the window opening behaviour. Certain occupant behaviours aimed at maintaining thermal comfort that can both increase the accuracy of energy performance predictions and also lead to increased energy savings in office buildings.

Paper 6.3: Domestic hot water decomposition from measured total heat load in Norwegian buildings

LIEN, Synne Krekling [1]; IVANKO, Dmytro [2]; SARTORI, Igor [1]

[1] SINTEF, Norway; [2] NTNU, Norway

Keywords: domestic hot water, heat load, measurement, load decomposition

In Nordic climates the energy use in buildings is dominated by space heating (SH) and domestic hot water (DHW); the latter one being even more important in highly energy efficient buildings, such as passive houses. Heating load measurements with hourly, and even sub-hourly, resolution from smart meters are becoming the standard. However, in most cases only the total heat use in the building is metered, without separation into DHW and SH use. This separation is desirable since the DHW and SH systems are technically detached, working in different regimes, and have different parameters influencing their performance.

Knowledge of separated DHW and SH load profiles would allow improved design and dimensioning of the energy system in buildings, reaching additional energy savings and enabling more effective demand response mechanisms.

The aim of this research is to estimate typical DHW load profiles for different building types by decomposition, using statistical methods. The energy signature method is used in combination with monthly variation factors of DHW heat use, in order to decompose total heat load into separate profiles for SH and DHW. Another approach, using time series analysis is also used for the same purpose. The results of the two methods are compared and verified against actual measurements of DHW for the building categories for which we have separate metering data, namely: apartment blocks, hotels and nursing homes. Since DHW use is significantly influenced by user behavior and the number of occupants, it was necessary to gather measurement data for a large number of buildings in each building category. Aggregating these data evens out the highest peaks in the DHW load, thus providing heat load curves that are representative of the building category at an aggregated level.

The results provide information on the daily variation and seasonality of the DHW heat use in different building categories. Furthermore, decomposing the DHW load from the total load is a prerequisite for using the measurement data to validate, still on aggregated level, calculation and simulation models of SH loads.

Paper 6.4: Numerical analysis of heat recovery options in old Finnish apartment buildings

HIRVONEN, Janne Petteri ; JOKISALO, Juha ; KOSONEN, Risto

Aalto University, Finland

Keywords: Ventilation heat recovery, Sewage heat recovery, Exhaust air heat pump, Apartment building

Most Finnish apartment buildings are heated with district heating (DH) and have no heat recovery (HR) systems of any kind. In this study, a typical residential building owned by the Helsinki municipal housing company was chosen as a reference case and an IDA-ICA model was created to match the heating demand. Then various heat recovery options were simulated and their emission reduction potential and cost-effectiveness were compared. Detailed heat pump systems were modeled using TRNSYS.

The reference case was an apartment building built in 2001 with a heated net area of 3800 m2, equipped with mechanical exhaust ventilation without heat recovery. Ventilation heat recovery was implemented either through a retrofitted mechanical supply and exhaust ventilation system or through the use of an exhaust air heat pump (EAHP). In addition, heat recovery from sewage was tested. These basic options were tested in different combinations and configurations.

The CO_2 emissions of district heating in Finland are 164 kg/MWh, remaining roughly constant over the year. The CO_2 emissions of electricity generation in Finland are lower on average, varying between 81 and 174 kg/MWh from summer to winter. This gives electrified on-site heating significant emission benefits compared to conventional district heating.

In the reference case, district heating consumption was 537 MWh with corresponding emissions of 105 t-CO_2. Using mechanical supply and exhaust ventilation with HR reduced the DH demand to 384 MWh and emissions to 80 t-CO_2. Installation of an EAHP reduced DH demand to 258 MWh and emissions to 66 t-CO_2, when the heat pump was connected in series to the DH loop. However, district heating guidelines restrict secondary heat sources to parallel connection only. This reduced the EAHP potential to the final DH consumption of 293 MWh and emissions of 73 t-CO_2. Similar restrictions applied to sewage heat recovery. The hybrid case with HR using heat pumps for both sewage and ventilation HR resulted in final DH demand of 162 MWh and emissions of 52 t-CO_2 in the series connected case. With the regulation following parallel connection it was 236 MWh and 66 t-CO_2.

The retrofit to mechanical supply and exhaust ventilation turned out to be more expensive than no action over a 30 year period. The lowest cost option was the EAHP alone, followed closely by the hybrid system with sewage HR as well. Regulations limit the emission reduction potential. However, 37% reduction in emissions is possible using cost-effective means.

Paper 6.5: Simplified Tool for Pre-Designing Ventilation Air Flow in Greenland

CHRISTENSEN, Jørgen Erik [(1)] ; VERGO, William Kristian Krogh [(1)]; GIMENO, Joan Ferris [(2)]

[1] Technical University of Denmark - DTU, Denmark; [2] Plan 1 Cobblestone Architects A/S, Valby, Denmark

Keywords: Greenland, overheating problems, simple freeware, thermal indoor climate, ventilation

The aim of the paper is to develop a simplified thermal calculating design tool for pre-designing of air flow for ventilation in Greenland. The approach is to define and describe a system specifically for Greenland in order to take into account that the situation there is indeed different from Denmark, thus the intension is to improve the level for calculation of the thermal indoor climate in buildings in Greenland.

In order to understand the relevance for the paper it is necessary to have a basic knowledge about Greenland. Greenland is located on Arctic Ocean and is the largest island in the world with a total area of 2,166,086 km² where only the Ice-free area is 410,449 km². Greenland has approximately 57,000 inhabitants. Greenland has their own language Greenlandic and Danish as there second language. The average temperature of Greenland is between -9 and +7 degrees Celsius. The low temperature have

led to the falls conclusion, that overheating problems in Greenland is non-existent and the Greenlandic Building regulation refer only to a verification of the atmospherically indoor climate according to Danish Standard 447 from 1981. There are no demand to control of the thermal indoor climate.

This paper deals specifically with overheating problem in Greenland. The location of Greenland between latitude 59° N to 82° N means sunlight 24 hours per day in the summertime. In addition, the solar radiation hits the vertical windows on a very low angle, which give the maximum transmission of direct solar radiation through the windows. The consequence is a significant amount of transmitted solar radiation to the buildings through the windows.

Because there are so few inhabitants in Greenland the consulting companies are few and small, and do not invest in Building simulation programs like BSim, ICA ICE, IES-VE, etc. since they are too expensive and will only be used very limited. In order to deal with the challenge a simple freeware Excel based program TCD 2 has been developed for analysing of the overheating problems in buildings.

Several users have tested the program and they all find it very user friendly and easy to use.

The preliminary results for the program show good compliance between results from TCD and BSim for the indoor temperatures. The program is easy to use, user friendly and with a Danish user guide, it will be possible for Greenlandic companies to get the program at no cost.

Paper 6.6: From TEK17 to ZEB-O - A case study for a residential building in northern Norway

CLAUß, John [1]; NYGÅRD, Eivind [2]; THOMSEN, Judith [1]

[1] SINTEF Community, Norway; [2] Gunvald Johansen Bygg AS, Norway

Keywords: zero energy building, zero emission building, heat pumps, district heating, IDA ICE

The municipality of Bodø has decided that the current city-airport will be moved further away from the city center by 2026. The ambition of "Ny by – ny flyplass" is a neighborhood where future technological and environmental-friendly solutions will be realized. This also means that the new buildings being built before 2026 ideally should use technologies and solutions that make it possible to couple those buildings with the new buildings in the neighborhood "Ny by – ny flyplass".

The work performed in this study is associated to the Sjøsiden project of a local entrepreneur. An energy system analysis has been performed for a two-family house which is a building from the portfolio of the entrepreneur. The energy systems considered in the analysis are district heating (DH), combined heat-and-power (CHP) and a seawater heat pump (SWHP).

Detailed building performance simulations of the residential building were performed using the software IDA ICE Version 4.8. The performance of the systems is evaluated based on the annual energy use and resulting annual emissions of the buildings. The results show that the SWHP leads to a lower annual energy use for heating and to lower annual carbon emissions compared to the DH system and a CHP plant. The energy use for the CHP plant is higher than the energy use for the DH system because more energy has to be delivered to meet the same demand due to the lower thermal efficiency of the CHP plant.

Furthermore, different measures are investigated to "upgrade" the case building from TEK17 to a zero emission building (ZEB). In general, it has been found that the TEK17 building does not reach a zero emission balance for any of the three energy systems. Therefore, the envelope of the building has been improved to passive house standard, the efficiency of the PV panels has been increased from 17 % to 22 %, and the total PV area has been increased to achieve a ZEB. If a SWHP is used, it is almost sufficient to improve the building envelope and the PV efficiency. This is important for a residential area where space for more PV panels is limited. For the DH system or the CHP plant, it is not sufficient to only improve the building envelope and the PV efficiency, but it would also be required to increase the total PV area to generate enough electricity to compensate for the imported electricity.

Session 7: Data-driven Models and BPS education

Paper 7.1: Influence of Data Pre-Processing Techniques and Data Quality for Low-Order Stochastic Grey-Box Models of Residential Buildings

YU, Xingji; GEORGES, Laurent

Norwegian University of Science and Technology, Norway

Keywords: Low-Order Grey-Box Models, Data Preprocessing, Optimizer

The energy consumption for space-heating, or the related energy costs, can be reduced using the building energy flexibility. In the one hand, thermal storage using the building fabric can be used to enable this flexibility. On the other hand, Model Predictive Control (MPC) has been proved to be an important technology to activate the flexibility. In practice, the accuracy of the control model can significantly influence the MPC performance. However, the mathematical complexity of the model should be limited to reduce computational time. Thus, deriving an appropriate control-oriented model for the building thermal dynamics is acknowledged as a important phase in the design of an MPC.

Grey-box modelling is a trade-off between data-driven and physical-based modelling approaches. This paper mainly investigates the influence of pre-processing techniques, typically filtering, on low-order grey-box modeling of residential buildings. In order to train the grey-box models, virtual experimental data is generated using building performance simulation (BPS), here a detailed multi-zone building model implemented in IDA-ICE. The case of the detached house located on a flat and open terrain in Oslo and heated using electric radiators is considered. Using BPS, different cases of weather data and excitation signals of the building can be easily compared, which is difficult to perform in real experiments. The weather corresponding to four different periods of the space-heating season is studied in this paper. Excitation signals using different levels are used to excite the system for each weather conditions. In addition, the excitation level is also decreased to explore the influence of data quality on the grey-box models. If a decent grey-box model can be identified with a moderate excitation signal corresponding to the usual building operation, the feasibility of implementing MPC for residential buildings can be dramatically increased. The MATLAB system identification toolbox is used to identify the parameters of the grey-box models. Deterministic grey-box models and stochastic grey-box models in innovation form (i.e. the prediction error is used for correcting states) are compared. Preliminary results show that, with the stochastic model, the Kalman gain and some parameters get unreasonable estimated value when longer sampling times are applied for the data. Therefore, prefiltering techniques are necessary for preprocessing the data so that the optimizer is able to obtain parameter values that can be physically explained. The paper will present how the pre-filtering techniques affect the performance of the identified grey-box models.

Paper 7.2: Data-based calibration of physics-based thermal models of single family houses

AMATO, Virginia; KNUDSEN, Michael Dahl; PETERSEN, Steffen

Aarhus University, Denmark

Keywords: Calibration, Building energy simulation, EnergyPlus, White box model

Building thermal simulation models are a useful tool for predicting the thermal performance of buildings. However, many studies have documented that there often are discrepancies between simulation results and real-world measurements, the so-called performance gap; this gap devaluates the value of building simulation. A solution to this is to calibrate the simulation model to fit the increasingly accessible measured data from smart energy meters and low-cost sensors. The aim of this paper is investigate how to match the simulation output from a detailed energy model of a typical Danish single-family house to measured hourly energy data already available from district heating companies and data from indoor climate sensors.

A model of a typical existing single-family house from 1968 is made using EnergyPlus. Even if all input parameters to EnergyPlus have a physical meaning, they are commonly subject to various assumptions, uncertainties and errors, e.g. incorrect specifications of the building envelope build-up and installations, unpredictable occupant behaviour, or modelling assumptions such as time discretization and zoning – all regarded as the reason why there is a performance gap. Next step is therefore to calibrate the model to fit measured data from the building by tuning uncertain input parameters.

Current research studies have used utility bills on a monthly basis as output data for the calibration of building energy models. However, the rapid development in metering and sensor technology has led to the accessibility of data with higher resolution and quality that could be useful for model calibration. The measured data available in this study is the domestic hot water and the total heat consumption on an hourly basis for the house as a whole, and the air temperatures measured in the rooms with a resolution of ten minutes. However, while the hourly total heat consumption of residential buildings (without distinction between space heating and domestic hot water) is currently measured and recorded by the local district heating company, domestic hot water consumption meters and air temperature sensors are not commonly installed in houses and therefore come with additional costs. Therefore, it is investigated to which extent the data obtained by additional sensors improve the

calibration accuracy, and how to reduce the expenses of additional sensors to a minimum. It is also investigated how thermal zoning of the simulation model affects the fit of the calibration procedure.

Paper 7.3: Datasets for grey-box model identification from representative archetypes of apartment blocks in Norway

BOTTOLFSEN, Hanne Liland (1); ANDERSEN, Kamilla Heimar (1); CLAUß, John (2); SARTORI, Igor (1)

[1] SINTEF Community, Oslo, Norway; [2] SINTEF Community, Trondheim, Norway

Keywords: validation, IDA-ICE, MPC, PRBS, datasets

It is estimated that there is substantial energy flexibility in the heating demand of buildings. To exploit this flexibility potential some form of smart control is necessary, that can manipulate the energy use based on external factors, such as weather and energy prices, while maintaining thermal comfort for the occupants. Such type of controls shall rely on accurate, robust and simple models of heat demand that are suitable for real time control. Grey-box models combine a relatively simple physical descriptions of the building with data-driven inference of key parameters and are often used for this purpose. A challenge with grey-box models is that the model identification process requires 'rich' datasets, meaning datasets containing enough statistical variability on both heating demand and indoor temperatures. Such datasets are scarcely available, usually only from dedicated experiments in living labs or similar research facilities.

The aim of this work is to present a series of datasets that can be used for the identification of grey-box models of apartment blocks. Based on previously developed archetypes in the TABULA/EPISCOPE project, a set of IDA-ICE models representing apartment blocks in Norway is available. The load profiles for the archetypes will be validated against measured datasets in a parallel research activity. Provided that the load profiles are validated, it is legitimate to assume that the indoor temperature profiles from the IDA-ICE archetypes are also representative for the real building stock. Therefore, heating load and indoor temperature profiles from the IDA-ICE models may in theory be used for creating grey-box models of those archetypes, likewise datasets from measurements, where available.

However, a successful identification process depends upon 'rich' datasets. We simulate special test periods during which the archetypes are excited with trains of heating events, Pseudo Random Binary Sequence (PRBS), aiming at exploring a wide and rapidly changing set of indoor temperatures around and outside the comfort zone, ca. between 20 and 24 °C. A test period lasts typically one to two weeks, and we repeat the experiment for every month of a typical meteorological year, so that it will be possible to study the influence of performing model identification in different periods of a year.

The generated datasets, both under normal operation and under special test periods, are going to be made openly accessible on an internet repository by the time of the BuildSim Nordic conference in October 2020..

Paper 7.4: Identifying grey-box models of Norwegian apartment block archetypes

BAGLE, Marius Eide; WALNUM, Harald Taxt; SARTORI, Igor

SINTEF Community, Norway

Keywords: Grey-box modelling, Model Predictive Control, Energy System Flexibility

A potentially large amount of flexibility in Norway resides in the space heating of residential buildings. To realize this potential, it is necessary to model heat demand with models that are accurate enough and suitable for real time control. Purely physical (white-box) models are ill-suited for the purpose due to the level of detail required, the high uncertainties associated with knowledge of key technical parameters and the difficulty to treat non-technical features such as user behavior. On the contrary, well-suited for this purpose are grey-box models, which combine a relatively simple physical descriptions of the building with data-driven inference of key parameters. However, identification of grey-box models poses a challenge: alongside energy use and weather data, it is indispensable to know also the indoor temperature, with the same hourly or sub-hourly resolution. Such data are scarcely available. Furthermore, it is not given that measurements from normal operation of buildings provide datasets that are 'rich' enough (containing enough statistical variability) to successfully drive the identification process, or if special test periods should be carried out. Such test would require the manipulation of indoor temperatures, possibly in periods of non-occupancy, for some weeks; a challenging task on real buildings.

This paper presents a method that aims at overcoming this bottleneck by combining features of both white-box and grey-box modelling. A set of white-box models (specifically, IDA-ICE models) representing the Norwegian stock of apartment blocks is available, based on ca. 20 archetypes previously developed in the TABULA/EPISCOPE project. Validation of the hourly load profiles of such archetypes against a large dataset of measurements is undergoing in a parallel research activity. Provided that load profiles are validated, it is legitimate to assume that the indoor temperature profiles from the IDA-ICE archetypes are also representative for the real building stock. Under this assumption, the grey-box models are identified from datasets generated by the IDA-ICE archetypes in two modalities: under normal operation and under special test periods with a duration of one to two weeks. During the test periods the IDA-ICE archetypes are excited with trains of heating events, Pseudo Random Binary

Sequence (PRBS), aiming at exploring a wide and rapidly changing set of indoor temperatures around the comfort zone, ca. between 20 and 24 °C. Finally, validation of the identified models will focus on short term predictions (one day to one week) as this is the typical range of control horizon for predictive controllers.

Paper 7.5: Global Marginal Carbon Footprint Evaluation of Internet Services with Building Energy Models

KUMAR, Eric Mahendra ✉; COCHRAN HAMEEN, Erica; LIANG, Wei

Carnegie Mellon University, United States of America

Keywords: datacenter, ecological costs, life cycle analysis, building simulation

Datacenter ecological cost modeling has traditionally been segregated between building systems and information technology models. Those models are built by experts in their respective domains. These domains are complex and they lack common parameterization to allow for direct modeling integration. This article demonstrates a robust four-step framework that integrates information technology workloads with building systems using only open source software. It first constructs a traffic simulator for internet services operating in a set of datacenters. Then second, the network traffic profile is input to EnergyPlus as information technology plug load for each datacenter. Third, the power demand profile from the EnergyPlus model is used to determine the levelized cost of energy over a matching time range. In the fourth step, the embodied costs of the infrastructure are assessed using an environmentally extended input/output model. The model contributes an openly accessible modeling framework that allows researchers to produce life cycle cost estimates of internet services.

Paper 7.6*: A Grey Box Model of the Heat Dynamics of a School Building

BANIS, Frederik ✉; **HVIID, Christian Anker** ✉; BERGSTEINSSON, Hjörleifur G.; BACHER, Peder; CALI, Davide; MADSEN, Henrik; POULSEN, Niels Kjølstad

Technical University of Denmark, Denmark

Keywords: Grey-Box models, Heating System, Dynamical system models

Model predictive control can help in reducing energy use in buildings for HVAC systems, minimising CO2 emissions, and maximising occupants' comfort within the built environment. An MPC for a building requires a reliable model of the building. Complex building energy performance simulation models (briefly here: white-box models) are accurate, but often too heavy and sometimes too unstable, hence those models cannot be the right choice for a model predictive control of real buildings. Grey box models can be very fast in terms of simulation time, but need a long training time with a big dataset of measured values, before they can reliably represent the real behaviour of a building. Grey-box models represent the dynamics of the building fabric, but often disregard or neglect the dynamics of the heating system, even though massflow and temperatures of the heating system are key elements of the overall efficiency and should be included in a model predictive controller focused on minimizing CO2-emissions.

* **Extended abstract** for paper Paper 7.6 is available at the end of this book.

Paper 7.7*: Video game-based learning for teaching building thermodynamics and control of HVAC systems

JOHRA, Hicham ✉; ROHDE, Lasse; PETROVA, Ekaterina A.

Aalborg University, Department of Civil Engineering, Denmark

Keywords: Game-based learning, Gamification, Energy efficiency, Indoor environment, Control of HVAC systems

Game-based learning has become a growing topic of research. It is now a common tool for learning technical and soft skills in certain companies. In line with the rapid development of E-learning in education, the use of video games for the introduction of complex scientific topics to students can be an efficient teaching method.

This paper presents "GEENIE" (Gaming Engine for ENergy and Indoor Environment), an interactive video game simulating the thermodynamics and indoor environment of a building. It is used in a University education program to introduce a course about control of Heating Ventilation Air Conditioning (HVAC) systems in buildings. The purpose of the game is to rapidly engage the students with the importance of having automated control systems in buildings to ensure high and stable indoor environmental quality (IEQ) with minimum energy use. Moreover, it allows students (players) to experience the interconnection between the different IEQ parameters and emphasizes the importance of searching for holistic compromises, rather than local optimum.

The GEENIE consists of an arcade video game station allowing players to control the heating, cooling, ventilation, lighting and shading device of a simulated building. The players must adjust the power of these systems to keep the indoor temperature, CO_2 concentration, and luminosity as close as possible to the comfort optimum, while the dynamic boundary conditions (outdoor weather and people load) induce disturbances to the latter. At the end of the game, a score is calculated as the average IEQ minus the total energy use. The game can also be run in "automated mode" where the computer controls the HVAC systems with either an ON/OFF, PI or predictive controller.

The main gamification aspect of this teaching tool is the competition between players for the highest score. It was observed that it rapidly draws the attention of the students and thus facilitates further discussions about building thermodynamics and IEQ. In addition, the game is designed to be difficult for human players. Consequently, the automated controllers largely outperform the players' manual control, emphasizing the importance of the course's topic.

*** Extended abstract** for paper Paper 7.7 is available at the end of this book.

Paper 7.8*: Discussing daylight simulations in a proposal for online daylighting education

GIULIANI, Federica (1); SAREY KHANIE, Mandana (2); SOKÓŁ, Natalia (3);
GENTILE, Niko (4)

[1] Università Niccolò Cusano: Rome, IT; [2] Technical University of Denmark: Kgs. Lyngby, DK; [3] Gdańsk University of Technology: Gdańsk, PL; [4] Lund University: Lund, SE

Keywords: Daylighting, Education, e-learning, BPS

Daylighting is a multidisciplinary field in building industry with undeniable benefits for occupants and energy saving. Building performance simulations (BPS) are essential to characterise daylighting design, its amenities and its potential for energy saving. So far, studies have demonstrated a strong knowledge gap for students and practitioners of the building sector in daylighting. As a direct result, there is a tendency to use design strategies with low awareness of environmental consequences (e.g. overheating, energy-intensive buildings, human distress, etc.). Moreover, the introduction of open-source simulation tools and gadgets has made it possible to use several simulation possibilities in an unsupervised fashion. This represents a danger in use of simulations tools with inaccurate inputs and principles to support the output results. The main issue is arguably the lack of a widely accessible, coherent and structured pedagogical offer that brings specialist knowledge on this subject. In such a perspective, we present a concept for an educational e-platform which introduces an advanced training program in daylighting aiming at expanding mass high-quality knowledge on the topic. The concept takes the name of New Level of Integrated TEchniques for Daylighting education (NLITED).

NLITED consists of a modular training programme for daylighting education, including BPS. The training program is developed by a strategic partnership between four European universities and it is addressed to both students, designers and lighting practitioners. On the practical side, NLITED is based on the integration of pedagogical techniques in a newly developed educational venue: a modular e-learning program (MEP) and physical intensive study program (ISP) in form of a summer school. The MEP will contain theoretical knowledge, while the ISP will be used for in-depth applied training and will focus on the application of simulative verification tools, consistent with the theoretical learning proposed in MEP. The ultimate goal of the educational project is to launch the NLITED program on a massive open online platform where several interested learners where several interested students can be reached in flexible teaching methods and tailor-made learning.

In this paper, we describe the NLITED concept and how daylighting BPS are implemented in the educational program.

*** Extended abstract** for paper Paper 7.8 is available at the end of this book.

Session 8: Input data workflow, boundary conditions, user interface, BIM

Paper 8.1: Using inference from user attribution of models to support high resolution modelling

HAND, Jon William ✉

University of Strathclyde, United Kingdom

Keywords: model attribution, inference, flow network generation

Simulation models often look complex but actually involve abstraction of the form, fabric, leakage and operational characteristics of buildings. Many projects would be better served by increasing the resolution of the building description as well as invoking more detailed solution techniques. One of the barriers is the domain knowledge required to, for example, create networks of leakage and air flow distributions as a replacement for user imposed air flows.

The author has explored how users might tag surfaces with attributes of their USE which supports inference into which of a score of different flow component types and linkages is appropriated. For example, if a surface is attributed as a DOOR with an UNDERCUT this can be combined with the geometry of the door surface and the zones that it is associated with the surface to select and attribute the most appropriate flow component, place it correctly into the network and overlay the network over the building form view for confirmation. Ditto for sash windows or slightly open doors or extract grills. As the building model evolves the changes are reflected in the flow network. There are several dozen combinations of USE attributes and these have expanded as we add more inferences between observations and network topologies.

Asking users to describe what they see better supports networks of one or two magnitudes greater complexity and which are better placed to support high resolution assessments. As a first step projects can add the network flow into the mix of domains to be solved to look at air quality issues each minute over a season. Some design questions would be better served by grid rooms to enable a mixed network flow and CFD assessment so that at each time step CFD is provided with fresh boundary conditions and can evaluate and return heat transfer coefficients to the building model. Whilst many tools provide automation this project focuses on how closely an attribution-drive approach matches what experts in network modelling might have designed. A number of case studies will be presented.

Paper 8.2: Working with a Small and Predictable Performance Gap

AZAR, Marc ✉; CARLING, Par

EQUA Simulation, Sweden

Keywords: Ashrea guideline 14 Gap Simulation

Much is written about the performance gap. Multiple studies show alarming discrepancies between design and actual building energy performance,Menezes et al. (2012); Turner and Frankel (2008). Should this

prove to be a universal truth, the need of more detailed dynamic modeling methods can certainly be put into question. The prevalence, of somewhat antiquated, monthly methods in many current building codes seem to support this view.

In this paper we demonstrate a case supporting the opposite viewpoint. When the motivation and tools are right, sufficient accuracy between prediction and actual outcome can be achieved. We present a building modelling case, where appropriate data was collected over a period of a full year for an office building with gross floor area of 31,809 meter squared in Stockholm, Sweden. We showcase how abiding by a Keep it Simple and Straightforward approach in modeling, one is able to achieve accurate energy performance predictions without sacrificing on capturing building's dynamics and internal states. However the selected project is not a singularity, but represent the mainstream in state of the art Swedish design practice. We end by highlighting some pitfalls with current guidelines regarding calculating goodness of fit measures between empirical data and a dynamic simulation model, and providing some recommendations for more appropriate metrics.

Paper 8.3: Exploring possibilities to quantify the qualitative description of occupant behavior

DZIEDZIC, Jakub Wladyslaw [1]; YAN, Da [2]; NOVAKOVIC, Vojislav [1]

[1] Norwegian University of Science and Technology, Norway; [2] School of Architecture, Tsinghua University, Beijing 100084, China

Keywords: Occupant behaviour, Agent-based modelling, Building performance simulation, BOT-ABM

Human behaviour is a multidisciplinary subject that is being investigated by numerous scientists around the world. The ability to understand and forecast reactions can be beneficial for all scientific branches that are related to this subject. With the increase in the accessibility of personal monitoring systems, a new era of human behaviour research has begun. Currently, in the market, there are many cheap and reliable solutions that can grant extra insights into the everyday lives of human beings. Regardless of whether the monitoring solutions are stationary or wearable, they are capable of providing very detailed information with high operational and temporal resolution. Access to these data has advanced our understanding of human routines and habits, but it does not provide insights into the "soft" data that define human beings.

Once the quantitative data has started to enrich scientific databases, the community has started to question whether such information is suitable to detect or record qualitative ("soft") output. Typed text is not included, but it is possible to extract existing data and to obtain "soft" data. This manuscript will try to address this issue. It proposes a straightforward solution that can have great potential for implementation purposes. It investigates the existing literature and tries to evaluate its applicability for numerical implementation. One of the highlights of the manuscript is the proposal of a novel modelling solution that can cooperate with other occupant behaviour-related simulation models. Finally, the manuscript tries to outline future steps to enable the possibility of translating or modelling quantitative input into qualitative output.

Paper 8.4: Undefined modelling parameters impact on building simulation results: using IDA ICE according to the Estonian methodology for calculating building performance

SAREVET, Henri; **KIIL, Martin**; SIMSON, Raimo; THALFELDT, Martin; KURNITSKI, Jarek

Tallinn University of Technology, Estonia

Keywords: Building simulation, building performance, building energy, IDA ICE

The Nordic countries have taken important and strict steps moving towards reducing building energy consumption. Energy performance estimation by dynamic building simulation has become a crucial part of the building design. The performance assessment methodology including pre-determined standardised input parameters vary from country to country. The purpose of this study was to analyse the impact of modelling parameters which are not pre-defined but influence the result, and define specific values to be used in the methodology to reduce the uncertainty and variations in the results. The assessed parameters include the definition of the first day of simulation, e.g. start-up date, weekday and calendar year; summertime usage schedule, pre start-up simulation specifics and simulation splitting. The simulations were conducted using dynamic simulation software IDA ICE. Calculations were carried out according to the Estonian national methodology for calculating energy performance of buildings. The study analyses the impact of modelling input data parameters which are not pre-defined in the methodology. The effects of these parameters are illustrated by modelling and simulating multiple typical 5-day usage office and educational buildings. This study highlights the importance of the initial modelling parameters determination on the building energy consumption calculation results.

Paper 8.5: The right way to do building simulations? Using Monte Carlo simulations, sensitivity analysis, and metamodeling on a design case

ØSTERGÅRD, Torben [1,2]; NIELSEN, Lars Broder [2]; JENSEN, Rasmus Lund [1]

[1] Aalborg University, Denmark; [2] MOE|Artelia Group, Denmark

Keywords: decision-support, design space exploration, integrated building design, parallel coordinates plot, regression

Monte Carlo simulations, sensitivity analysis and metamodeling are becoming popular in academia but are rarely applied in real building projects. In this case study, we demonstrate how a combined framework of these methods can aid decision-making in relation to building performance of nine 16-story residential buildings. We describe the processes before, during, and after a meeting between building engineers and the building owner. For preparation, BeDesigner was used to create, run, and analyse 5.000 Be18 simulations in roughly 4 hours. The meeting is initiated with a presentation of sensitivity analysis results to focus the attention towards the most influential design inputs. The 5.000 simulations are visualized with parallel coordinates plots in

DataExplorer, which enable decision-makers to observe the consequences of different design choices and regulatory requirements. Real-time sensitivity analysis, TOR, highlights the parameters affected the most by the applied constraints, while histograms indicate favourable or disadvantageous design choices. However, no solutions exist among the 5.000 simulations, which is due to the vastness of the multi-dimensional input space and the decision-makers' numerous requirements. Using metamodels, 500.000 additional input combinations are calculated and from this extensive dataset a variety of solutions are found. It becomes clear that a "no-renewables" ambition necessitates costly countermeasures and makes it difficult to realize the architectural and indoor climate requirements. In conclusion, the combined framework improves the information quality for decision-making and significantly increase the likelihood of finding diverse, high-performing solutions within the same time-frame as traditional practice.

Paper 8.6*: Update of a living building-simulation tool

JENSEN, Ole Michael; WITTCHEN, Kim B.; SØRENSEN, Christian Grau; KRAGH, Jesper; ROSE, Jørgen; SVANE, Nanna Dyrup; SØRENSEN, Karl Grau

Aalborg Univsersity, Denmark

Keywords: Building simulation, API interface, tool update

In the early 80'es, researchers at Danish Building Research Institute SBi created a successful building simulation tool called tsbi, and since year 2000: BSim with a full 3D geometry model and Windows compliant. At that time, C++ was a new promising programming language and BSim and its extensions was created based on that technology.

After two decades, the researchers together with the programming team decided to rebuild BSim. It was acknowledged that BSim needed a new platform for compatibility reasons and a new user interface to meet user requirements. A special challenge on the doorstep of this rebuilding was how to make the new BSim ready for online simulation and to establish an API (Application Programming Interface),

This paper deals with the researchers' analyses of BSim concerning functionality, user interface performance etc. Moreover, it deals with the smooth transformation from the old to the new BSim. The researcher team dealt with this transformation by creating a parasite BSim that was able to operate the old BSim. The team created the operating system as 'tentacles' designed in C++. Then the team carefully was able to build a new BSim core by use of Rust programming language. At first, the new interface will only be a thin layer around the old BSim, interacting via this parasite. Gradually the thin layer will be more elaborate, and at the end replacing the old BSim, but without loss of functionality and speed of simulation.

*** Extended abstract** for paper Paper 8.6 is available at the end of this book.

Paper 8.7*: Semi-automatic geometry extract from Revit for earlier and faster building performance simulations

SVANE, Nanna Dyrup [1,2]; PRANSKUNAS, Artüras [1]; LINDGREN, Lars Broder [2]; JENSEN, Rasmus Lund [1]

[1] Aalborg University; [2] MOE A/S

Keywords: Interoperability, BIM, Building performance simulations, Semi-automatic, Revit API

The construction industry is experiencing increasing requirements for energy efficiency and indoor environmental quality with often-conflicting requirements. In order to achieve a sustainable building and an efficient building design process, it is necessary to have iterative building performance analyses (BPS) starting from early phases to the final design.

The large BIM platforms allow extract of data to BPS tools in formats like IFC and gbXML. However, the extracts are often faulty, deficient and not adapted to local standards for geometric measurements. Furthermore, the different designers have different BIM approaches, which often are not adapted for the purpose of building performance simulations.

Due to the never perfect interoperability and inconsistent modeling, the performance analyses are often performed with manual modeling, which causes late start and delivery of relevant analyses as well as ineffective use of resources.

This paper describes a developed methodology for semiautomated data extract between the BIM software Revit and the Danish BPS tool BSim to overcome the described challenges. The method involves both data extract and a translation to the input file for BSim through the Revit Application Programming Interface (API) and visual programming in Dynamo.

The semi-automatic approach involves a user interpretation of relevant rooms based on Revit spaces defined by the BPS-specialist. In addition, the method enriches the geometry extract with space information that is not present in the BIM-model. The space information involves usage patterns, constructions, surfaces, climate systems, etc. based on industry standards and key figures for the generation of a complete input file for BSim. After the simulation is performed, relevant data of both input and results are generated and displayed both in report format and in the Revit model.

The functionality of the method has been tested and verified for a number of cases with different complexity. The renewed practice will facilitate earlier analyses since modeling time and time for setup of systems is significantly reduced. Furthermore, the method will eliminate errors and discrepancies related to different modeling techniques and understandings of the BIM model.

* **Extended abstract** for paper Paper 8.7 is available at the end of this book.

Workshops

Workshop 1: IDA Indoor Climate and Energy 5.0 - New features

VUOLLE, Mika ✉ with other EQUA staff

EQUA Simulation Finlad Oy, Finland

Keywords: IDA ICE

New features of IDA Indoor Climate and Energy 5.0 will be presented, especially plant modelling and PV simulations

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Workshop 2: Master planning based on NZEB for Positive Energy Districts

HAASE, Matthias ✉ with Xingxing Zhang

SINTEF Community, Norway

Keywords: Energy Master Planning, environmental impacts, NZEB

Bringing Energy Master Planning on a district level gives the possibility to untangle the academic discussions on the dynamics of energy. Consumers and producers are integral parts of the solution by understanding and influencing energy use/consumption both on individual and societal level. Communication issues between consumers and citizens will be eased and their role empowers them in limiting energy use/consumption and thus in creating the necessary communication and or engagement.

As a sustainable energy transition will see increased electro-mobility, its impact on the energy system needs to be understood and well-integrated in planning. The Positive Energy Districts in this work consists of several buildings (new, retro-fitted or a combination of both) that actively manage their energy consumption and the energy flow between them and the wider energy system. Positive Energy Blocks/Districts make optimal use of advanced materials, local RES, local storage, smart energy grids, demand-response, cutting edge energy management (electricity, heating and cooling), user interaction/involvement and ICT. Positive Energy Districts are designed to be integral part of the district/city energy system and have a positive impact on it. Their design is intrinsically scalable and they are well embedded in the spatial, economic, technical, environmental and social context of the project site.

This workshop focuses on discussing what limiting energy consumption entails, how this is related to consumption patterns in general, how much we should or could limit energy consumption. The consumer and the producer need to act and react. In Positive Energy Districts the objectives of climate mitigation and adaptation goals, local energy, air quality and climate targets and a secure and resilient energy system were met. Furthermore, it should lead to significant increase share of i) renewable energies, ii) waste heat recovery and iii) appropriate storage solutions (including batteries) and their integration into the energy system and iv) reduce greenhouse gas emissions.

Integrated requirements for Positive Energy Districts are discussed based on NZEB and their environmental, economic and social performance indicators were identified. Related to environmental impact the ISO14031 Standard presents 3 categories of performance indicators: Management Performance Indicators (MPIs), Waste Indicators (WI) & Environmental Condition Indicators (ECI). How can these be integrated into Building Performance Simulations? Who are the stakeholders? What is the relation to EN ISO 52000? What are Base case, baseline and useful scenario developments? How does the concept of resilience fit into the Energy Master Planning?

Workshop 3: Workshop on high resolution modelling

HAND, Jon William ✉ with Petter Wallentén

University of Strathclyde, United Kingdom

Keywords: high resolution modelling, future trends

Simulation use in projects often looks complex but actually involve considerable abstraction of the form, fabric and operational characteristics of buildings. We habitually constrain the physics via user imposed directives. We largely ignore the complexity of heat and mass transfer paths within facades or their 3D characteristics. We persist in the convenient fiction of prescribed heat transfer coefficients and that thermostats sense air temperature. We treat appliances and occupants as simple entities. We ignore the dynamics of system components with our steady-state approaches. We treat large open plan spaces as uniform as fully mixed. And we direct reporting agents to only tell us about a subset of what has been predicted.

And we do all of this in the face of overwhelming evidence of a disconnect between predictions and observations.

This workshop is about breaking such habits. It's about undertaking high resolution assessments rather than expecting users to impose simplifications. The aim is to provide a realistic set of performance data for design teams to work with. If it is no big deal to include extended descriptions, gridding schemes and represent occupant behaviour then aspects such as local comfort assessments can become the norm. Breaking our habitual need for near-instant solutions might address the disconnect and yield more robust designs.

This workshop is aimed at both practitioners and developers who would like to explore options for habit breaking and test out the implications of high-resolution models for simulation in practice. How might work-flows evolve? What additional attributes to we need to include to ensure that we account for visual and thermal comfort for each employee? How do practitioners explore patterns within performance data which is a magnitude richer than we are currently used to? We will use high resolution models and ESP-r as a focus for discussion and aim to capture ideas from participants as to how the community can form a new normal for design assessments.

Author index

Extended Abstracts

- **Paper 1.6 Clustering and classification of building structures and their construction years with respect to monthly electricity consumption**
  HAN, Mengjie; RAZA, Mohsin; ZHANG, Xingxing; QUINTANA, Samer

- **Paper 1.7 Validation of Norwegian Residential Building Archetypes Based on Empirical Data and Numerical Simulations**
  ANDERSEN, Kamilla Heimar; LIEN, Synne Krekling; BOTTOLFSEN, Hanne Liland; FAGERHEIM, Aksel Garvik; SARTORI, Igor

- **Paper 1.8 Numerical Simulation in Transient Conditions of a University Building with Complex Topology Equipped with Greenhouses in Winter Conditions**
  CONCEIÇÃO, Eusébio Z.E.; LÚCIO, Mª Manuela J.R.; AWBI, Hazim B.

- **Paper 4.6 Definitions of Floor Area and Evaluating Impacts in Energy Simulation**
  ALLEN-SANDOZ, Nicholas Frederick

- **Paper 4.7 A parametric tool for combined overheating and daylighting assessments**
  GKOUVELOU, Eleni; MOSKOVELI, Dimitra; KHANIE, Mandana Sarey

- **Paper 7.6 A Grey Box Model of the Heat Dynamics of a School Building**
  BANIS, Frederik; HVIID, Christian Anker; BERGSTEINSSON, Hjörleifur G.; BACHER, Peder; CALI, Davide; MADSEN, Henrik; POULSEN, Niels Kjølstad

- **Paper 7.7 Video game-based learning for teaching building thermodynamics and control of HVAC systems**
  JOHRA, Hicham; ROHDE, Lasse; PETROVA, Ekaterina A.

- **Paper 7.8 Discussing daylight simulations in a proposal for online daylighting education**
  GIULIANI, Federica; SAREY KHANIE, Mandana; SOKÓŁ, Natalia; GENTILE, Niko

- **Paper 8.6 Update of a living building-simulation tool**
  JENSEN, Ole Michael; WITTCHEN, Kim B.; SØRENSEN, Christian Grau; KRAGH, Jesper; ROSE, Jørgen; SVANE, Nanna Dyrup; SØRENSEN, Karl Grau

- **Paper 8.7 Semi-automatic geometry extract from Revit for earlier and faster building performance simulations**
  SVANE, Nanna Dyrup; PRANSKUNAS, Artüras; LINDGREN, Lars Broder; JENSEN, Rasmus Lund

Clustering and classification of building structures and their construction years with respect to monthly electricity consumption

Mengjie Han[1*], Mohsin Raza[1], Xingxing Zhang[1], Samer Quintana[1]
[1]School of Technology and Business Studies, Dalarna University, Falun, Sweden
** corresponding author: mea@du.se*

Abstract

Urban planning and city energy management are interconnected to buildings, their construction materials structures and built years, as these parameters directly affect the energy demand. Data-driven approaches for classifying buildings according to their energy performance may help urban management to make sustainable decisions. The aim of this study is to adopt monthly electricity consumption of different buildings to extract those with similar features in terms of monthly electricity consumption. This study then examines different categories of building structures and their construction years for understanding the influence on their consumption patterns. Monthly electricity data for the year 2018 was collected from a locally owned housing company in Borlänge, Sweden. Based on the electricity consumption data, a dimension reduction is used before implementing clustering analysis. Buildings were categorized in three groups: high, medium and low electricity consumption. The results show that a multi-family house built in 1950s and 1970s are the most representative building structure consuming lowest electricity. On the other hand, apartment buildings built in the period of 1950s to 1970s are the most common buildings and could indicate high electricity consumption. However, the cluster with highest electricity consumption does not have sufficient observations and each individual feature needs to be examined by adding more variables in the future.

Introduction

Building energy consumption is usually affected by its physical properties, construction years, outdoor environment and occupant behaviour. Moreover, the interactions between different factors make the prediction of energy consumption more difficult. Over-and underestimation in energy consumption at the design stage strongly affects the performance of the building later (Stein and Meier, 2000). Achieving high energy-efficiency in buildings has become a primary objective that many stakeholders strive for (Mathew et al., 2015). Residents consume at least 20% electricity and they have a large potential for energy savings (Teeraratkul et al., 2018). Having a better understanding of electricity consumption patterns is an effective way for residents to change their daily electricity consumption behaviour and save their energy costs.

Over the last decades, significant research efforts have been devoted to energy load prediction and pattern profiling/classification. Electricity consumption pattern recognition has been extensively studied. Several statistical methods, time series analysis methods, and mathematical modelling methods, have been used to analyse residential electricity consumption data and extract typical consumption patterns (Cominola et al., 2018). Clustering refers to an unsupervised procedure which groups similar patterns into same groups, and it is one of the most important tasks in exploratory data analysis (Hartigan, 1975).

Pattern recognition of residential electricity consumption refers to discover common consumption regularities for different buildings from collected data, which can provide valuable insights for developing personalized marketing strategies, supporting targeted demand side management, and improving energy utilization efficiency (Wen et al., 2019). The pattern recognition of electricity consumption is also an important way to achieve knowledge discovery in smart grid (Shukla and Singh, 2016). As observed from aforementioned studies, clustering algorithms have been used mostly to discover residential electricity consumption patterns with different similarity measurements. Among these studies, K-means method has shown its superiority in electricity consumption data analysis compared with other clustering algorithms (Benmouiza and Cheknane, 2013). However, K-means has some inherent deficiencies that may affect the performance of electricity consumption pattern mining. Traditional similarity measurements, such as Euclidean distance, cannot discover the shape similarity of ECPs (Wen et al., 2019). As a result, a research gap is found in the optimization of the number of centres instead of setting arbitrary numbers based on projected data.

Aim

The aim of this study is to identify different patterns of electricity consumption by considering representative building structures and construction years through bottom-up approach consisting of unsupervised learning by using PCA for dimensional reduction and K-means algorithm for clustering analysis. There are two paradigms to model energy consumption in residential buildings: a top-down approach and a bottom-up approach. A top-down approach estimates the total energy consumption in a residential sector by means of macroeconomic variables (Muratori & Roberts, 2013). In this study, data was collected individually and the patterns are extracted based on monthly electricity data at the micro-data level, which indicates a bottom-up approach. It is an initial case study in a medium-sized municipality, Borlänge city, in Sweden. This study will be able to play vital role in future urban planning and development of Borlänge with respect to infrastructure and design of multifamily houses. This will help the decision-making processes in relation to maintaining or renovating different types of buildings based on their energy consumption and year of construction.

Case information and data acquisition

Case study in Borlänge municipality, Sweden

Borlänge municipality was built in 1944. The administrative area is 5 867 km^2 and consists of several population centres: Borlänge city, Romme, Ornäs, Torsång, Halvarsgårdarna, Idkerberget, Norr Amsberg, Repbäcket. Tunabyggen, established in 1984, works with a socially beneficial perspective. They have about 5 100 homes and about 370 commercial premises. The strategic plan of Borlänge municipality for the year 2020-2030 shows that municipality has a future task to construct 1 500 new apartments and houses.

Collecting electricity consumption data and building feature data requires integrating information from different sources. Matching individual building data has been implemented by the project group before the analysis. Electricity consumption data was collected from Tunabyggen AB (local housing company) in pdf (portable data format) containing 375 pages. Each page contains year, address, ID, monthly meter reading consumption of electricity (kWh), district heating (MWh), flow (m3). There are also specific days on which data was not collected. The file contains addresses of 210 buildings and 431 meter reading for the year 2018. We have finally figured out a dataset containing addresses of the building, type of construction, geolocation of the buildings, meter number, monthly energy consumption in the form electricity (khW), district heating (MWh) and flow (m^3).

Building structures and construction years were manually collected from the web source www.hitta.se. This was validated with cross check with map.google.com.

Methodology and model development

In whole-building energy consumption simulation, there are two paradigms of modelling approaches in residential buildings: a top-down approach and a bottom-up approach (Swan and Ugursal, 2009). The top-down approach estimates the total energy consumption in a residential sector by means of macroeconomic variables (Muratori et al., 2013). The bottom-up approach, on the other hand, estimates the energy consumption of an area by a process of synthesis and models individual end uses at the building level (McKenna and Krawczynski, 2015). The bottom-up approach consists of two distinct categories: (1) statistical models regarding energy consumption as a function of house characteristics. They employ regression, conditional demand analysis, or neural networks to predict consumption based on the historical data (Swan and Ugursal, 2009). Many researchers employed artificial neural network and support vector machine analysis to investigate energy consumption in buildings; (2) engineering models utilizing physical principles to calculate the building energy consumption based on the building's physics (Zhao and Magoulès, 2012). This requires detailed data on physical variables such as area and thermal characteristics of building envelopes, indoor and outdoor temperatures, appliances, solar radiation, building occupancy and so on.

The methodology adopted in this study is bottom-up approach consisting of unsupervised learning by using PCA for dimensional reduction and K-means algorithm for clustering analysis. Building structures and construction years based on clusters are then summarized for each cluster. For a detailed framework, this study extends the methodology in a previous work (Jin et al., 2019) by looking at the building structures and construction years.

Dimension Reduction

Dimension reduction projects high dimensional data to a lower dimension. Less dimension leads to a condensed data representation and it also helps in visualizing data. PCA has been widely used in statistical analysis. It is a multivariate statistical method to investigate the correlation among multiple variables and to reveal the internal structure of a number of variables through a few principal components. To retain as much information of the original variables as possible, a small number of principal components are derived from the original variables, and they are not correlated to each other. Specifically, the function of PCA is to transform a set of variables which may have correlation into a set of linearly independent variables through orthogonal transforms. The set of transformed variables are usually called principal components.

Specifically, for a d-dimensional sample $X = (x^{(1)}, x^{(2)}, \dots x^{(n)})$, the first step is to centralize the observations:

$$x^{(i)} = x^{(i)} - \frac{1}{n}\sum_{j=1}^{n} x^{(j)}. \qquad (1)$$

A $n \times d$ matrix $\boldsymbol{X}$ is then constructed for storing the sample. Eigenvalues of the covariance matrix, $\boldsymbol{\Sigma} = \frac{1}{n-1}\boldsymbol{X}^T\boldsymbol{X}$ are sorted $\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_d$. Eigenvectors corresponding to the largest l eigenvalues are identified: $\boldsymbol{w_1}, \boldsymbol{w_2}, \dots \boldsymbol{w_l}$. For each sample data point, the transformation $x^{(i)}{}_{1\times d}\boldsymbol{w}_{d\times l}$ reduce the dimension from d to l.

K-means clustering

Clustering analysis is also a statistical analysis method to study the pattern recognition problems in data mining. K-means clustering analysis is an unsupervised learning process that identifies potentially similar patterns in a dataset without any prior information. As a simple and efficient algorithm, K-means clustering has been widely used to analyse smart meter data. It can recognize different patterns of electricity consumption and identify residents with the same electricity consumption pattern, thereby to support decision-making and implement more flexible.

Results and discussion

Instead of randomly choosing the number of dimensions to reduce down, it is generally preferable to choose the number of dimensions that add up to a sufficiently large portion of the variance (for example, 95%). A float value between 0 and 1 is used for indicating the ratio of variance to be preserved in PCA. The technique used is to plot the explained variance as a function of the number of dimensions by using the cumulative sum as shown in Figure 1, where a flex point in the curve indicates that the desired variance is obtained.

The horizontal axis shows the number of projected dimensions, while the vertical axis represents the explained variance by PCA. From Figure 1, the number of dimensions reduced of data frame is 2 with explained variance over 99.5% for implementation of K-means algorithm. Increasing the number of components will not significantly increase the explained variance.

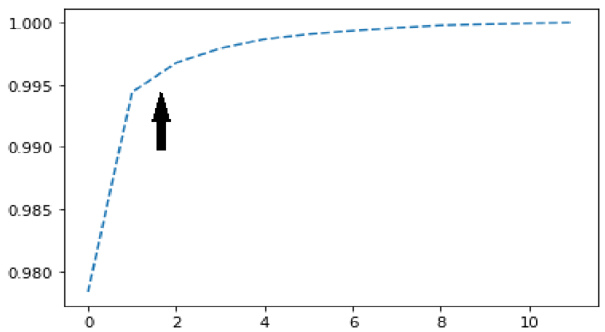

Figure 1: Explained variance as a function of the number of dimensions

For the implementation of K-means, we need to find out optimal number of clusters in which the index indicating within clusters sum of square is calculated. The Elbow method is a technique used to get the sum of square. The idea is to run K-means for different number of clusters and to see which one of those amounts is the optimal number. The objective is to find a balance point on which the samples are the most homogeneous in a group and the clusters are the most different from one another. We calculate the distances between samples and the centre of the cluster from which the sample belongs. The best ultimate is that in-group distance is the smallest possible. In this study, we run K-means clustering for a range of cluster numbers, *k* (1 to 9), and for each value of *k*, the sum of squared distances from each point to its assigned entre (distortions) is calculated. When the distortions are plotted, the plot like an arm as shown in Figure 2 forms the “Elbow” (the point of in on the curve) where we have the optimal value of k. In another word, the distance from the calculated distortion to the line connecting two extreme distortions is maximized. The balance point indicates the optimal number of clusters in the Elbow method and thus the value of *k* is 3.

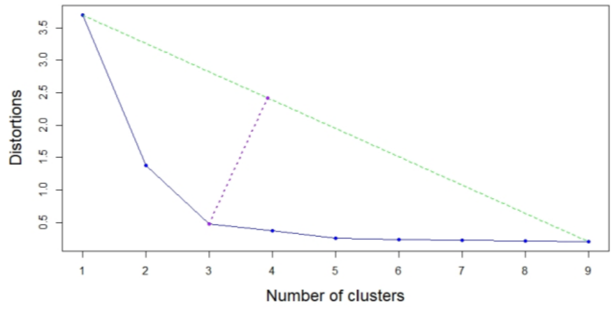

Figure 2 The Elbow method for showing optimal number of clustering

Based on the collected data, we have conducted PCA and K-means, where three clusters were finally identified (C1, C2 and C3). Table 1 shows each cluster with peak and valley values based on average monthly electricity consumption in each cluster. As shown in the table, the peak values are in January and valley values are in June or July. C2 has the highest variance with more than 5000 kWh difference between the peak month and valley month. On the other hand, difference for C3 is less than 500 kWh. C1 is in the middle in terms of both monthly consumption and variance. We will further scrutinize the features of the buildings in each cluster.

Table 1: Cluster values.

Cluster	Valley	Peak	Total
C1	4 351	6 446	64 575
C2	18 976	24 662	259 848
C3	697	1 159	11 153

There are eight different types of building structures used in this study. The highest number of buildings structure constructed in Borlänge municipality is the structure called a multi-family house, which is 129 in numbers out of 210 total numbers of buildings. One apartment block forms the second largest structure. Building structures, their quantity and explanation of abbreviation are shown in Table 2. Regarding the building construction year, it was found that earliest building was constructed in 1930 and it was of type a multi-family house. The newest building was constructed in 2002 with same building structure. Year of construction is grouped by 20 years and we have identified the number of different building structures in each period.

Table 2: Building structures and their quantity

Building structures	Quantity
Multi-family house	129
One apartment block-multifamily house	3
Unspecified places (VS)	3
Gathering place (Sam)	3
One apartment block	33
Apartment buildings and villas (ST)	2
Apartment buildings	28
Non-living area (NL)	9
Total	210

It can be summarized from the data that C1 contains 46 buildings, C2 contains just 5 buildings and C3 contains 159 buildings out of total 210 building. Figure 3 shows the average monthly electricity consumptions for each of the building clusters, where C2 consumes highest electricity and C3 consumes the lowest.

Buildings of multi-family house that were built in 1970s and 1990s form the largest number of buildings in C1, which indicates that these types of buildings can represent the most of the features of C1.

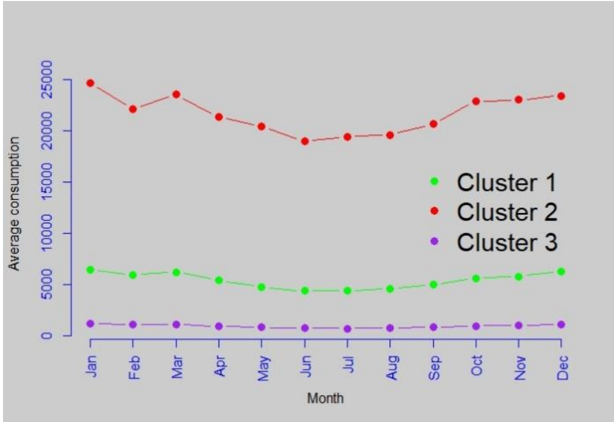

Figure 3 Average monthly electricity consumption

It is also found that C2 only has five buildings, where apartment buildings are the most. 60% of the buildings were built in 1950s and 40% were built in 1970s. What it can be seen is that apartment buildings for these two periods are representative and could indicate high electricity consumption compared to other building structures. For C3, multi-family house and one apartment block are the most common building structures. Multi-family house built in 1950s and 1970s and one apartment block built in 1950s are the most representative buildings for C3 that consumes lowest total annual electricity.

Conclusion

This study starts with the missing data padding of electricity consumption and we find out the most suitable electricity pattern by making use of PCA and K-means methods. We have also classified building structures and construction years with respect to their electricity consumption and found out the relations between electricity consumption and building structures as well as the construction years. Buildings samples in Borlänge can be made into three clusters. For the cluster with lowest electricity consumption, multi-family house built in 1950s and 1970s are the most common types. Buildings with same features can be considered as lower energy use buildings. However, cluster of high electricity consumptions has only five observations. Although apartment buildings built in 1950s to 1970s are representative, individual study for the reason of high consumption is needed. This study has contributed to figure out energy consumption patterns at the urban scale, which has rarely been formulated in the previous study.

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Validation of Norwegian Residential Building Archetypes Based on Empirical Data and Numerical Simulations

Kamilla Heimar Andersen[1*], Synne Krekling Lien[1], Hanne Bottolfsen[1], Aksel Garvik Fagerheim[2], Igor Sartori[1]
[1]SINTEF Community, Oslo, Norway
[2]Aalborg University, Aalborg, Denmark
* *corresponding author: Kamilla.andersen@sintef.no*

Abstract

This study investigates the validation of Norwegian apartment archetypes developed in the Building Performance Simulation (BPS) program IDA ICE and empirical data from a large building stock, with a focus on space heating. The results of this validation, using CV(RMSE), NMBE, and R^2 as validation parameters show that the archetypes developed with the TABULA/EPISCOPE values in IDA ICE need further tuning to provide properly validated archetypes according to the threshold values for space heating.

Introduction

Building Performance Simulations (BPS) is often used to describe the characteristics of buildings and simulate the reality due to the many useful and cost-effective features. Nevertheless, many previous studies have shown that a significant deviation exists between simulation results and actual performance of the buildings, especially for low-energy ones (deWilde, 2014) (Loukou et al., 2019) (Gram-Hanssen et al., 2016). Further efforts are needed to identify more realistic input values, fill and brigde the gaps. This study aims to validate a set of Building Performance Simulation (BPS) models in IDA ICE representing the Norwegian stock of apartment blocks, previously developed in the TABULA/EPISCOPE project, against a large dataset of measured buildings in Norway. The validation focuses on the heating demand (space heating) of the empirical data and the numerical simulation. To validate the archetypes, we compare the difference between the archetypes and the energy measurements in terms of annual energy performance (space heating), load duration curve, and typical daily load profiles.

Methodologies

Numerical simulations, together with empirical data, form the basis for this validation study and are presented in the sections below. The conversion of weather data and the validation methods are also presented below.

Numerical modeling

The numerical models, the archetypes in IDA ICE used in this study were previously developed by Rønneseth et al. in 2019. The archetypes have adopted the TABULA/EPISCOPE values for model 80-60 (supply and return temperatures at maximum power at dimensioning outdoor temperature at -20 °C) variant 1, variant 1* (renovated u-values on windows and infiltration rate) and variant 2. More information about the TABULA/EPISCOPE project can be found here: https://episcope.eu/building-typology/country/no/.

Four archetypes were chosen in this study corresponding to the same floor area of 1672 m^2 and consisting of 24 apartments in total divided into four floors. There are three zones in each apartment, consisting of one bedroom, one day room, and one bathroom. The bathroom has electrical radiators, while the bedroom and day room has water radiators. The archetypes cohort and construction period can be seen in Table 1.

Table 1: Archetypes cohort and their construction year used in this study.

Archetype cohort	Construction period
AB03	1971-1980
AB06	2001-2010
AB07	2010-2020 (TEK10: https://dibk.no/byggeregler/tek/)
AB08	After 2020 (NS 3700:2013 Kriterier for passivhus og lavenergibygninger)

Empirical data

Empirical data from Norwegian apartment buildings in specific construction years have been chosen for this analysis. Measurements were conducted from 2014-2019 and origin from Trondheim and Oslo in Norway. Hence the choice of weather files for the numerical simulations. Information about the different archetype empirical data can be seen in Table 2, below.

Table 2: Empirical data information.

Cohort [-]	Nr. of files [-]	Total floor area [m^2]
AB03 Trondheim	10	46 030
AB06 Trondheim	7	20 105
AB07 Trondheim	32	93 750
AB08 Trondheim	2	5 780
AB0607 Oslo	44	Normalized at 27 000 m^2 per file Sum: 1 188 000
Sum	**95**	**1 353 665**

One limitation in the Oslo empirical data was that these measurements did not have any available m^2 and only an approximate construction year, so it was chosen to mix the two archetypes together as one archetype, with the cohort AB0607.

Weather files

To increase the comparability between simulations and building measurements, all simulations were run with "local" climate data. Four weather files in total were generated from the locations Trondheim (three) and Oslo (one). Each weather file corresponded to each archetype based on where and when the measurements in the empirical data were conducted, see Table 3, below.

Table 3: Corresponding weather file for each archetype.

Cohort	Location
AB03	Trondheim 2018
AB06	Trondheim 2017
AB07	Trondheim 2017
AB08	Trondheim 2015
AB0607	Oslo 2017

Validation metrics

Normalized Mean Bias Error (NMBE), Coefficient of Variance Root Mean Squared Error (CVRMSE) and Coefficient of Determination, the R^2 have been chosen in this study. The R^2 can be interpreted as the proportion of response variation "explained" by the regressors in the model (Kvålseth O. T., 1985). According to ASHRAE 14-2014 and IPMVP EVO 10000-1:2012, the NMBE normalizes the average difference between the empirical data point and the numerical simulation point. The NMBE is an acceptable indicator of the overall bias of the numerical model (global under-estimation or global over-estimation). However, positive bias compensates for negative bias (cancellation effect). The CV(RMSE) quantifies the difference between one point in the empirical data and one point in the numerical simulation data. The CV(RMSE) is more suitable to determine the model fit by calculating the normalized RMSE between the numerical simulations and the empirical data. It is not subjected to cancellation and compensation effects.

Equation 1 describes the Normalized Mean Bias Error (NMBE) [%] function, according to ASHRAE Standard 14-2014.

$$\mathbf{NMBE}\ [\%] = \frac{\frac{\sum_{i=1}^{n}(Ye - Yn)}{ne}}{\overline{Ye}} * 100 \qquad \mathbf{(1)}$$

Ye = Empirical data point

Yn = Numerical simulation point

ne = Number of empirical data points

$\overline{Y}$e = Mean of the empirical data points

Equation 2 describes the Coefficient of Variation Root Mean Squared Error (CV(RMSE)) [%] function (Ashrae Standard 14-2014).

$$\mathbf{CV(RMSE)}\ [\%] = \frac{\sqrt{\frac{\sum_{i=1}^{n}(Ye - Yn)^2}{ne}}}{\overline{Ye}} * 100 \qquad \mathbf{(2)}$$

Ye = Empirical data point

Yn = Numerical simulated point

ne = Number of empirical data points

$\overline{Y}$e = Mean of the empirical data points

Equation 3 describes the Coefficient of Determination (R^2 [-]) can be calculated by the following steps shown below (Kvålseth O. T., 1985) (https://scikit-learn.org/stable/modules/model_evaluation.html#r2-score)

1) Calculating the mean of the data:

$$\overline{ye} = \frac{1}{ne}\sum_{i=1}^{n} ye$$

2) Residual sum of squares of the residuals:

$$SSres = \sum_i (ye - yn)^2 = \sum_i ei^2$$

3) The total sum of squares:

$$SStot = \sum_i (yi - \overline{y})^2$$

$\overline{Ye}$ = The mean of the empirical data

Ye = Empirical data point

ne = Number of empirical data points

Yn = Numerical simulation data point

ei = Residuals

Final R^2 formula is described below.

$$\mathbf{R^2}\ [-] = \mathbf{1} - \frac{\mathbf{SSres}}{\mathbf{SStot}} \qquad \mathbf{(3)}$$

The NMBE, CV(RMSE), and R^2 were calculated with a script in Python.

The following threshold values for validation of the numerical simulations are shown in Table 4 for CV(RMSE), NMBE, and R^2.

Table 4: Threshold values used for validation of the numerical simulations.

Parameter	Threshold	Reference
NMBE [%]	< 5 %	ASHRAE 14-2014, EVO 10000-1:2012
CV(RMSE) [%]	< 30 %	ASHRAE 14-2014, EVO 10000-1:2012
R^2 [-]	> 0.5	-

Results and discussion

Energy use

The short name for the empirical data and corresponding archetype will be denoted as ABXX-E, while the numerical simulations and corresponding archetype will be denoted as ABXX-N in this section.

The average total energy (kWh/m^2) use for the archetypes is shown in Table 5, below. Variant 1 is the original building properties, while the variant 2 has upgraded windows and infiltration, and variant 2 is full renovation.

Table 5: Average total annual energy use (kWh/m² year) for all archetypes.

Archetype	**Energy use var.1 [kWh/m² y]**	**Energy use var.1* [kWh/m² y]**	**Energy use var.2 [kWh/m² y]**
AB03-E		97	
AB03-N	113	98	**93**
AB06-E		103	
AB06-N	**58**	47	44
AB07-E		58	
AB07-N	**38**	31	18
AB0607-E		48	
AB0607-N	**47**	36	30
AB08-E		32	
AB08-N	**18**	-	-

It was chosen to continue analyzing archetype AB06, AB07, AB08, and AB0607 with var.1, as seen in the table above with a **bold** indicator. This due to no renovation or building improvements that are known when the measurements were conducted. However, for the AB03 archetype, it is known that the windows and infiltration improvements have been performed after construction. Therefore, it was chosen to continue with var.2 for AB03, as seen in bold numbers in the table above. AB08 was built according to passive house standard, there is no renovation above this and is therefore not evaluated for var.1* or 2.

The NMBE, CV(RMSE), and R^2 have been calculated for hourly values and can be seen in Table 6. The output results are marked with a **bold** indicator if they satisfy the threshold values according to Table 4, above.

Table 6: CV(RMSE), NMBE, and R^2 are calculated for the empirical data, and the numerical simulation data with annual hourly averaged values (8760 data points), with the unit Wh/m².

Archetype	**NMBE [%]**	**CV(RMSE) [%]**	**R^2 [-]**
AB03 var.2	**3.7**	48	**0.50**
AB06 var.1	31	47	**0.52**
AB07 var.1	23	49	**0.50**
AB0607 var.1	**2**	48	**0.62**
AB08 var.1	40	84	0.28

As one can see from Table 6 above, the archetypes can be considered as not valid according to the threshold values for three archetypes regarding NMBE, all for CV(RMSE), and one for R^2 as they are above 5% (NMBE), 30% (CV(RMSE)). The main reason for this is due to widespread data points in the comparison sets, creating a large difference between the empirical data and numerical results. However, the R^2 is above 0.5 in four out of five archetypes. This means that over 50 % of the proportion of variance in the dependent variable can be explained by the independent variable.

Typical average profiles

A typical day for archetype AB06 divided into four seasons (winter, spring, summer, and autumn) can be seen in Figure 3 and Figure 4, below. The typical day is the average day of the whole season in Wh/m² with 24 data points. Winter was defined from December-February, spring from March-May, summer from June-August, and autumn from September-November.

The empirical data and numerical simulation for all four seasons show that the empirical data consumes up to 50 % more than the numerical simulation. In the winter and autumn, the energy use (space heating) of the empirical data and the numerical simulations go in opposite directions, especially at noon. This can be due to the tabulated values in the numerical simulation, providing a lower space heating at noon and afternoon. Other energy parameters correlated to the space heating are internal gains, solar radiation, outdoor temperature, heating/cooling setpoint, to mention a few who also can affect the space heating.

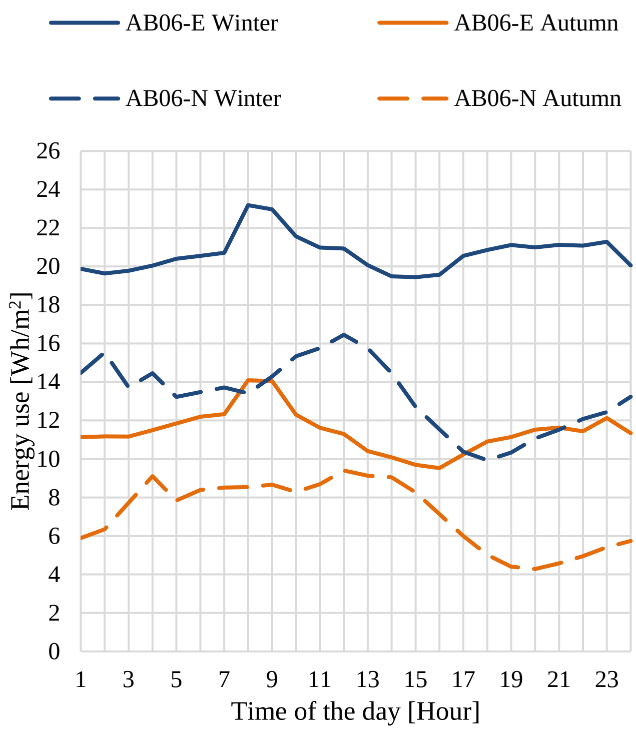

Figure 1: A typical workday is presented with the season's winter (blue lines) and autumn (orange lines) for empirical data, numerical simulations, and scaled numerical simulations.

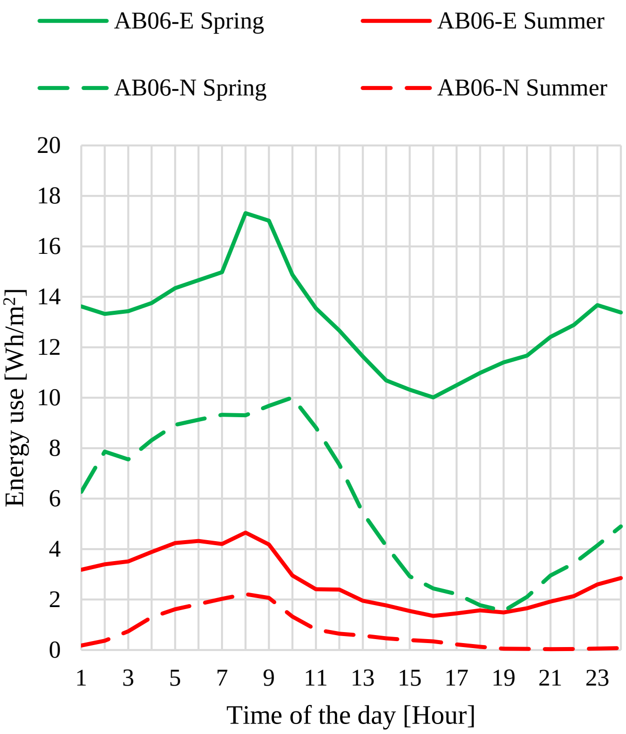

Figure 2: A typical workday is presented with the season's spring (green lines) and summer (red lines) for empirical data, numerical simulations, and scaled numerical simulations.

Conclusion

This study aimed to validate a set of Building Performance Simulation (BPS) archetype models in IDA ICE representing the Norwegian stock of apartment blocks against a large dataset of measured buildings in Norway. The validation focused on the heating demand (space heating) of the empirical data against numerical simulations in IDA ICE. Each empirical archetype was validated with annual hourly values (8760 data points) to investigate the different threshold values according to NMBE, CV(RMSE), and R^2. The main finding in this study shows that the numerical simulations, the archetypes, can be validated accordingly to the R^2, which is > 0.5 for annual hourly values. However, this is not the case for the passive house archetype (AB08). Nevertheless, for the threshold values regarding NMBE (< 5%) and CV(RMSE) (< 30%), the annual hourly values are not valid for space heating.

The tabulated input values in the numerical simulations are too idealized and do not provide realistic energy profiles. We will continue to investigate and tune the archetypes in IDA ICE.

Acknowledgment

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Numerical Simulation in Transient Conditions of a University Building with Complex Topology Equipped with Greenhouses in Winter Conditions

Eusébio Z. E. Conceição[1*], Mª Manuela J. R. Lúcio[1] and Hazim B. Awbi[2]
[1]FCT - University of Algarve, Campus de Gambelas, 8005-139 Faro, Portugal
[2]School of Construction Management & Engineering, University of Reading, Reading, RG6, 6AW, United Kingdom
** corresponding author: econcei@ualg.pt*

Abstract

In the present paper is applied a numerical model which incorporates the building thermal behaviour with the human thermal-physiology. The building model uses an equations system, based in energy and mass balance integral equations, solved using the Runge–Kutta–Felberg method with error control.

In this numerical study is analysed a university building with complex topology, in winter and transient conditions. The thermal comfort, using the PMV index, and the air quality, using the carbon dioxide concentration, are evaluated. The building, with 319 compartments and with four floors, is equipped with two warm internal greenhouses in each floor.

The warm internal greenhouses contribute to increase the air temperature and the comfort levels. The indoor air quality is acceptable in all occupied spaces.

Introduction

In the South of Portugal, with a mediterranean climate, it is very important to develop university buildings adapted to this region, in order to promote the increase of the occupants' comfort conditions, namely the thermal and air quality, as well as promoting the reduction of energy consumption levels.

This work is a continuation of Conceição *et al.* (2008). In the previous study a greenhouse applied in a kindergarten was made. However, in this study, the greenhouse is applied to a university building with complex topology.

In winter conditions renewable resources are used, like direct solar radiation, to increase the internal air temperature level. The energy management in this kind of situation, to obtain a better thermal comfort field inside a building environment, is frequently made using (1) internal greenhouses, (2) heating systems using warmed water in external collectors, or simply, (3) use passive strategies that expose directly the windows to solar radiation (Conceição *et al.*, 2019). In this work the internal greenhouses and the passive strategies that expose directly the windows to the solar radiation are applied.

The numerical model, used in this work and developed by the authors in the last years, see Conceição *et al.* (2019), Conceição and Lúcio (2010) and Conceição *et al.* (2012), as examples, is based on energy and mass balance integral equations system and works under transient conditions. All equations are developed, by the numerical software, using the building geometry developed by the Computing Aid Design (CAD).

To evaluate the thermal comfort level in moderate environments, during winter conditions, the PMV (Predicted Mean Vote) and the PPD (Predicted Percentage of Dissatisfied people) indexes are used in ISO (2005) and ASHRAE-55 (2017) and developed in Fanger (1970). For acceptable thermal comfort conditions, the ISO (2005) and ASHRAE-55 (2017) defines three comfort categories (A, B and C).

To promote thermal comfort conditions different techniques can be used such as the control using preferred air temperature (Conceição *et al.*, 2009), using thermal comfort level (Conceição *et al.*, 2018) and using the adaptive thermal comfort level (Conceição *et al.*, 2010).

The numerical model evaluates the thermal comfort level, based in the human thermo-physiology, for each space. This thermal comfort level is associated to the mean value that the occupants are subjected. Some examples of this application are showed in Conceição and Lúcio (2010b), in study of shading devices promoted by external trees in summer conditions, and in Conceição and Lúcio (2009), in the study of a school building subjected to solar radiation with different orientations.

The air quality evaluation is made using the carbon dioxide concentration, in accordance with ASHRAE 62 (2019). In this study the airflow rate of exchanging air with the external environment is made. Examples of studies that use techniques to evaluate the airflow rate can be analysed in Conceicão *et al.* (1997) or in Conceição *et al.* (2012).

Numerical Model

The numerical model used in this work, which simulates the thermal response of buildings with complex topology, is presented in detail in, as example, Conceicão *et al.* (2000) and Conceição and Lúcio (2010a) and is based on the balance integral equations of energy and mass and works in transient conditions.

The energy balance integral equations, are developed for the air, the different transparent bodies, the interior bodies, and the opaque bodies of the building. In the opaque surfaces several layers are considered, while in the transparent surfaces only one layer is considered. In the compartment air is considered the space surrounding boundaries.

The mass balance integral equations, for the water vapour and for the air contaminants, are developed for the spaces and for the solid matrix (opaque and interior bodies).

In the resolution of the equations system, the Runge–Kutta–Felberg method with error control is used.

The Building Dynamic numerical model, used in this study, was validated in Conceição *et al.* (2004), in winter conditions, and Conceição and Lúcio (2006), in summer conditions.

The indoor air temperature, air relative humidity, air velocity and Mean Radiant Temperature are used to evaluate the thermal comfort level. The adaptive thermal comfort indexes consider not only the previous variables, but also the external air temperature.

The balance integral equations system, used in the numerical model, is developed through a virtual building using CAD.

Numerical Methodology

The numerical study was developed with a university building, mainly consisting of classrooms, laboratories, offices and other spaces. The simulation is made on 21st December for a latitude of 39º North. The building (Figure 1), distributed by four floors, considers 319 interior spaces, 329 transparent surfaces (windows) and 3585 opaque surfaces.

This figure present, in grey, the exterior walls, in blue, the windows, in green, the doors, and in orange and red, different roofs.

The numerical model uses the three-dimensional virtual building, developed using CAD, not only to generate the integral balance equations system, but also to calculate the area and identify the thermal proprieties of (1) opaque bodies; (2) transparent bodies; (3) interior bodies and (4) spaces volume.

In this simulation the occupation, in general, is verified during 01h30m and the break, in general, is verified during 15 minutes. However, some spaces present other cycles. The occupied cycle considers people (with an activity level of 1.2 met) with clothing level of 1 clo (for a typical winter day).

In the ventilation cycle is considered an airflow rate calculated in accordance with the Portuguese standard RECS (2013) and experimental measurements. The airflow rate per occupant is used in occupied spaces and is calculated based in the Portuguese standard in function of the kind of space. The air exchange rate, used in not occupied spaces, is calculated in accordance with obtained experimental data, using the tracer gases techniques (Conceição *et al.*, 2008).

This study, made in winter conditions, considers two greenhouses (in each level of the 3 floors) spaces with a large window area turned mainly to South: one to South and East and another to South and West.

In the East-South side, the air from the greenhouse (space 34, wall) is transported to seven spaces. In this study only are presented, as example, the spaces 41, 42, 51 and 52. In the West-South side, the air from the greenhouse (space 12, wall) is transported to ten spaces. In the present study only are presented, the spaces 2, 13 and 21.

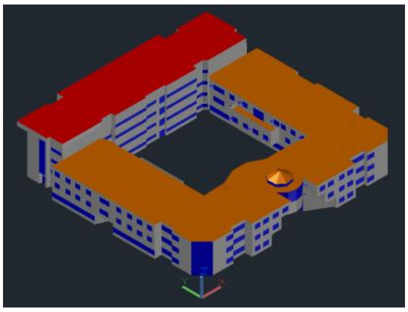

Figure 1: *External perspective of the university building. South-West View.*

In the study two situations were studied, namely (1) without greenhouse (the airflow rate, in the inlet process, came from the outside environment to the occupied space and, in the outlet process, came from the occupied space to the outside environment) and (2) with greenhouse (the airflow rate, in the inlet process, came from the warm greenhouse to the occupied space and, in the outlet process, came from the occupied space to the outside environment).

The numerical simulation considers, as external environmental conditions, the evolution of external air temperature; air relative humidity; air velocity and air velocity direction (obtained through an external meteorological station).

Results

The simulation presented in this section shows the evolution of internal air temperature, thermal comfort level, using the PMV index, and the indoor air quality level, using the carbon dioxide concentration.

All compartments and building structures were simulated. However, in this work only are considered results of some spaces in the first floor.

In Figures 2 and 3 are presented the evolution of air temperature in spaces of the first floor, in winter conditions. In both figures, and in the next, W is associated to the situation without greenhouse, while the G is associated to the situation with greenhouse.

The air temperature in each occupied space is higher (1 to 3 ºC) when the greenhouse is used than when the greenhouse is not used. The air temperature in the greenhouse (spaces 12 and 34) is lower (4 to 6 ºC) when is considered the greenhouse than when is not considered.

When the greenhouse is not considered, the internal air temperature, in spaces with window turned East, increases in the morning and, in spaces with window turned West, increases in the afternoon. However, when the greenhouses are used, the internal air temperature in spaces with windows turned East or West increases both in the morning and in the afternoon.

In Figures 4 and 5 is presented the evolution of the PMV index in spaces of the first floor, in winter conditions.

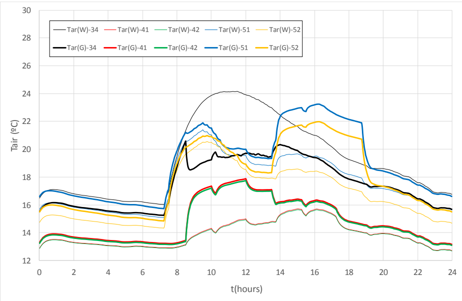

Figure 2 – Evolution of air temperature (Tair) in the first floor, in the East side building, in winter conditions.

Spaces subjected to the influence of air from the greenhouse increase the thermal comfort level. However, the thermal comfort level with acceptable conditions only is verified in (1) spaces with windows turned East and subjected to heated airflow from a greenhouse with windows turned to South and East and (2) spaces with windows turned West and subjected to heated airflow from a greenhouse with windows turned to South and West.

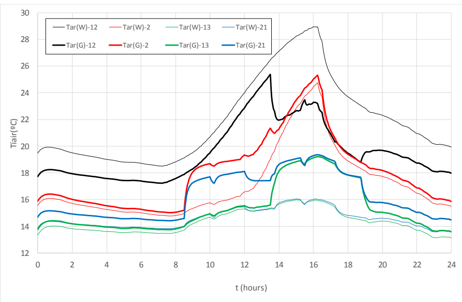

Figure 3 – Evolution of air temperature (Tair) in the first floor, in the West side building, in winter conditions.

The airflow is proportional to the occupation level. Thus, as the airflow coming from the greenhouse to the laboratories (see as example greenhouses 51 and 52) is higher than the airflow coming from the greenhouse to the office (see as example offices 41 and 42), the air temperature and the PMV index of the laboratories are higher than the verified in the office.

When the airflow coming from the greenhouse to the space is the same (see as example spaces 2, 13 and 21), the highest temperature (or comfort) levels, are verified in spaces with windows subjected to highest radiation level (see as example office 2).

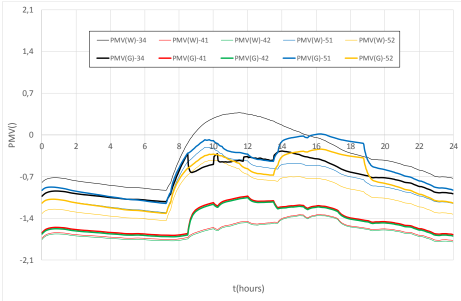

Figure 4 – Evolution of PMV index in the first floor, in the East side building, in winter conditions.

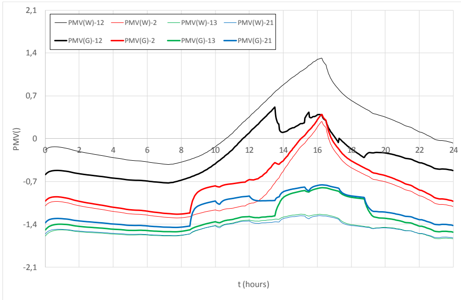

Figure 5 – Evolution of PMV index in the first floor, in the West side building, in winter conditions.

In Figures 6 and 7 are presented the evolution of carbon dioxide concentration in spaces of the first floor, in winter conditions.

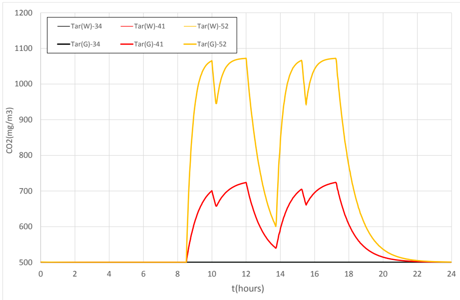

Figure 6 – Evolution of Carbon Dioxide concentration in the first floor, in the East side building, in winter conditions.

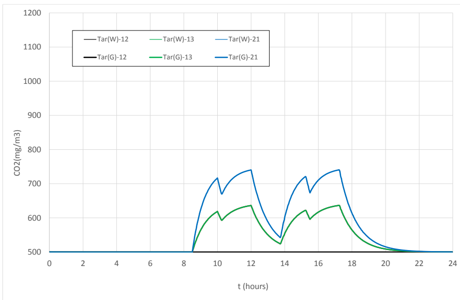

Figure 7 – Evolution of Carbon Dioxide concentration *in the first floor, in the East side building, in winter conditions.*

The carbon dioxide concentration is lower than the recommendation values (ASHRAE 62, 2019). Thus, the indoor air quality is acceptable for all compartments.

Conclusion

The greenhouses present an important contribute to increase the air temperature in all occupied spaces in winter conditions. In general, the greenhouses increase the air temperature up until 3ºC.

The thermal comfort levels in spaces subjected to the influence of air from the greenhouses increase the thermal comfort levels. However, acceptable thermal comfort levels only are verified in spaces with window turned East and subjected to heated airflow from greenhouses with windows turned to South and East and in spaces with windows turned West and subjected to heated airflow from greenhouses with windows turned to South and West.

The indoor air quality levels are acceptable, in accordance with international standards, in all occupied spaces.

Acknowledgement

The author would like to acknowledge to the project (SAICT-ALG/39586/2018) from Algarve Regional Operational Program (CRESC Algarve 2020), under the PORTUGAL 2020 Partnership Agreement, through the European Regional Development Fund (ERDF) and the National Science and Technology Foundation (FCT).

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Definitions of Floor Area and Evaluating Impacts in Energy Simulation

Nicholas Allen-Sandoz
Jaros Baum & Bolles, New York, USA
nickallensandoz@gmail.com

Abstract

The modeled conditioned floor area must be the same for the baseline and proposed design, and aligned design documents. Deviations between modeled area and area specified in design documents commonly occur. Narratives are commonly provided to explain the difference. Gross floor area reported in design documents is based on the definition in the International Code Council's International Building Code, which differs from the ANSI/ASHRAE/IES Standard 90.1 definition. Section 11 and Appendix G of ANSI/ASHRAE/IES Standard 90.1 do not explicitly specify how building area should be inputted into the model.

Introduction

Interpretations of floor area definitions can lead to inaccurate performance of new construction and challenges with calibration for existing buildings. Figure 1 shows an example thermal zone with considerable wall thickness. Interpretations of modeled conditioned floor area can affect the envelope fenestration and skylight area allowances. Assumptions for occupant densities on a per floor area basis can impact assumed minimum ventilation requirements and domestic hot water loads. HVAC performance is impacted due to changes in system load sizing and applicable minimum efficiency requirements due to unregulated internal load assumptions based on floor area. Interpretations of the lighted floor area versus conditioned floor area affect the baseline interior lighting power density allowance. Evidence of different modeled conditioned floor area interpretations that are permitted for rating authorities such as with the United States Green Building Council's Leadership in Energy & Environmental Design which describe an allowed +10% variance.

Standard Definitions of Floor Area

As per the International Building Code, FLOOR AREA, GROSS is defined as

> The floor face of exterior and courts, without deductions for corridors, stairways, ramps, closets, the thickness of interior walls, columns or other features. The floor area of a building, or portion thereof, not provided with surrounding exterior walls shall be the usable area under the horizontal projection of the roof of floor above. The gross floor area shall not include shafts with no openings or interior courts.

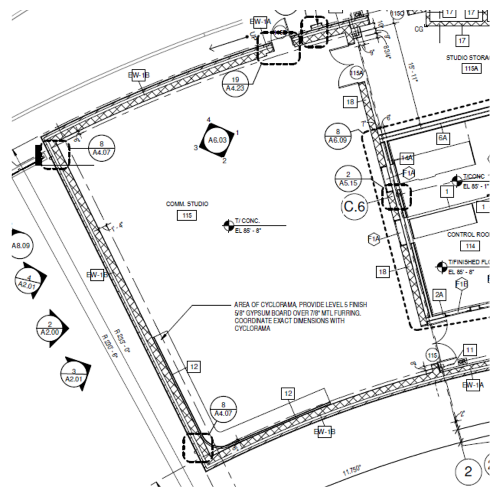

Figure 1: Example thermal zone

As per ANSI/ASHRAE/IES Standard 90.1-2019 Conditioned floor area, is defined as

> Floor area, gross: sum of the floor areas of the spaces within the building, including basements, mezzanine and intermediate-floored tiers, and penthouses with a headroom height of 7.5 ft or greater**.** It is measured from the exterior faces of walls or from the centerline of walls separating buildings, but excluding covered walkways, open roofed-over areas, porches and similar spaces, pipe trenches, exterior terraces or steps, chimneys, roof overhangs, and similar features.

Figure 2 illustrates the same thermal zone show in Figure 1 and with the IBC floor area definition shown in pink and the ASHRAE Standard 90.1 floor area in yellow.

Other studies have been performed by National Renewable Energy Laboratory entitled Standard Definitions of Building Geometry for Energy Evaluation by Deru & Torcellini (2005) to clarify definitions of building geometry definitions but do not provide simulation results to evaluate the magnitude of impacts between interpretations. They describe gross conditioned floor area as measured from the inside surface of exterior walls but then describes gross roof area as measured from the exterior face of exterior walls. Thus, a given thermal zone with a roof surface will have a gross roof area greater than that of the conditioned floor area.

Some simulation tools may not have the ability to differentiate gross roof area of given thermal zone versus gross conditioned floor area and most tools will indicate a zone's roof area as identical to the modeled floor area. Simulating dedicated unconditioned zones to reflect exterior wall thickness would present arduous modeling development effort.

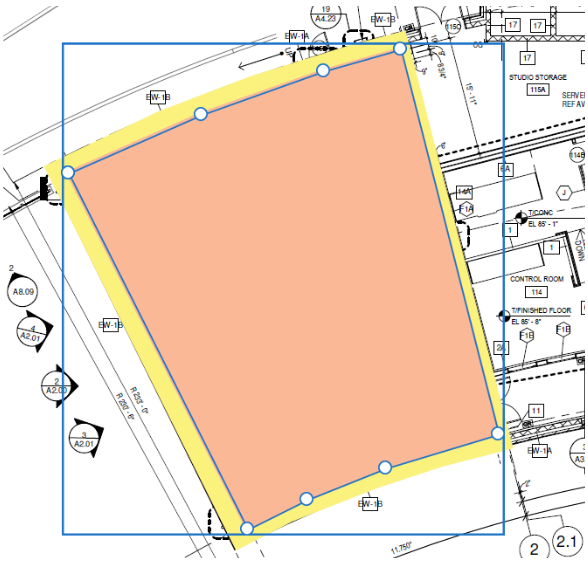

Figure 2: International Building Code floor area in pink and additional floor area of ANSI/ASHRAE/IES Standard 90.1 in yellow.

Method

Two prototype models have been developed using each floor area interpretation to illustrate the differences in building properties based on assumed floor area and are summarized in Figure 3, Figure 4 and Table 1. The prototype building shall be an academic building simplified to only include containing classrooms, offices, restrooms and corridors in climate zone 5A and are summarized in Table 2. Thermal zone and block layout follows a perimeter and core pattern with the perimeter zone extending 15' (4.572 meters) from the modeled edge of the building. Hourly building energy modeling is conducted using eQUEST 3-65 software build 7175 with DOE2.3 calculation engine for rapid simulation runtime and according to the methodology described in ANSI/ASHRAE/IES Standard 90.1 90.1-2016 Appendix G. COMNET Reference Appendices and ANSI/ASHRAE/ANSI 90.1-2013 User's Manual were used as references to resolve ambiguities present and to establish unknown building operating parameters (e.g. equipment plug loads, lighting hours of operation, etc.).

Summary of Modeling Inputs

Prototype model is a large academic building located in climate zone 5A using BRIDGECT TMY2 weather data. The building is an H shape and has 4 stories above grade. No shading by adjacent structures or terrain have been modeled. The classes are in session and offices are occupied all year excluding the 85 days of the year the school is unoccupied for winter, spring and summer breaks. A typical weekday is occupied from 7am to 6pm and unoccupied on the weekends. Occupied heating and cooling zone temperature setpoints are 21.1°C and 23.9°C, respectively. During unoccupied periods, HVAC systems do not provide ventilation and cycle intermittently to meet heating and cooling zone temperature setback setpoints of 17.8°C and 27.8°C, respectively.

Table 1: Summary of Modeled Conditioned Floor Area

Standard	*Floor Area (m^2)*	*Conditioned Volume (m^3)*
90.1	*13,470*	*53,372*
IBC	*12,281*	*46,662*

Table 2: Summary of Modeled Space Types

Standard	*Floor Area (m^2)*			
	Class room	*Office*	*Corridor*	*Rest room*
90.1	*7,649*	*1,816*	*2,787*	*1,217*
IBC	*6,798*	*1,614*	*2,787*	*1,082*

Classrooms, offices and restrooms are located within perimeter zones and include exterior wall thickness. The floor area of corridors remain unchanged since they include no exterior exposure and exterior wall thickness is not considered.

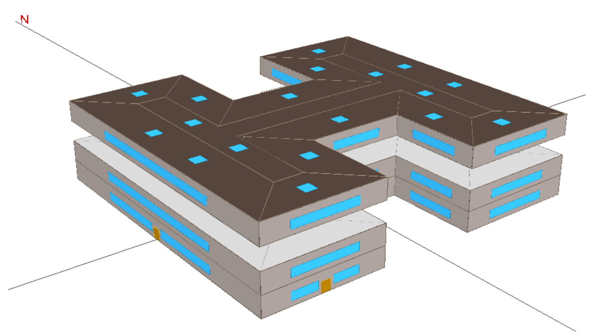

Figure 3: eQUEST rendering of prototype school building

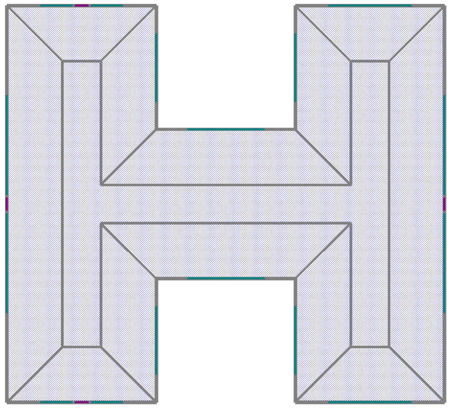

Figure 4: eQUEST rendering of perimeter-core thermal block mapping

Envelope Area

In both the cases of the design model, the International Building Code and ANSI/ASHRAE/IES Standard 90.1 design fenestration area and skylight area are the same but according to Appendix G of the standard, the baseline building's fenestration and skylight allowances change since interpretation of conditioned floor area changes and therefore simulated above grade wall area changes and is summarized in Table 3 and Table 4.

Table 3: Summary of Modeled Vertical Envelope Areas

Standard	*Above Grade Wall Area (m^2)*	*Vertical Fenestration Area (m^2)*	*WWR*
90.1 App G	*5,209*	*1,147*	*22.0%*
90.1 Design	*5,209*	*1,147*	*22.0%*
IBC App G	*5,093*	*1,121*	*22.0%*
IBC Design	*5,093*	*1,147*	*22.5%*

Window to Wall Ratio (WWR) is the ratio of building vertical fenestration area percentage of gross above-grade wall area. Gross above grade wall area includes fenestration area. Appendix G requires school buildings to have a 22% regardless of design fenestration area as per Table G3.1 and Table G3.1.1-1 of ANSI/ASHRAE/IES Standard 90.1 .

Table 4: Summary of Modeled Roof & Skylight Areas

Standard	*Roof Area (m^2)*	*Skylight Area (m^2)*	*Skylight to Roof Ratio*
90.1 App G	*3,266*	*98*	*3.0%*
90.1 Design	*3,266*	*98*	*3.0%*
IBC App G	*2,978*	*89*	*3.0%*
IBC Design	*2,978*	*98*	*3.3%*

Envelope Performance

The design model will include minimally compliant prescriptive envelope performance factors found in Table 5.5-5 of ANSI/ASHRAE/IES Standard 90.1-2019. Roofs are U-0.032 for insulation entirely above deck. Above grade walls are U-0.055 for steel-framed walls. The fenestration is fixed units with U-0.36, SHGC-0.38 and 1.1 VT/SHGC.

The baseline building is modeled according to the values prescribed in Appendix G of ANSI/ASHRAE/IES Standard 90.1-2016. Roofs are U-0.063 for insulation entirely above deck. Above grade walls are U-0.084 for nonresidential steel-framed walls. The fenestration is 20.1% to 30.0% with U-0.57 and SHGC-0.39. All entrance doors are over 50% glass and therefore qualify as fenestration as per definitions section of ANSI/ASHRAE/IES Standard 90.1-2016 for *door*.

Envelope Tightness

Air Change per Hour (ACH) is calculated according to Section G3.1.1.4 of ANSI/ASHRAE/IEC Standard 90.1-2016 and is summarized in Table 5. Modeled schedules include a 1.0 fraction for each hour HVAC fans systems are running continuously during occupied hours and 0.25 fraction for each hour HVAC fans systems cycle during unoccupied hours.

Table 5: Summary of Modeled infiltration inputs

Standard	*Surface Area (m^2)*	*Infiltration ACH*
90.1	*53,372*	*0.183*
IBC	*48,662*	*0.189*

Internal Loads

Table G3.1 of ANSI/ASHRAE/IES Standard 90.1 instructs that the interior lighting power in the baseline building shall be determined using the values in Table G3.7 of ANSI/ASHRAE/IES Standard 90.1. The ANSI/ASHRAE/IES Standard 90.1-2016 definition of *gross lighted floor area* is the *gross floor area* of lighted *spaces*. In both the cases of the design model, the International Building Code and ANSI/ASHRAE/IES Standard 90.1 design lighting watts is the same but according to Appendix G of the standard, the baseline building's allowance of lighting watts changes since interpretation of conditioned floor area changes. The modeled interior lighting is summarized in Table 6.

Table 6: Summary of Modeled lighting inputs

Standard	*Lighting Watts*	*Lighting Power Density (W/m²)*
90.1 App G	*163,560*	*12.14*
90.1 Design	*91,614*	*6.80*
IBC App G	*147,030*	*11.97*
IBC Design	*91,614*	*7.46*

The design model will include all prescriptive lighting controls found in Table 9.6.1 of ANSI/ASHRAE/IES Standard 90.1-2016. *All other classrooms/lecture halls/trainings rooms* are Modeled as 0.066 W/m^2 (0.71 W/ft^2) with the following controls; local control, partial automatic on, bilevel lighting control, automatic daylight responsive controls for sidelighting, automatic daylight responsive controls for toplighting (top floor only) and automatic full off. *Enclosed and >250 ft^2* are Modeled as 0.061 W/m^2 (0.66 W/ft^2) with the following controls; local control, partial automatic on, bilevel lighting control, automatic daylight responsive controls for sidelighting, automatic daylight responsive controls for toplighting (top floor only) and automatic full off. *All other corridors* are modeled as 0.038 W/m^2 (0.41W/ft^2) with the following controls; local control, automatic daylight responsive controls for toplighting (top floor only), automatic partial off and automatic full off controls. *All other restrooms* are modeled as 0.059 W/m^2 (0.63W/ft^2) with the following controls; automatic daylight responsive controls for toplighting (top floor only) and automatic full off controls.

The proposed occupancy sensor reduction % is based on Table G3.7 of ANSI/ASHRAE/IES Standard 90.1-2016. *All other classrooms/lecture halls/trainings rooms* uses no occupancy sensor reduction. *Enclosed office* uses a 37% reduction based on 30%*1.25 with partial automatic on credit based on footnote b. *All other corridors* uses a 25% reduction. *All other restrooms* use a 45% reduction.

The baseline is modeled as 0.13 W/m^2 (1.4 W/ft^2) for *all other classrooms/lecture halls/trainings rooms*, 0.1 W/m^2 (1.1 W/ft^2) for *enclosed office*, 0.05 W/m^2 (0.5 W/ft^2) for *all other corridors* and 0.084 W/m^2 (0.9 W/ft^2) for *all other restrooms* and summarized in Table 7.

Table 7: Summary of Modeled unregulated internal loads.

Standard	*Equipment Watts*	*Equipment power density (W/m²)*
90.1	*146,436*	*10.87*
IBC	*131,378*	*10.70*

Equipment power densities are modeled as 0.13 W/m^2 (1.39 W/ft^2) for *all other classrooms/lecture halls/trainings rooms*, 0.09 W/m^2 (1.0 W/ft^2) for *enclosed office*, 0.0343 W/m^2 (0.37 W/ft^2) for *all other corridors* and 0.01 W/m^2 (0.1 W/ft^2) for *all other restrooms.*

The occupant density is based on the Minimum Ventilation Rates in Breathing Zones as described in Table 6-1 of ANSI/ASHRAE Standard 62.1-2019 for “classrooms (age 9 plus)” and “office space” and is summarized in Table 8.

Table 8: Summary of modeled occupant density

Standard	*# of people*	*m² per person*
90.1	*2,432*	*5.54*
IBC	*2,162*	*5.68*

Mechanical Systems

Appendix G Baseline HVAC system types are System 5 – PVAVS with hot water reheat served by a natural draft fossil fuel boiler. The design model includes the same HVAC system type. The design model will include ANSI/ASHRAE/IES Standard 90.1-2016 code compliant and beyond code systems such as condensing boilers, energy recovery systems, demand-based ventilation controls, minimally compliant EER and IEER values and variable speed fans with static pressure reset controls. Static pressure reset controls modeled as a custom fan part load performance curve with coefficients described EDR's Advanced VAV Design Guide.

A possible mix of interpretation could be if the mechanical engineer uses ANSI/ASHRAE/IES Standard 90.1 definition of floor area for determination of design ventilation rates but then the energy modeler uses the IBC definition of floor area for the basis of the Appendix G minimum ventilation modeling inputs.

The occupant density, people outdoor air rate (Rp) and area outdoor rate (Ra) are based on the Minimum Ventilation Rates in Breathing Zones as described in Table 6-1 of ANSI/ASHRAE Standard 62.1-2019. For *classrooms (age 9 plus)* as 5.0 L/s per person and 0.6 L/s/m^2, *corridor* as 0.3 L/s/m^2 and *office space* as 2.5 L/s per person and 0.3 L/s/m^2 and the modeled ventilation rates are summarized in Table 9.

Table 9: Summary of Modeled ventilation rates

Standard	*Total L/s*
90.1 App G	*17,334*
90.1 Design	*17,334*
IBC App G	*15,499*
IBC Design	*17,334*

Domestic Hot Water

A possible mix of interpretation could be if the plumbing engineer uses ANSI/ASHRAE/IES Standard 90.1 definition of floor area for determination of annual water consumption but then energy modeler uses the IBC definition of floor area for the basis of the Appendix G water consumption modeling inputs and are summarized in Table 10.

Table 10: Summary of annual domestic hot water consumption

Standard	*Liters per person per day*	*Total thousand liters per year*
90.1 App G	*4.54*	*3,092*
90.1 Design	*2.27*	*1,546*
IBC App G	*4.54*	*2,748*
IBC Design	*2.27*	*1,546*

The occupant density is based on the Minimum Ventilation Rates in Breathing Zones as described in Table 6-1 of ANSI/ASHRAE Standard 62.1-2019 for "classrooms (age 9 plus)" and "office space"

Results

Site to source energy ratios are 2.8 and 1.05 for electricity and gas, respectively based on US averages. The emission factors are 0.075 and 0.053 metric tons of CO_2 per MMBtu of source for electricity and gas, respectively based on New England (NEWE) eGRID. Source of factors are based on US averages Energy Star Portfolio Manager. For percent improvement beyond code, a building performance factor of 0.49 has been used. Tables 11, 12 and 13 summarize the results of the models.

PBP – Proposed building performance
BBUE – Baseline building unregulated energy
BBRE – Baseline building regulated energy
BBP – Baseline building performance
PIt – Performance index target
PI – Performance index
% improve – Percent improvement beyond ANSI/ASHRAE/IES Standard 90.1-2016

Table 11: Summary of results of 90.1 prototype models

Parameter	*Site Energy (MJ)*	*Source Energy (MJ)*	*GHG Emissions (MT CO_2e)*
PBP	*3,792*	*8,258*	*241*
BBUE	*1,289*	*3,609*	*92*
BBRE	*5,696*	*10,000*	*334*
BBP	*6,985*	*13,609*	*429*
PIt	*0.58*	*0.63*	*0.6*
PI	*0.54*	*0.61*	*0.57*
% improve	*7.1%*	*3.0%*	*5.4%*

*MJ = 1 million Joules
*MT CO_2e = Metric ton of carbon dioxide emissions

Based on using ANSI/ASHRAE/IES Standard 90.1-2019 code prescriptive requirements and some additional beyond 90.1-2019 code requirements, the performance results show modest improvements beyond ANSI/ASHRAE/IES Standard 90.1-2016 which is aligned with general expected change in performance stringency between ANSI/ASHRAE/IES Standard 90.1-2016 and ANSI/ASHRAE/IES Standard 90.1-2019.

Table 12: Summary of results of IBC prototype models

Parameter	*Site Energy (GJ)*	*Source Energy (GJ)*	*GHG Emissions (MT CO_2e)*
PBP	*3,897*	*8,021*	*243*
BBUE	*1,156*	*3,238*	*82*
BBRE	*5,279*	*9,304*	*310*
BBP	*6,435*	*12,542*	*392*
PIt	*0.58*	*0.62*	*0.6*
PI	*0.61*	*0.64*	*0.62*
% improve	*-4.1%*	*-2.9%*	*-3.6%*

Table 13: Summary of differences between IBC and 90.1 results

% improve	*Site Energy (GJ)*	*Source Energy (GJ)*	*GHG Emissions (MT CO_2e)*
90.1	*7.1%*	*3.0%*	*5.4%*
IBC	*-4.1%*	*-2.9%*	*-3.6%*
Difference	*11.2%*	*5.9%*	*9%*

Discussion

The difference in the baseline building's system sized cooling capacity from output reports can be as high as 456 MJ/h (432,000 Btu/h) tons between ANSI/ASHRAE/IES Standard 90.1 and International Building Code models.

Both iterations of the prototype building fall under 9.0 EER, 9.1 EER efficiency range of > 801 MJ/h (>760,000 Btu/h). However, given the high change in capacity observed and increments of capacities in Table 6.8.1-1 of ANSI/ASHRAE/IES Standard 90.1 for different efficiency values, smaller prototype buildings may fall under different baseline cooling efficiency capacity ranges between International Building Code and ANSI/ASHRAE/IES Standard 90.1 floor areas.

Several questions remain as to which method of floor area is most accurate. Further analysis is warranted to understand if the air volume of a thermal zone should include the thickness of a wall. Total considered air volume could consider wall construction, for example, some wall constructions may include air gaps and their associated air volume will mix with thermal zone air volume through infiltration and exfiltration effects. Different considerations should be made with mass wall constructions without air gaps.

The International Building Code definition of floor area appears to be more appropriate in determining baseline lighting power density allowances. Further consideration is warranted to understand ANSI/ASHRAE/IES Standard 90.1 lighting committee's methodology for determining prescriptive lighting power density requirements and whether a normalized exterior wall thickness is applied for area calculations and photometric light output analysis.

Conclusion

The ANSI/ASHRAE/IES Standard 90.1 definition of floor area is more advantageous for performance modeling results compared to IBC definition of floor. Energy simulation to meaningfully inform design decisions should align with design engineer's assumptions of conditioned floor area. Rating authorities that establish minimum above code performance (e.g. 10% beyond code) should establish the prescribed modeled floor area method. Projects that choose IBC floor area method for simulation may be allowed to adjust the modeled above-grade and roof areas to reflect the actual areas and to reduce the magnitude of design fenestration or skylight areas exceeding prescribed allowances. If rating authorities allow both floor area methods, then the minimum energy performance targets should be made less stringent for models following IBC conditioned floor area methods. Extent of impacts towards existing building calibration analysis requires additional analysis.

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A parametric tool for combined overheating and daylighting assessments

Eleni Gkouvelou[1], Dimitra Moskoveli[1], Mandana Sarey Khanie[1]
[1]Technical University of Denmark, Kgs. Lyngby Copenhagen, Denmark

Abstract

With energy efficient strategies focusing on reduction of the heat losses, indoor daylight has been compromised, downgrading the health and comfort needs of their occupants. The paper presents a Grasshopper 3D tool for simultaneous assessment of overheating and daylighting. A parametric analysis of two reference offices in Danish context using the developed tool is presented. The results indicate the challenge of adequate daylight in deep offices and the problem of overheating in shallow ones. Large glazing areas are preferable in deep offices in orientations with low solar radiation, choosing the right window types. Additionally, wider and higher-placed windows benefit daylight access.

Introduction

The reduction of energy consumption is a key concern of the European Union. Several European governments have set high goals for reducing the greenhouse gas emission up to 90% by 2050 by increasing energy efficiency (European Parliament (2010)). In these targets, the building sector plays a crucial role since it depletes 40% of the total delivered energy and 36% of total CO2 emissions in Europe (European Commission (2017)), which are primarily attributed to energy consumed in heating, cooling, and lighting. These high standards along with the global warming effect has increased the overheating risks, especially during the cooling season (Taylor et al. (2014)). This sensitive matter emerges for working environments, where people spend up to 90% of their time according to Leech et al. (2002) and a significant part of the net energy demand of office buildings is attributed to heat losses from large fenestration systems increasing cooling demands (Grynning et al. (2014)). Therefore, an energy efficient design can not only be achieved by the reduction of the energy consumption but also by the improvement of the indoor climate (Gkouvelou and Moskoveli (2019)).

Daylight plays a major role to building's energy performance by minimizing the electric lighting energy, reducing the internal heat gains and the heating demands in winter (Ruck et al. (2000)). Sufficient exposure to sunlight improves occupants' well-being by promoting visual comfort and resetting the internal circadian body clock (Webb (2006)). However, one of the major drawbacks of maximizing daylight is related to the thermal discomfort by causing overheating risks.

As the facade defines the way the solar radiation is transmitted, its proper design is necessary to achieve acceptable overheating and daylight conditions (Nielsen (2012)). For this reason, simulation studies are quite important in early design stages. However, conducting complete simulation studies where energy performance, indoor climate and thorough daylighting evaluations can be done in early design stages are still not straightforward, since an excessive number of simulations has to be performed in different platforms with probably incoherent assumptions and settings. Finally, the obtained data coming from different platforms require several processing steps in a short time to assist design decisions. As a result, such simulation studies are normally done in the later design stages leading to design conflicts. Such shortcomings call for methodologies and tools to perform a complete building performance assessment minimizing errors and assumptions from conceptual phases for smoother transitions to the final design.

This paper presents a developed tool in Grasshopper 3D, which is a visual scripting tool that brings different building performance computational engines together, to assist engineers and designers to develop a qualified facade design. The tool is to be used in the early design stages, mitigating overheating risks without compromising daylighting admission. Two different simulation workflows for a comprehensive overheating and daylighting analysis were coupled in order to assess different design parameters based on their agreement with Danish standards and regulations. As a first step, the criteria of exceeded overheating hours and achieving sufficient daylight availability in space were defined. The parameters which have a significant impact on both overheating and daylight were analyzed based on a literature survey. Finally, using the developed tool a parametric study on two reference office spaces was conducted.

Methodology

Parametric design tool

A parametric tool was developed which is characterized by the integration of the thermal and daylighting simulation analysis in one workflow. It also provides a considerable quantity of annual climate-based simulations which are carried out through EnergyPlus and DAYSIM, respectively, using Honeybee and Ladybug plug-ins. Basic principles of Python are also used to automate the simulation process. Finally, the simulation outputs can be arranged in Excel files using TT Toolbox plugin.

A simulation-based parametric study

The study was set up for two single sided-window office rooms with different depths following the following steps:

1. Identification of the overheating and daylighting criterion.
2. Set up of the geometrical model based on the MIT reference office (Reinhart et al. (2013)).
3. Adjustment of the model specifications.
4. Determination of the investigated parameters.
5. Set up of the final workflow applying parametric relationships between and within the parameters.
6. Integration of the thermal and daylighting simulation.

Overheating and daylight criteria

One of the ways to identify occupant thermal discomfort is through operative temperature, which is a commonly useful metric for overheating assessments (Trimble Inc (2019)). According to Danish standard DS 474 (1995), with respect to overheating tolerance, on warm days when occupants are dressed in light clothing and perform sedentary activity, the requirement may be that the operative temperature during the time of occupancy shall not exceed 26^{o}C for more than 100 hours (Criterion 1a: Hours of exceedance $<$ 100) and 27^{o}C for more than 25 hours (Criterion 1b: Hours of exceeds $<$ 25) during a typical year. According to Danish Building Regulation BR18 (2018), sufficient daylight access can be achieved according to the following recommended criteria. The glass area should be at least 10 per cent of the relevant floor area without shading and adjusted for any correction. Alternatively, the internal light intensity from daylight should be at least 300 lux in more than half of the relevant floor area for more than half of the daylight hours (Criterion 2: $\mathrm{sDA}_{300,50\%} > 50\%$).

Reference model

The reference model based on MIT reference office with dimensions of 3.6m width, 8.2m length and 2.8m height, was built in Grasshopper 3D. From a conservative overheating point of view, the room had only one external wall allowing heat losses with the interior walls to be considered as adiabatic. As for the

Table 1: Conditions of the model specifications.

Model specifications	Conditions
Weather data	Copenhagen DRY
Position of zone	middle, 1st floor
Size of zone	width: 3.6 m height: 2.8 m
External ground surface	3 times the zone dimensions 20% reflectance
Building facade surface	3 times zone's width and height 35% reflectance
Window sill surface	external wall's thickness 35% reflectance
Interior wall surfaces Ceiling Floor	50% reflectance 80% reflectance 20% reflectance
Heating setpoint	23^{o}C (occupied) 15^{o}C (unoccupied) 15^{o}C (cooling season)
Cooling setpoint	100^{o}C
Ventilation rates	Zone *I*: 69.52 l/s (occupied) 9.52 l/s (unoccupied) Zone *II*: 44.7 l/s (occupied) 18 l/s (unoccupied)
Infiltration	0.5 l/s/m^2
Occupancy	from 8:00 to 18:00 Zone *I*: 6 occupants Zone *II*: 4 occupants
Lighting	schedule based on daylight control Zone *I*: 300 W Zone *II*: 200 W
Equipment	from 8:00am to 6:00pm 8 W/m^2

accuracy of daylight metrics, it was placed at 2.8m from the ground floor level, assuming the height on the ground floor equal to the height of the investigated zone. The weather data and the zones' size and position were specified for both analyses. Inputs such as the airtightness, internal loads, setpoints, heating, cooling and ventilation system were set for the thermal simulation analysis, while inputs such as the optical material properties and the lighting control were defined for the daylighting simulation analysis. The specifications, as presented in Table 1, were mainly based on the Danish Building Regulation 2018 (BR18) or on the industry standards and recommendations from research papers, where internal loads and schedules were taken from the MIT reference office (Reinhart et al. (2013)).

Heating and cooling: Since the purpose of this study was not to evaluate the system's efficiency or the energy consumption, an ideal heating system was set for the thermal simulation analysis, which is available in EnergyPlus as Ideal Loads Air System. This system represents a decentralized HVAC unit that combines the heating, cooling and fresh air supply system into one single system. Keeping the specified air flow rates constant, this system moderates the supply air temperature in such a way to meet heating and cooling loads. The periods during heating and cooling season were determined from the heating and cooling degree-hours, based on the hourly dry bulb temperature retrieved from the weather file. The cooling period included the months from June to August, while the heating period included the rest months. The heating air system was in operation only during the heating season and the heating setpoint was set to be 23^oC during occupied hours in order to avoid the operative temperature to drop below 20^oC as DS 474 (1995) requires. The heating setback of 15^oC was set for the rest office hours and also during the cooling period in order to prevent the operation of the heating system in the summer. The cooling setpoint was set to be 100^oC to avert cooling because the study seeks to identify overheating phenomena instead of addressing them.

Ventilation: Considering category I and low polluting buildings according to DS/EN 15251 (2007), the air supply rate was defined and adjusted for each zone based on the occupancy and only the building emissions during unoccupied hours.

Infiltration: The infiltration rate was set to be 0.5 l/s per m^2 taking into account the requirements of Building Class 2020 for new buildings (BR18 (2018)). This setting was regarded a more conservative representation of the reality which increases the airtightness of the building envelope intensifying the overheating problem.

Lighting: The link between the daylighting and thermal workflow is the manual electric lighting control based on the occupancy and daylight availability. The lighting schedule that was extracted from the daylight simulations was implemented to the thermal comfort analysis in order to consider the reduction in electricity consumption and in this way, to reduce the heat gains when the daylight supply was higher. The lighting design was considered the same with that one of the MIT reference office, which was based on a furnishing layout of six work stations, separated in three rows. The placement of the luminaires was based on this layout with an installed lighting power of 100W for each row (Reinhart et al. (2013)). Two lighting control groups were created with the one to be closer to the window with a depth of 5m and include two out of three rows, while the other lighting zone includes only the back row. In the deep zone, the two lighting control groups created two lighting schedules. However, EnergyPlus takes into account only one lighting schedule, so *zone I* was separated into two adjacent subzones. In this zone, it was considered critical to measure the operative temperature in the front thermal subzone.

Investigated parameters

The design parameters and their levels of variation that were chosen to be examined concerning the indoor thermal environment and daylight availability are listed in Table 2 and some specific ones are described below.

Table 2: Levels of the investigated parameters.

Parameters	Abbreviation	Explanation
Zone depth	*I*	8.2m
	II	5m
Thermal mass	*TM1*	Concrete wall
	TM2	Aluminium panels
Orientation	*S*	South
	SW	Southwest
	W	West
	NW	Northwest
	N	North
	NE	Northeast
	E	East
	SE	Southeast
Window type	*5025*	Tvis=0.46
		SHGC=0.25
	6633	Tvis=0.61
		SHGC=0.33
	7040	Tvis=0.66
		SHGC=0.39
	lowe	Tvis=0.73
		SHGC=0.54
Glazing to floor ratio	*Rmin*	corrected 10% of Afloor
	R25	25% of Afloor
	R35	35% of Afloor
	R45	45% of Afloor
Sill height	*S0*	0m
	S1	1m
Head height	*Hmax*	up to the ceiling
	Hmin	0.8m under the ceiling

R35 and *R45* were excluded from the simulation model of *zone I* since the resulting glazing area was larger than the external wall's area.
The case with *R25* and *5025* was also excluded because it created the same glazing area with the corrected *Rmin* based on this window type.

Zone depth: According to the separation in lighting control groups, two zones were investigated, with the *Zone I* to be 8.2m deep, whereas the depth of *Zone II* was reduced to 5m, as can be seen in Figure 1.

Thermal mass: This parameter was applied only to the facade. As the most common construction types in office buildings, one sandwich panel (concrete 200mm - insulation 200mm - concrete 100mm) (*TM1*) and one unitised facade (steel panel 30mm - insulation 200mm - steel panel 30mm) (*TM2*) were examined. Since the intention was to assess the abil-

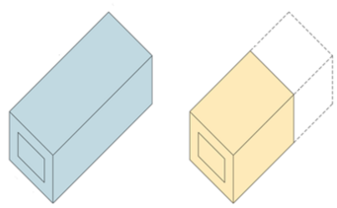

Figure 1: The deep Zone I (left) and the shallow Zone II (right)

ity of the building envelope to store and re-release heat throughout a day and not to check the heat flow into or out of the building, the insulation thickness was kept constant resulting in similar U-values (0.17 W/m^{2}K) for the two types. Regarding the construction of the rest building elements, plasterboard was used for the ceiling and the insulated internal walls, while concrete material with the same properties of the external wall was applied to the floor.

Window type: Four window types were chosen from Pilkington Danmark A/S with different visible transmittance (*Tvis*) and solar heat gain coefficient (SHGC) as shown in Table 2. The U-value of the window including the frame was set to be constant at 0.9 [W/m^{2}K].

Glazing to floor ratio: The minimum glazing to floor ratio was determined to be 10 per cent of the floor area and corrected for the conditions that reduce daylight access (BR18 (2018)). According to Johnsen and Lumbye (2018), in order to assess that the room has sufficient daylight, Equation 1 must be taken into account:

$$A_{\mathrm{Gkor,i}} \geq A_{\mathrm{G,min}} \tag{1}$$

where,
$A_{\mathrm{Gkor,i}}$ is the actual glass area for window i in m^2 corrected with all the factors
$A_{\mathrm{G,min}}$ is 10% of the floor area in m^2

The minimum glazing area of 10% of the floor area was adjusted by the correction factors of the reduced light transmittance (F_{LT}) and the room depth (F_{RUM}) as Equation 2 depicts (Johnsen and Lumbye (2018)):

$$A_{\mathrm{Gkor,i}} = F_{\mathrm{LT}} \cdot F_{\mathrm{RUM}} \cdot A_{\mathrm{Gvin,i}} \tag{2}$$

where,
$A_{\mathrm{Gvin,i}}$ is the actual glass area for window i in m^2

In rooms with depth more than 5m, the glazing area increases to consider the rapid decrease of daylight levels in a distance from the window. So a correction factor of 0.64 was used for *zone I* and the correction factor of the light transmittance was calculated for both zones according to Equation 3 (Johnsen and Lumbye (2018)):

$$F_{\mathrm{LT}} = \frac{LT_{\mathrm{akt}}}{LT_{\mathrm{ref}}} \tag{3}$$

where,
LT_{akt} is the actual light transmittance of the glazing
LT_{ref} is the reference light transmittance of 0.75

Window placement: The higher a window head is, the deeper can a zone be lit, while glazing surfaces below a certain height have a minimum effect (Hasim A. and Jitka M. (2015); Robinson and Selkowitz (2013)). In addition, the window head along with the window sill height influence the daylight illuminance levels and uniformity in space (Zomorodian et al. (2016)). Hence, two window sill and head heights were chosen.

parameter	Levels of parameters	No. Of cases Modelled for ZI Passing Criterion 1	% of cases Modelled for ZI Passing Criterion 1	No. of cases Modelled for ZII Passing Criterion 1	% of cases Modelled for ZII Passing Criterion 1
Orientation	S	0	0%	31	24%
	SW	0	0%	34	27%
	W	24	43%	40	31%
	NW	48	86%	83	65%
	N	56	100%	108	84%
	NE	48	86%	81	63%
	E	14	25%	40	31%
	SE	0	0%	29	23%
Thermal mass	TM1	99	44%	231	45%
	TM2	91	41%	215	42%
Glazing type	50-25	39	61%	157	61%
	66-33	60	47%	118	46%
	70-40	59	46%	106	41%
	lowe	32	25%	65	25%
Glazing ratio	Rmin	134	52%	249	97%
	R25	56	29%	101	39%
	R35			60	23%
	R45			36	14%
	total:	190	42%	446	44%
Sill height	S0	23	48%	161	63%
	S1	24	50%	168	66%
	total:	47	49%	329	64%
Head height	Hmax	33	52%	173	54%
	Hmin	33	52%	171	53%
	total:	66	52%	344	54%

Figure 2: Criterion 1: Bin analysis for the synthesis of all parameters.

Results

The results depict the agreement of each parameter with overheating criterion 1 and daylight criterion 2 respectively in different subsections, through a bin analysis method for all simulated cases of zone *I* and zone *II*. The tables provide the number and percentage of the simulated cases that passed the corresponding criterion for zone *I* and zone *II* respectively, which is visualized with data bars. A combination of the parameters that passed both overheating and daylight criteria follows.

Influence on overheating

According to Figure 2, the two zones behave the same way in terms of overheating criterion for the different parameters. However, as Figure 3 shows for two extreme cases, zone *II* marks higher values in operative temperature, even more than 30^{o}C, for a longer period during a typical working week from 19th to 24th of July, revealing a lasting overheating problem. It can be seen that narrow and shallow zones face challenges to control extreme temperatures in terms of cooling energy. The results show that none of the simulated cases in the deep zone passed criterion 1 on South, Southwest and Southeast orientations. The percentage of cases simulated for East and West orientations is also quite low (25% and 43% for zone *I* and 31% for zone *II*) in terms of overheating criterion. All cases of the deep zone and most of the cases of the shallow zone (84%) passed criterion 1 on North orientation. No significant contribution of the thermal mass to the overheating mitigation can be viewed. Only fewer cases with concrete passed the criterion. 61% of the cases with a window type with the lowest solar heat gain coefficient (*5025*) passed

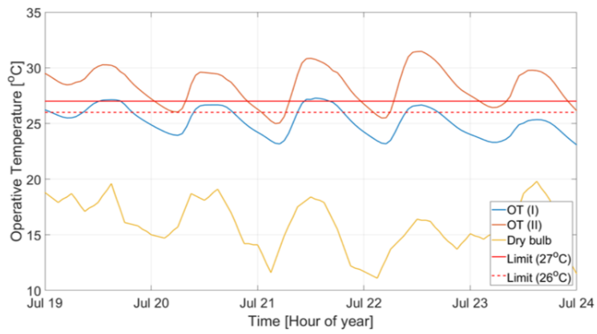

Figure 3: Operative temperatures for zones I and II during a typical week of the summer.

the overheating criterion, whereas only a quarter of cases with a window type of *lowe* complied with criterion 1. A strong relation between glazing to floor ratio and overheating criterion can be seen. Interestingly, almost all cases in zone *II* (97%) did not experience overheating issues with the minimum glazing to floor ratio. However, an increase of glazing to floor ratio decreases dramatically the percentage of passing cases, increasing the overheating risks. In zone *I*, the passing cases with *R25* are slightly over the half the cases with *Rmin* because the former ratio creates the maximum glazing surface, allowing a higher amount of solar radiation to enter the zone. Regarding the window placement, there is no impact on the overheating risk.

Influence on daylighting

Figure 4 shows clearly the higher impact of zone depth in achieving adequate daylight levels. Almost half cases of the deep zone passed the daylight criterion compared to the shallow zone. Larger differences in the results for different levels of the parameters and lower percentages in agreement with the daylight criterion are revealed for zone *I* compared to zone *II*. The impact of the orientation on daylight insufficiency is intensified in the deep zone, on North and Northeast orientations, followed closely by East and Northwest. An effect of the thermal mass in daylight penetration can be observed. The increased wall thickness of the thermal mass of the concrete (*TM1*) yields a slight decrease in spatial Daylight Autonomy, $sDA_{300,50\%}$. This shadowing effect of *TM1* is more clear in the deep zone, since just 29% of its cases with thermal mass of concrete passed criterion 2. As it was expected, considerably higher percentages of solar radiation were reserved in cases with window types with lower visible transmittance. Especially in zone *I*, only 9% of the simulated cases with *5025* passed criterion 2, whereas the passing cases with *lowe* increased to 47%. Thus, the window type of *5025* is not favorable in deep zones. Due to the close values of the visible transmittance in *6633* and *7040*, negligible deviations are demonstrated between the percentages of the passing cases with these window types. Just 1% of cases simulated for zone *II* and 14% of cases

parameter	Levels of parameters	No. Of cases Modelled for ZI Passing Criterion 2	% of cases Modelled for ZI Passing Criterion 2	No. of cases Modelled for ZII Passing Criterion 2	% of cases Modelled for ZII Passing Criterion 2
Orientation	S	43	77%	97	76%
	SW	37	66%	93	73%
	W	19	34%	87	68%
	NW	11	20%	79	62%
	N	7	13%	73	57%
	NE	6	11%	73	57%
	E	9	16%	79	62%
	SE	26	46%	90	70%
Thermal mass	TM1	64	29%	323	63%
	TM2	94	42%	348	68%
Glazing type	50-25	6	9%	131	51%
	66-33	42	33%	177	69%
	70-40	50	39%	179	70%
	lowe	60	47%	184	72%
Glazing ratio	Rmin	36	14%	2	1%
	R25	115	60%	176	69%
	R35			239	93%
	R45			254	99%
	total:	151	34%	671	66%
Sill height	S0	4	8%	97	38%
	S1	19	40%	124	48%
	total:	23	24%	221	35%
Head height	Hmax	29	26%	162	51%
	Hmin	13	12%	139	43%
	total:	42	33%	301	47%

Figure 4: Criterion 2: Bin analysis for the synthesis of all parameters.

for zone *I* passed criterion 2 with the minimum corrected glazing to floor ratio. This ratio is proved to be inadequate, an observation that is based on the occupancy schedule and not the sunlit hours though, as the standard documents. A significant improvement in daylight conditions can be revealed with an increase of 10% in glazing to floor ratio in both zones. However, in zone *I*, even with a glazing to floor ratio of 25%, covering a maximum glazing surface of 75% of the external wall, 60% of cases passed the daylight criterion rendering deep zones quite challenging. On the other hand, the maximum glazing to floor ratio of 45% in zone *II* ensures sufficient spatial Daylight Autonomy almost for all cases. The table data indicate that lower placed windows result in a lower percentage in achieving the acceptable spatial Daylight Autonomy, particularly in zones where the distance from the window is longer, such as zone *I*. The increase of window sill height at 1m distance from the floor level was quite beneficial for this zone. As for window head height, cases with *Hmax* show a slightly higher percentage of passing cases.

Synthesis

As shown in Figure 5, only 4% of the cases simulated for zone *I* passed both criteria at the same time and 13% for zone *II*. The few cases that have passed both criteria in the zones are configurations that migitate overheating while providing sufficient daylight in the space. Among these fewer cases, North orientation in office rooms is more satisfactory than the South orientation to achieve an agreement with both criteria. However, as for zone *I*, 13% of cases for the North orientation fail to pass daylight criterion. On Southeast orientation, although 70% of cases in zone *II* passed daylight criterion (Figure 4), they all failed overheating criterion. Finally, zone *I* failed criterion 1 in South, Southwest and Southeast. Hence, these orientations are difficult orientations to

parameter	Levels of parameters	No. Of cases modelled for ZI Passing all Criteria	% of cases modelled for ZI Passing all Criteria	No. of cases Modelled for ZII Passing all Criteria	% of cases Modelled for ZII Passing all Criteria
Orientation	S	0	0%	3	2%
	SW	0	0%	3	2%
	W	2	4%	3	2%
	NW	6	11%	36	28%
	N	7	13%	53	41%
	NE	2	4%	29	23%
	E	0	0%	1	1%
	SE	0	0%	0	0%
Thermal mass	TM1	4	2%	63	12.3%
	TM2	13	6%	65	12.7%
Glazing type	50-25	0	0%	45	18%
	66-33	3	2%	44	17%
	70-40	9	7%	33	13%
	lowe	5	4%	6	2%
Glazing ratio	Rmin	2	1%	2	1%
	R25	15	6%	43	17%
	R35			49	19%
	R45			34	13%
	total:	17	4%	128	13%
Head height	Hmax	1	2%	25	8%
	Hmin	0	0%	15	5%
	total:	1	1%	40	6%
Sill height	S0	1	2%	15	31%
	S1	2	4%	2	4%
	total:	3	3%	17	18%

Figure 5: Criterion 1 and 2: Bin analysis for the synthesis of all parameters.

find design solutions for both criteria. The parameters that stand out in cases that passed both criteria are few. The agreement with both criteria was achieved with the thermal mass of the steel panels (*TM2*), which creates less shadowing effect. The results of the window type are contradictory in the two zones. It can be viewed that since the deep zone is quite challenging to achieve the required spatial Daylight Autonomy, increasing the visible transmittance increases the agreement with the daylight criterion, and the choice of *7040* is proved to be the best in terms of agreement with both criteria. On the other hand, the most preferable choice to find the balance between overheating and daylight conditions in zone *II* is the window type of *5025* as its low solar heat gain coefficient can be beneficial to control the excessive solar heat gains. The significantly low percentages of cases that pass both criteria with *lowe* indicate that the high solar heat gain coefficient of this window type results to significant overheating problems in both zones. Therefore, the choice of the window type should be based on the zone depth and together with an appropriate glazing to floor ratio could profit the daylight levels, especially in the deep zones. More importantly, the findings show that the minimum required glazing to floor ratio is insufficient to cover both criteria in most cases. A higher glazing to floor ratio of *R25* or *R35* gives a higher percentage in terms of agreement with both criteria. However, the choice of a glazing to floor ratio of *R45* should be made with precautions since it increases the overheating risks. As the vertical window placement affects the daylight availability and not the overheating, the effect of the parameters of window sill and head height followed almost the same trend as in criterion 2. Table 3 summarises the combinations of the most influential simulated parameters that achieve both the overheating and daylight criterion for each zone. This table outlines the following points:

Table 3: Combinations that complied with criteria 1 and 2

Zone	Glazing to floor ratio	Orientation	Window type
I	*Rmin*	*W*	*7040, 6633*
	R25	N	*lowe, 7040*
		NE	*7040*
		NW	*7040, 6633*
II	*Rmin*	*S*	*lowe, 6633*
	R25	*W*	*5025*
		SW	*5025*
		E	*5025*
		NW	*5025, 6633, 7040*
		N	*6633, 7040, lowe*
		NE	*6633, 7040*
	R35	NW	*5025, 6633, 7040*
		N	*5025, 6633, 7040*
		NE	*5025, 6633, 7040*
	R45	*NW*	*5025*
		N	*5025, 6633, 7040*
		NE	*5025*

- Decreased glazing to floor ratios are preferable towards South and increased glazing to floor ratios are favored in the North.
- North directions towards East and West are favorable due to less overheating issues.
- In south oriented shallow zones with the use of a minimum glazing to floor ratio to prevent overheating issues, window types with high visible transmittance are appropriate. Window types with a low solar heat gain coefficient are preferable in orientations with high overheating risks.
- The window type of *lowe* can be seen only in three combinations because of the great need for increasing the agreement with the daylight criterion.
- Higher glazing to floor ratios combined with window types with low solar heat gain coefficient are approved in orientations with low solar radiation.

Discussion

This parametric-based simulation study increases the awareness of designing healthy daylit spaces with a satisfactory thermal indoor environment. In this study, the overheating assessment was conducted during the period from April to September since the hourly operative temperature exceeds 26^{o}C most of that time.

Regarding overheating criterion, although the percentage of passing cases did not differ for both zones, the number of aggregated overheating hours was quite higher in the shallow zone due to the distribution of solar heat gains in a smaller floor area. As it was anticipated, higher number of cases failed to pass daylight criterion in the deep zone, since facades have a limited ability to distribute daylight into the depth of a space (Ruck et al. (2000)). The percentages of agreement with both criteria were quite low for both

zones, revealing the necessity to control the solar heat gains following other strategies.
The orientation is not always determined by the designer, but it can determine the selection of other choices, such as the glazing ratio and the window type so as to control the solar heat gains. With the lowest risk of overheating, North gives freedom in the options that have to be chosen to fulfill the daylight target for both zones.
The contribution of the thermal mass to the reduction of overheating hours is not clear. This is due to the low thermal capacity applied only to the facade, which was covered from high glazing areas. The impact could be more visible if the two types of thermal mass were applied to more construction elements. The shadowing effect of the increased thickness of the concrete wall was more noticeable in the deep zone, which has a higher risk at non-agreement with daylight criterion.
The choice of a window type should be dependent on the zone depth due to the risk of daylight insufficiency. Deep zones oriented towards North with high SHGC and Tvis, such as *lowe*, benefit daylight without causing overheating problems. However, the window type of *7040* is considered more appropriate for agreement of both criteria than the one of *lowe*, which causes higher overheating issues. Window types with quite low SHGC, such as *5025*, are recommended in shallow zones to tackle the overheating problems because these zones can be lit more easily.
Due to a limitation in the simulation, the occupied hours were taken into account for the annual climate-based daylight analysis instead of the sunlit hours. Therefore, the almost total failure in daylight criterion with the required minimum glazing to floor ratio in the shallow zone can not fully contradict to the requirement of BR18 for achieving daylight sufficiency with the minimum glazing to floor ratio of 10 per cent. We can see in the results that large glazing areas with window types of low Tvis and SHGC to control the overheating issues, are preferable to fulfill the overheating and daylighting requirements if these window configurations are placed in North, Northwest and Northeast. So designers that attempt to control unwanted solar heat gains should always consider the drawbacks of inadequate daylight levels, combining the right window types with the right glazing to floor ratio.
The parameter of the window height adjusted the width of the window according to the glazing area that was determined by the glazing to floor ratio. So an increased window sill height widened the distribution of the glazing surface on the facade, whereas an increased head height narrowed it. Due to the simulation set up, a few combinations were considered for the assessment of these two parameters. Cases, where large glazing to floor ratios created larger glazing areas than the area the window sill and head height allowed to create, were excluded from the results in order to avoid any wrong estimations. Therefore, it is considered important to mention that the evaluation of window sill height was based on *Hmax* for zone *I* and both window head heights for zone *II* taking into account only the minimum glazing areas. As regards the evaluation of window head height for zone *I*, all the glazing to floor ratios at the floor level *S0* were considered. In zone *II*, the minimum glazing to floor ratios at both sill heights were considered and only the window sill height at floor level was considered for the rest glazing to floor ratios. The vertical window placement did not have any influence on overheating as the same glazing area was distributed on the facade regardless of the parameter of window sill and head height allowing the same solar heat gains.
Finally, in deep zones the main challenge is to bring the daylight into the depth of the zone, thus pertaining to design solutions that would push the daylight inside are useful. On the other hand, the shallow zones suffer mainly from the overheating issues and more attention should be made to reduce these conditions using the affecting parameters.

Conclusion

The growing threat of overheating alerts the designer to perform an integrated thermal comfort and daylighting analysis in order to guarantee comfortable thermal conditions with the minimum overheating risks, maximizing the benefits of daylight. This study identifies the design equilibrium according to Danish building regulations and standards concluding towards guidelines that direct the design in a right way. Based on the presented study the following statement can be concluded:

- Adequate illumination should be the priority in deep zones, whereas higher overheating issues are more probable in shallow zones.
- Higher thermal capacity is needed to minimize overheating. The wall thickness of the external wall has a shadowing effect, which can be an obstacle for sufficient illumination.
- In orientations with low risk of overheating, alternative design choices can be practiced more easily.
- Overheating reduction can be achieved using window types with low SHGC, while daylight insufficiency in deep zones can be addressed using window types with high visible transmittance.
- Large glazing areas are favorable for sufficient levels of daylight, but only in orientations with the lowest solar radiation.
- The vertical placement of the window can contribute significantly to increase the daylight availability when placed at a height that reaches up to the ceiling and distributed horizontally at 1m from the floor level.

The findings above are based on several affecting parameters in facade design on daylighting and thermal conditions. However, evaluation of more parameters and strategies is necessary to optimise the facade design. An extension of results from reference zones to actual buildings is the next step to, as a first step, validate the developed tool for all geometry types and the ease of usage, and as a second step to have a better understanding on facade optimisation with focus on daylight benefits and reduction of overheating.

Acknowledgment

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A Grey Box Model of the Heat Dynamics of a School Building

Frederik Banis[1], Christian Anker Hviid[1], Hjörleifur G Bergsteinsson[1]
Peder Bacher[1], Davide Cali[1], Henrik Madsen[1], Niels Kjølstad Poulsen[1]
[1]Technical University of Denmark, Copenhagen, Denmark

Abstract

Model predictive control (MPC) can support the reduction and flexibility of energy consumption in buildings for heating, ventilation and air conditioning (HVAC) systems. This support may entail the the reduction of CO_2 emissions, while increasing the comfort of occupants within the built environment. MPC for buildings requires reliable building models. Complex building energy performance simulation models (briefly here: white box (WB) models) are detailed representations, but often computationally heavy. Consequently, such models cannot be the right choice for MPC for HVAC control in buildings. Black box (BB) models can be fast in terms of simulation time. Due to that they do not include laws of physics, they may lack the ability to generalize on to unobserved parameter spaces. Grey box (GB) combine WB and BB models and therefore leverage both physical and statistical benefits. However, GB models in context of buildings often focus on the dynamics of the building fabric. Yet, mass flow and temperatures of the heating system are key elements of the overall efficiency and as such, GB models should account for them. An MPC may then use such models and optimize for chosen objectives. Such objective may be, for example, the minimization of CO_2-emissions or costs by utilizing the available flexibility potential.

2 Introduction

Grey box (GB) models in context of optimized building' operation provide benefits compared to the complex and physics–based WB models and solely data–driven black box (BB) models. grey box (GB) models are naturally reduced–order models (ROMs) — see Reynders et al. (2015) — as opposed to BB models, which may suffer from over-fitting. See for example Nelles (2001). BB furthermore rely heavily on the quality of the training data, while this undesirable effect is comparably reduced in GB models. A key cause is the choice of sufficient degrees of freedom in the candidate model structure enabling such a model to generalize on new data while limiting the number of free parameters in the estimation problem. See Brastein et al. (2018); Massa Gray and Schmidt (2018). Related in this regard, Harb et al. (2016) demonstrate that simpler candidate models provide sufficient performance. For example, they identify a `4R2C` structure as best model evaluated on three different building types in opposition to models of up to `8R3C` complexity. A `4R2C` model, for example, consists hereby of four resistances and two capacities in the model structure. Reynders et al. (2015) illustrate that not only the resistive-capacitive (RC) layout of a model impacts its reliability, but also how it accounts for external system drivers and internal system drivers. Examples are solar radiation gains dependent on sky cover, or, internal gains dependent on human behavior. Moreover, the examined building determines which model structure performs well. See also Bacher and Madsen (2011) regarding the identification of GB models for heat dynamics of building using a forward selection strategy. Furthermore, they also highlight that for a heavy–flooring a single capacity model may provide already satisfactory performance. Along those lines, one may consider the need to use nonlinear models within model predictive control (MPC) concepts. On the contrary, Pedersen et al. (2019) demonstrate that linear models perform well within linear model predictive control (LMPC) compared to nonlinear model predictive control (NMPC); LMPC may suffice in terms of precision while reducing the computational load compared to NMPC. In order to account for the prediction of external drivers, such as temperature forecasts, we may augment GB models as suggested in Zhou et al. (2008). See also Rasmussen et al. (2020) in this regard. This demonstrates the flexibility of using GB modeling approaches, enabling the addition of both WB and BB model outputs where useful.

In this work, we show how to produce a reliable GB model for the characterization of the heating system dynamics of a school building. A two–pipe radiator system connected to the city district heating system provides heat to the building.

GB models rely on training data sets of high quality. For the GB models in this paper, the training data set was generated through detailed measurements of the step–response. However, a significant investment is required to obtain useful experimental step–response data. It is therefore of interest to investigate if a detailed WB model of the building is able to generate the training data instead. One key metric to assess, especially in district heating (DH) systems, is the return temperature. Thus, in order to qualify the GB model in this respect, we produced a WB model as well. The models are based on measurements obtained during a holiday period.

The overall objective of the work is therefore to create a model of the building with dynamics of the heating system. An MPC can optimize the efficiency of the heating system by actively contributing to a reduction of the return temperature. In this regard, knowledge of the heating system dynamics is key. The heating curve can consequently be used by an MPC in order to balance forward and return temperatures, as well as energy output. It can then contribute to the achievement of better heating efficiency, CO_2 emission reduction while maintaining indoor thermal comfort.

This paper is organized as follows. Section 2.1 provides a description of the considered school building. In Section 3 we describe the methods used throughout this paper. Section 4 documents the results obtained throughout a case study using the described building. In Section 5 we discuss the obtained results. We close the paper in Section 6 with the conclusions.

2.1 Modeled Building

All information listed here is provided by Bruun (2019). A related publication in the context of this building and related research activities is Lex et al. (2019). The considered building is a school building with three floors and a basement. The uppermost floor is a partially refurbished roof attic.

The building includes 10 classrooms, normally ventilated by balanced mechanical ventilation. The facade and internal walls consist of solid brick (300 mm, (estimated $U = 1.5$) and 180 mm respectively). Windows have wooden frames and double–pane low-E glazing (estimated $U_w = 1.4$). Floors are made from wood joist floors. The roof is partly uninsulated ($U = 2.0$), partly insulated slate roof ($U = 0.29$). The building is supplied by electricity and DH. The DH system on the building side consists of three hot water (HW) circuits, one for the air-handling-unit, the domestic water supply, and space heating respectively. Heat transfer from the DH side to the building is established by plate heat exchangers. The space heating circuit is supplied at a temperature level of up to 60 °C. The forward temperature is adjusted by the building management system (BMS) according to the ambient temperature. The radiators in the subsequent rooms within the building are of different types and specifications, including cast–iron, panel convectors, and plane convectors.

3 Methods

3.1 White Box Model

GB models rely on training data sets of high quality. For the GB models in this paper, the training data set was generated through detailed measurements of the step–response. However, reliable step–responses often require a significant investment to obtain. It is therefore of interest to investigate if a detailed WB model of the building is able to generate the training data. Consequently, the school building was modeled in the building performance tool IDA ICE[1]. The model is illustrated in Figure 1.

The model was based on available technical drawings and contains all individual rooms, staircases, doors, and openings as accurately as possible. Materials and insulation standards were estimated by visual inspection and with consideration to the year of construction (1924–1929). No significant retrofit was noted anywhere, except for the insulated part of the roof attic, and for a few radiators. Mechanical ventilation was installed in recent years, but was shut down during the holiday period. Lighting was off, and occupants not present. Infiltration was set to a low fixed value of 0.07 $^{l}/_{(s \cdot m^2)}$ to reflect closed windows and doors. About 1000 kg of wooden furniture was added to each classroom as internal thermal mass. The actual weather was imported and global irradiation was converted to diffuse horizontal and direct normal irradiation using the weather model Tian et al. (2018). The sizes, manufacture, and heating capacities of the radiators were registered, normalized to 70/40/20 °C and entered into the model with the radiator exponent of $n = 1.3$. In this manner, the heating power of every radiator is calculated at runtime as a function of water supply temperature and indoor temperature. The resulting return water was logged.

Figure 1: Illustration of the building as represented in the white box (WB) model.

3.2 Grey Box Models

Following the notation given in Kristensen et al. (2004), we can state the observed system as a stochastic differential equation (SDE):

$$\mathrm{d}x_t = f(x_t, u_t, t, \theta)\mathrm{d}t + \sigma(u, t, \theta)d\omega_t \quad (1)$$

$$y_k = h(x_k, u_k, t_k, \theta) + \epsilon_{y,k} \quad (2)$$

We observe the continuous time (CT) system $\mathrm{d}x_t$ through discrete time (DT) measurements y_k disturbed by noise ϵ_k. We determine maximum likelihood (ML) estimates of parameters θ in (1) and (2)

[1] Equa AB, www.equa.se

by maximizing the likelihood function:

$$L(\theta, y_N) = \Big(\prod_{k=1}^{N} p(y_k|y_{k-1}, \theta)\Big) p(_{y_0|\theta}) \quad (3)$$

3.3 Candidate Models

We formulate `4R3C`, `5R4C` and `6R5C` candidate models. See Figure 2 for an example.

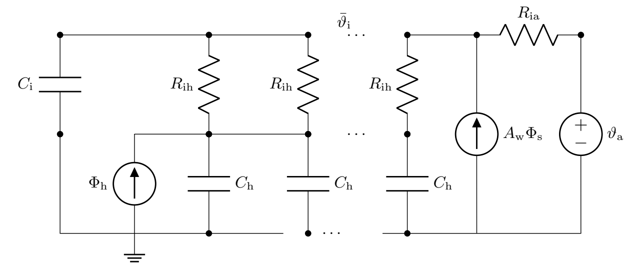

Figure 2: Model structure example with one thermal zone. The heating power Φ_h supports the average interior temperature level $\bar{\vartheta}_i$. Capacitive elements share the overall heat capacity C_h, resistive elements the overall heat transfer resistance R_{aah}. R_{DA} accounts for the resistance associated with heat dissipation from the interior to the ambient. The heat contribution of heater n Φ_n relates to the thermostatic control function. We measure $\Phi_{m,h}$. C_i specifies the heat capacity of the interior.

The models consist of $j \in \mathcal{J}$ heater temperature states $d\vartheta_{h_j}$ and a single interior temperature state $\bar{\vartheta}_i$. n_c is the number of heater compartments. We describe the heater dynamics as:

$$d\vartheta_{h_j} = \frac{n_c}{C_h}((\vartheta_{h_j,in} - \vartheta_{h_j}) f_{therm}(\vartheta_{set,i}, \bar{\vartheta}_i)\tau + \frac{1}{R_{ih} n_c}(\bar{\vartheta}_i - \vartheta_{h_j}))dt + d\omega_{\vartheta_j} \quad (4)$$

The input temperature of the first heater h_1 is the forward temperature. Consequently, we assume no dissipation of heat from the point of forward temperature measurement until the contribution to the average interior temperature $\bar{\vartheta}_i$. C_h is the overall specific heater thermal capacity, R_{ih} is the overall specific heater heat transfer resistance. $d\omega_{\vartheta_j}$ is a Wiener process with respect to the heater j temperature dynamics $d\vartheta_{h_j}$. We represent the mean interior temperature state $\bar{\vartheta}_i$ as:

$$d\bar{\vartheta}_i = \frac{1}{C_i}\Big(\frac{1}{R_{ih} n_c}\sum_{j}^{n_c}(\vartheta_{h_j} - \bar{\vartheta}_i) + \frac{1}{R_{ia} n_c}(\vartheta_a - \bar{\vartheta}_i) + A_w \Phi_s\Big)dt + d\omega_{\vartheta_i} \quad (5)$$

C_i is the interior specific heat capacity, R_{ia} is the thermal dissipation resistance through walls, A_w is the active wall surface with respect to specific solar radiation Φ_s. ω_{ϑ_i} is a Wiener process with respect to the mean interior temperature dynamics $d\bar{\vartheta}_i$.

We observe the measured thermal heating power $\Phi_{m,h}$, represented in the model as Φ_h plus random noise ϵ_{Φ_h} as stated below. Notice that we disregard subscripts k indicating the current iterate for brevity.

$$\Phi_h = (\vartheta_{for} - \vartheta_{ret}) f_{therm}(\vartheta_{set,i}, \bar{\vartheta}_i) \quad (6)$$

We model the heating power measurement $\Phi_{m,h}$ as:

$$\Phi_{m,h} = \Phi_h + \epsilon_{\Phi_h} \quad (7)$$

Then, the output temperature to the last heater h_{n_c} is the return temperature:

$$\vartheta_{ret} = \vartheta_{n_c} \quad (8)$$

3.4 Thermostatic Control Function

The thermostatic control function (9) describes the sensitivity of the heating system to deviations in the mean interior temperature $\bar{\vartheta}_i$ from the setpoint $\vartheta_{set,i}$:

$$f_{therm}(\vartheta_{set,i}, \bar{\vartheta}_i) = \frac{1}{1 + e^{(-1\cdot(\vartheta_{set,i} - \bar{\vartheta}_i)\cdot\alpha)}} \cdot c_{p,w}\dot{m}_{max} \quad (9)$$

$\vartheta_{set,i}$ is hereby the mean interior temperature setpoint, $\bar{\vartheta}_i$ is the mean interior temperature. α is the thermostatic control slope. By modifying the latter we can adjust the sensitivity of the heating system to temperature deviations. $c_{p,w}$ is the specific isobaric heat capacity of the carrier fluid, that is, water. $\dot{m}_{max}$ is the maximal heating system mass flow.

4 Results

For the kernel density estimates throughout this paper, we use as estimation bandwidth Scott's rule as given in Scott (2015) and the Gaussian kernel.

4.1 Identification Experiment

We use the excitation sequence ϑ_{sp} depicted in Figure 3 throughout the period `2019-12-18 00:00:00` to `2019-12-27 15:00:00`. In the following, we refer to this period as the *identification period*. Windows remained closed throughout the identification period and the ventilation system was inactive. The unused building is in consequence free from human influence and unaffected by air change through open windows and doors. ϑ_{sp} is partly characterized by:

- a constant period in the first quarter of the identification period

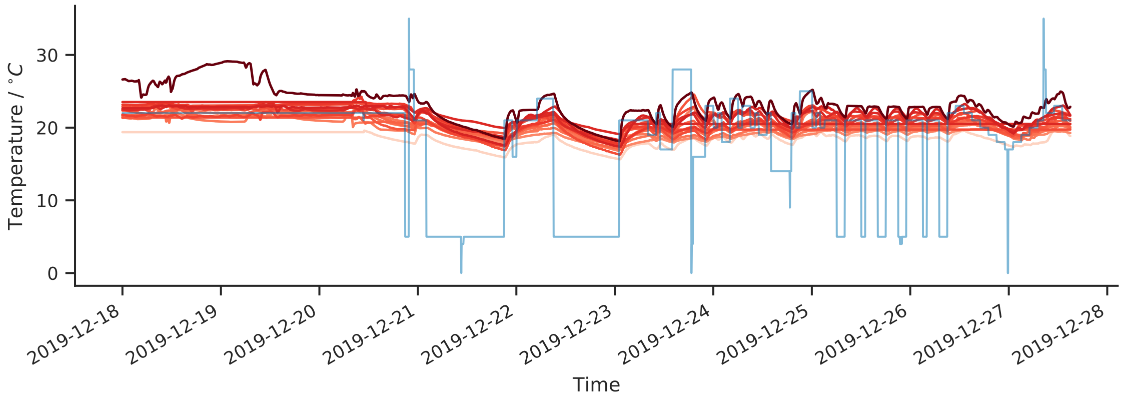

Figure 3: The excitation signal (blue) specifies the temperature setpoint to the thermostats in subsequent rooms (red).

- two large low–frequency steps in the second quarter
- a random high–frequency phase in the third quarter
- large high–frequency steps in the third and fourth quarter
- a high–frequent step sequence in the last quarter

4.2 Model Comparison

4.2.1 White Box Models

The WB model results are depicted in Figure 4. The simulated interior temperatures align with the observed temperatures but lie slightly below which is probably because the indoor temperature sensors are influenced by being mounted on the internal brick wall. The return temperatures from the radiator circuit is a measure of the efficiency of the heating system. Especially in locations with district heating fueled by biomass, the overall efficiency of the system depends on the return temperature. It follows that some DH companies reward low return temperature. For the local situation, the offset of approx. 10°C illustrated by the WB model translates into potentially 10% heat cost savings.

4.2.2 Grey Box models

We aim to approximate the return temperature ϑ_{ret}, the mean indoor temperature $\bar{\vartheta}_{\mathrm{i}}$, and the required heating power $\Phi_{\mathrm{m,h}}$ subject to ambient conditions. For our objective of deriving a GB model applicable to control ϑ_{ret}, we consequently choose the latter as the primary model component. As ambient processes, we consider the ambient temperature ϑ_{a} and specific solar radiation Φ_{s}.

Figure 5 depicts this situation in the case of the `4R3C` model configuration. The forward temperature in the second subplot, depicted as a dotted line, oscillates throughout periods of standstill of the heating system. Compare also $\vartheta_{\mathrm{set},i}$ in Figure 3. A local controller actuating the heating circuit pump causes these oscillations and complicates the system identification (Sys-ID) procedure. The model fails to describe the return temperature and interior temperature well throughout the two large low–frequency steps in ϑ_{sp}. Yet, the model achieves the highest accuracy in representing $\underline{\vartheta}_i$ in comparison to $\underline{\vartheta}_{\mathrm{ret}}$ and Φ_{h}, see Figure 6.

We compare the residuals of this 3–heater compartment model ($n_{\mathrm{c}} = 3$) to `5R4C` ($n_{\mathrm{c}} = 4$) and `6R5C` ($n_{\mathrm{c}} = 5$) models in Figure 6. The two latter models include additional heater compartments, see Figure 2. By visual inspection, the more complex models `5R4C` and `6R5C` do not offer an advantage over the `4R3C` model. Examination of results similar to the ones depicted in Figure 5 point to the same conclusion.

While switching in the heating system does occur, nominal operating conditions include a constant operation scenario around the setpoint temperature $\vartheta_{\mathrm{set},i}$. Considering the residual $\epsilon_{\vartheta_{\mathrm{ret}}}$ for the constant period in the first quarter of the identification period indicates, as well, that the `4R3C` model provides comparably sufficient performance while offering a lower model complexity.

4.2.3 Residual Comparison

When comparing measurements obtain from the modeled building and WB model predictions, we observe a higher mean interior temperature $\bar{\vartheta}_{\mathrm{i}}$ and a lower mean return temperature $\bar{\vartheta}_{\mathrm{ret}}$ predicted by the WB model. See Figure 8. The GB model yields similar temperature distributions of both $\bar{\vartheta}_{\mathrm{i}}$ and ϑ_{ret} as present in the building measurements.

The comparison pinpoints an important issue about GB modeling of heating system dynamics: that this relies potentially on data from sub–optimal operation periods.

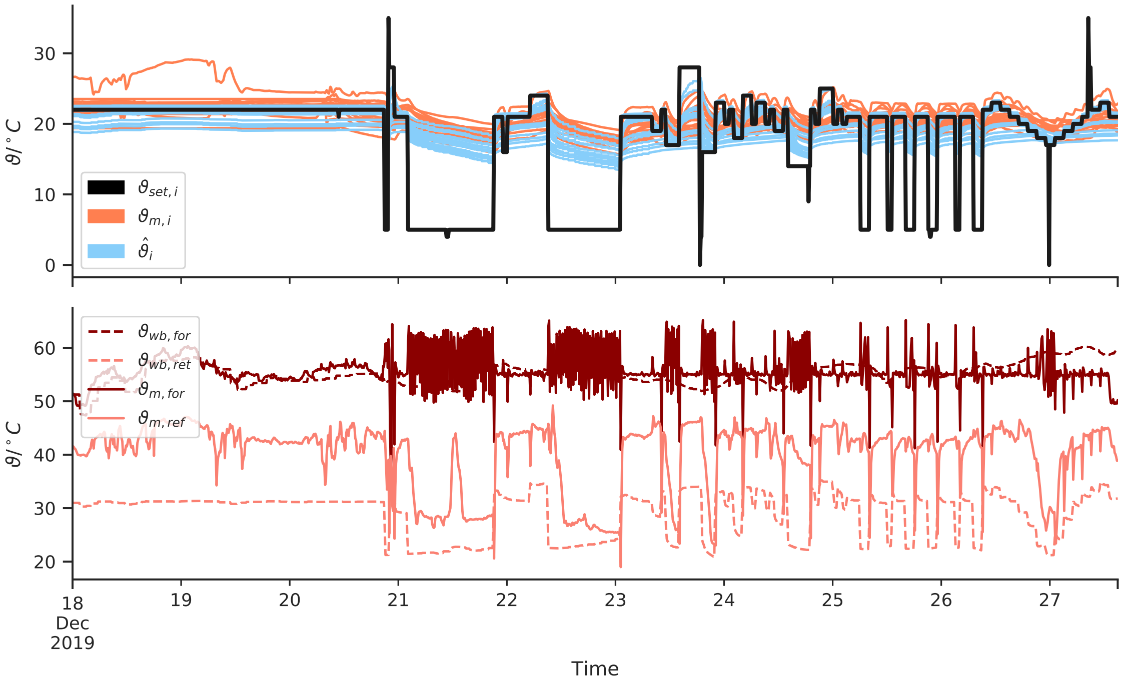

Figure 4: Interior temperature set point (top plot, black lines: $\vartheta_{\mathrm{set,i}}$). The white box (WB) model provides an estimate of the interior temperatures (top plot, blue lines: WB model prediction $\hat{\vartheta}_{\mathrm{i}}$, red lines: measured room temperatures $\vartheta_{\mathrm{m,i}}$) and both the forward and return temperatures (lower plot, dark red lines: forward temperatures, light red lines: return temperatures).

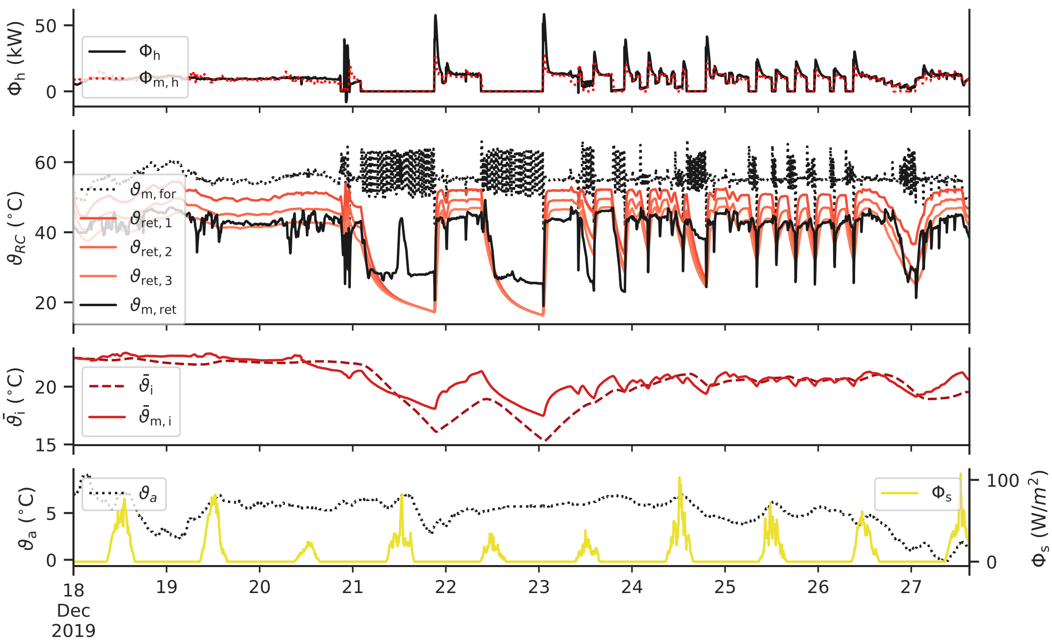

Figure 5: 4R3C model. Heating power consumption estimate Φ_{h} versus measurement $\Phi_{\mathrm{m,h}}$. Return temperature estimate ϑ_{ret}. Mean indoor temperature estimate $\bar{\vartheta}_{\mathrm{i}}$ versus measurement $\bar{\vartheta}_{m,i}$. Ambient temperature ϑ_{a}, specific solar radiation Φ_s.

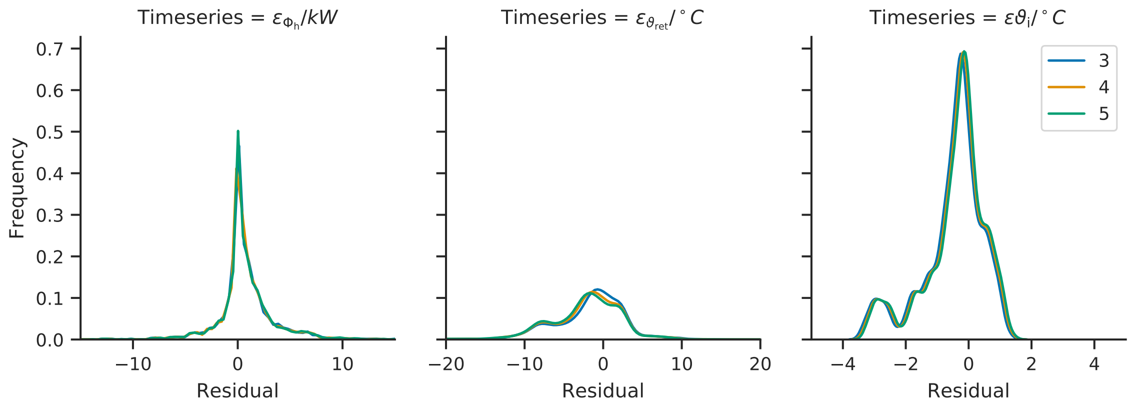

Figure 6: Heating power residual $\epsilon_{\Phi_\mathrm{h}} = \Phi_\mathrm{h} - \Phi_\mathrm{m,h}$, return temperature residual $\epsilon_{\vartheta_\mathrm{ret}} = \vartheta_\mathrm{ret} - \vartheta_\mathrm{m,ret}$ and indoor temperature residual $\epsilon_{\vartheta_\mathrm{i}} = \bar{\vartheta}_\mathrm{i} - \bar{\vartheta}_\mathrm{m,i}$ for different model complexities n_c.

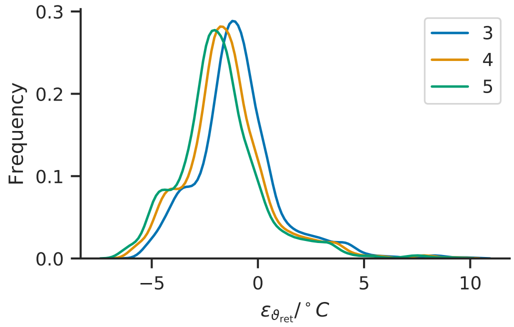

Figure 7: Return temperature residual $\epsilon_{\vartheta_\mathrm{ret}}$ throughout the constant period in the first quarter of the identification period.

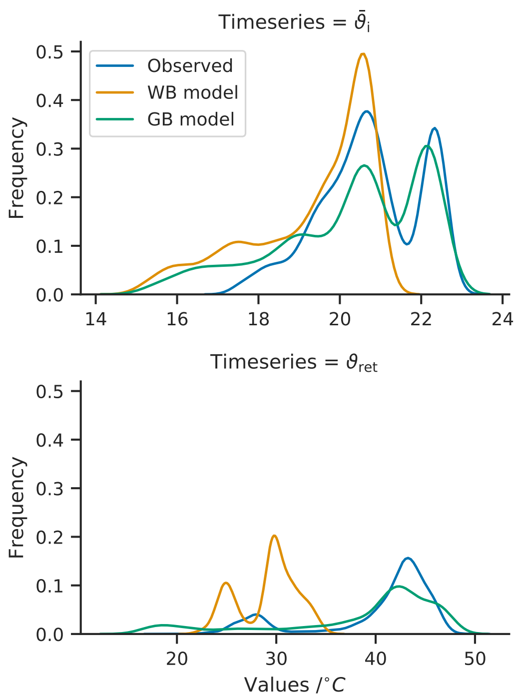

Figure 8: Comparison of the mean interior temperature $\bar{\vartheta}_\mathrm{i}$ and return temperature $\bar{\vartheta}_\mathrm{ret}$ distributions.

5 Discussion

The reduction of the return temperature increases efficiency and can yield economic rewards as mentioned above. Furthermore, prohibitively high return temperatures may lead to economic penalties. Through this, control of the return temperature is important in buildings with DH supplied heating power.

MPC can utilize GB models in order to support a desirable system operation. The representation of uncertainty by means of the GB model enables the implementation of stochastic MPC based on such model.

A challenge in designing model–based controllers is the deduction of a well–posed model. We can obtain GB models through Sys-ID experiments. Classical challenges associated with the latter are permissive excitation signals or periods Ljung (1999); Nelles (2001), where we cannot conduct Sys-ID experiments. By using a detailed WB model of the considered building, we can partly alleviate these issues, provided that the WB model approximates the true system sufficiently well in the operating perimeters.

The identified GB models based on the true system provided the performance depicted in Figure 5, yet we did not perform out–of–sample evaluation of this model. Due to the limited size of the available Sys-ID data set, we refrained from splitting the latter into identification and evaluation subsets. A related issue is the influence of human behavior, which for the considered school building, is considerable. Evaluation of the obtained model on school days and diverse ambient conditions can enable us to assess the model accordingly.

A challenge in building HVAC systems control is to account for heterogeneous climatic zones within the building. A mean interior temperature $\bar{\vartheta}_\mathrm{i}$ considered in the GB model may therefore only yield sub–optimal performance with respect to such climatic zones. We can augment the GB models in order to consider distinct thermal zones. Then, a control of $\vartheta_{\mathrm{i},z}$ is possible, where z is the temperature in the subsequent thermal zone. While we did not investigate this further in the context of this paper, the treatment of multiple thermal zones in the building can be a necessity in order to achieve a satisfactory control performance.

6 Conclusion

In this paper, we aim to derive a grey box (GB) model of the heating dynamics of a school building. Using the GB model, we aim to represent the heating circuit return temperature, the interior temperature, and the heating power. We may use such model in model predictive control (MPC) approaches in order to drive the system while accounting for objectives such as the reduction of CO_2 emissions.

The evaluation of the derived model in out–of–sample experiments is pending. Furthermore, we may augment the model in order to account for subsequent thermal zones in the building. Then, control of the temperature at per–zone level is possible.

When improving the white box (WB) model derived in IDA/ICE further, such as to obtain a sufficient degree of accuracy throughout considered operating conditions, we may use such WB model in future studies to learn about how to apply the GB model. Thus, it is possible to identify GB models in operating conditions normally permissive for system identification (Sys-ID) experiments, and to further simulate longer periods with different controls to study the achievable potential in different scenarios.

7 Acknowledgments

This work has been supported by Innovation Fund Denmark through the CITIES research center (no. 1035-0027B) and Smart Cities Accelerator 2016-2020 Interreg-ØKS: grant 20020999. This project is partially supported by the Danish national funding with the project of "Intelligent Energy Management for Multi-family Buildings" (proj 64017-05184). Great acknowledgment also to the Høje Taastrup Municipality and the school "Borgerskole" for their support in this research project.

8 Appendix

Nomenclature

α	Thermostatic control slope
$\bar{\vartheta}_{\mathrm{i}}$	Mean interior temperature
$\dot{\vartheta}_{\mathrm{h}_j}$	Heater j temperature dynamics
$\dot{m}_{\max}$	Maximal heating system mass flow
ϵ_y	Meaurement error
$\epsilon_{\Phi_{\mathrm{h}}}$	Thermal heating power residual
$\epsilon_{\vartheta,\mathrm{i}}$	Mean interior temperature residual
$\epsilon_{\vartheta_{\mathrm{ret}}}$	Return temperature residual
$\mathcal{J}$	Set of heater temperature states
ω	Standard Wiener process
$\omega_{\bar{\vartheta}_{\mathrm{i}}}$	Wiener process of the mean interior temperature dynamics
Φ_{h}	Thermal heating power
$\Phi_{\mathrm{m,h}}$	Thermal heating power measurement
Φ_{s}	Specific solar radiation
σ	Nonlinear diffusion coefficient function
τ	RC–temperature tuning factor
θ	Model parameters
$\underline{\bar{\vartheta}}_{\mathrm{i}}$	Mean interior temperature measurement
ϑ_{a}	Ambient temperature
ϑ_{for}	Forward temperature
$\vartheta_{\mathrm{i},z}$	Interior temperature of zone z
$\vartheta_{\mathrm{m,ret}}$	Return temperature measurement
ϑ_{ret}	Return temperature
$\vartheta_{\mathrm{set},i}$	Interior temperature setpoint
A_{w}	Active wall surface with respect to solar radiation
C_{i}	Interior specific heat capacity
$c_{\mathrm{p,w}}$	Specific isobaric heat capacity of water
C_h	Specific heater thermal capacity
f	Nonlinear dynamical function
f_{therm}	Thermostatic control function
L	Likelihood function
N	Number of measurements
n_{c}	Number of heater compartments
p	Probability density
R_{ia}	Thermal dissipation resistance through walls
R_{ih}	Heater heat transfer resistance
t	Time variable
$u_t,\ u_k$	System input (CT, DT)
$x_t,\ x_k$	System state (CT, DT)
y_k	System output (DT)
z	Zone z

Acronyms

BB	black box
BMS	building management system
CT	continuous time
DH	district heating
DT	discrete time
GB	grey box
HVAC	heating, ventilation and air conditioning
HW	hot water
LMPC	linear model predictive control

NMPC nonlinear model predictive control
ML maximum likelihood
MPC model predictive control
ROM reduced–order model
RC resistive-capacitive
SDE stochastic differential equation
Sys-ID system identification
WB white box

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Video game-based learning for teaching building thermodynamics and control of HVAC systems

Hicham Johra*, Lasse Rohde, Ekaterina Aleksandrova Petrova
Aalborg University, Department of the Built Environment, Aalborg, Denmark
** corresponding author: hj@build.aau.dk*

Abstract

This paper presents GEENIE, a video game simulating the thermodynamics of a building. The game is used to introduce a university course about control of Heating, Ventilation and Air Conditioning systems. The purpose of the game is to rapidly engage the students with the importance of having automated control systems in buildings to ensure a high quality indoor environment with minimum energy use. GEENIE consists of an arcade video game station with physical controllers allowing players to adjust the heating, cooling, ventilation, lighting and shading device of the simulated building subjected to dynamic boundary conditions. A score is calculated as a function of the average indoor comfort and the energy use. Reaching a higher score motivates the players to optimize their manual control strategy, but also to understand building thermodynamics and indoor comfort. Moreover, the players can compete against automated controllers. The latter outperform human manual control, emphasizing the importance of the course's topic.

Description of the game

If a picture is worth a thousand words, how many words is a game worth then?

Gameplay and game objective

GEENIE (Gaming Engine for ENergy and Indoor Environment) is an interactive video game simulating the thermodynamics of a building. The GEENIE has been developed in the LabVIEW programming environment (developed and commercialized by *National Instruments)*.

Figure 1: A player with the video game GEENIE.

Through this video game, the students (players) can experience the dynamics of the indoor environment, and the interconnections between the different HVAC systems and IEQ parameters, which emphasizes the importance of searching for holistic compromises, rather than local optimum.

The GEENIE consists of an arcade video game station allowing players to adjust (with hand controllers) the heating, cooling, ventilation, lighting and shading device of a simulated building (see Figure 1 and Figure 2). The players must control the power/activation level of those systems to keep the indoor operative temperature, CO_2 concentration, and illuminance as close as possible to the comfort optimum, while the dynamic boundary conditions (outdoor weather conditions, people loads) induce variations to the system.

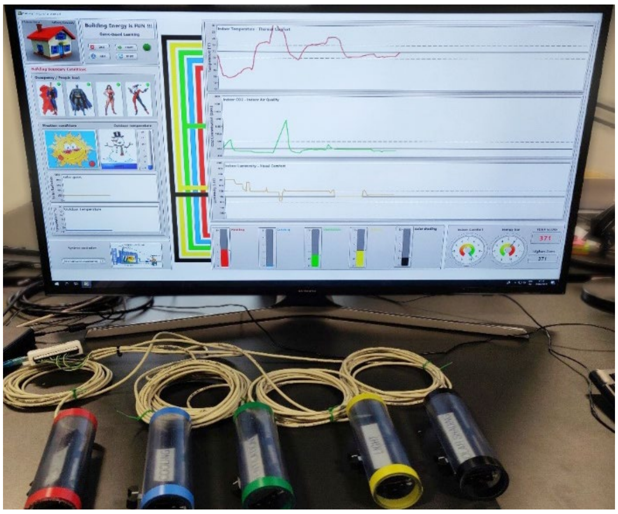

Figure 2: View of the video game GEENIE with the five controllers (sliders) for the HVAC systems.

During the two-minute duration of the game, an IEQ index (from 0 to 10 points) is calculated as a function of the indoor thermal comfort, indoor air quality and indoor illuminance of the simulated building. To maximize this index, the players must keep the indoor operative temperature at 22 °C, the illuminance at 400 lux, and the CO_2 concentration at 600 ppm or lower. Similarly, an energy usage penalty index (from 0 to 10 points) is calculated as a function of the power/activation level of the building systems. The players must minimize this penalty index by keeping the intensity of the HVAC systems as low as possible, which can induce a compromise with the IEQ index.

Both the IEQ and energy usage indexes are clearly visible on the game interface as live indicators of the current performance. A combined score is calculated as the cumulated energy usage penalty index subtracted from the cumulated IEQ index. At the end of the two-minute game, the final score is displayed and recorded. The objective of the game is to achieve the highest total score possible.

Players are encouraged to replay the game to improve their total score. The game duration is kept short so that the players stay focussed and are motivated to replay the game several times using different strategies.

The game can be played in two different modes: a "tutorial" mode or a "real game" mode. The tutorial mode has constant boundary conditions and is only intended for the players to get accustomed to the manual control sliders, the game interface and the dynamics of the simulated indoor environment (presented hereafter in the context of steady-state boundary conditions):

- Higher heating power increases the indoor temperature.
- Higher cooling power decreases the indoor temperature.
- Higher ventilation rate decreases the indoor CO_2 concentration, increases the ventilation heat losses.
- Higher artificial lighting increases the illuminance and increases the internal heat gains.
- Higher activation of the solar shading device decreases the solar gains and the indoor illuminance during daytime.

Because the tutorial mode has constant boundary conditions, it is fairly easy for the players to reach a good total score. However, the score is not recorded at the end of a game in tutorial mode. Conversely, the "real game" mode has time-varying boundary conditions, which is realistic since real-world buildings are always subjected to dynamics boundary conditions. It is thus much more challenging for the players to constantly adjust the intensity of the different HVAC systems to achieve good IEQ. Only the score of the "real game" mode is recorded and considered for the competition between players.

Instead of the manual control by the players, the game can also be run in "automated" mode with the computer adjusting automatically the intensity of the HVAC systems to maintain a good IEQ. The "automated" mode is used for the demonstration of automated controllers in buildings. Three automated controllers can be selected: "ON/OFF control", "Smart control", "Perfect control".

Video game interface

Figure 3 shows an overview of the GEENIE user interface. Figure 4 details the different parts of this graphical user interface (GUI):

1. The main game management to start or interrupt a new game, reset the game to the starting point, open the help file, and close the video game interface.
2. The boundary conditions window provides a live overview of (A) occupancy level (B) winter/summer season, (C) night/daytime, (D) outdoor temperature, and (E) solar irradiation.
3. Selection of the controller type: "manual control" (HVAC management by human players), "ON/OFF" control, "Smart" control, or "Perfect" control.
4. The five vertical sliders indicators show the current power/activation level of the five building systems.
5. The three graphs display the history-curves of the three IEQ parameters of interest in the game: operative temperature (red line), CO_2 concentration (green line) and illuminance (yellow line). The thick black lines indicate the optimal value of the respective IEQ parameters. The black dotted lines represent an acceptable range for the IEQ parameters.
6. The gauge indicators show the current IEQ index and the current energy usage penalty index. The cumulated total score for the current game is listed in the lower corner, next to highest scores for human players and automated controllers, respectively.

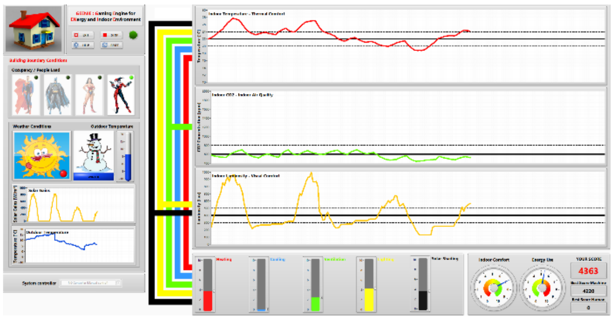

Figure 3: Overview of the GEENIE interface.

Figure 4: Different elements of the GEENIE interface.

Gamification and motivation

The main gamification aspect of the GEENIE lies in the competitive element of striving to beat the highest scores. This is classic game mechanics to engage students and trigger their curiosity about the topic of interest that is introduced by the GEENIE.

During the game and in between the different games, the teachers can exchange with the players to explain the underlying "logic" of the building thermodynamics and the pitfalls to avoid when controlling the HVAC systems. This includes guiding players to find a good compromise between energy use and IEQ performance. Moreover, the students are encouraged to discuss with each other to exchange their understanding of the game and adopt an optimum control strategy.

The game is designed to be difficult for human players. Consequently, the automated controllers (particularly the "Smart" and the "Perfect" controllers) largely outperform the players' manual regulation. This emphasizes the limitations of humans for continuously adjusting the intensity of HVAC systems, and thus highlights the importance of having reliable building automation.

HVAC controllers

If the game runs in "automated" mode, the computer controls the HVAC systems with three possible control strategies: "ON/OFF" control, "Smart" control and "Perfect" control. These denominations are purposely kept simple as they are intended for an audience with no background in control systems. The heating and the cooling systems are regulated according to the indoor temperature. The ventilation system is regulated according to the indoor CO_2 concentration. The artificial lighting and the shading device are regulated according to the indoor illuminance. For each of the aforementioned process variable, the controller's setpoint is kept constant at a value corresponding to the highest IEQ index: 22 °C for heating and cooling; 600 ppm for ventilation; 400 lux for lighting and shading device.

The "ON/OFF" control mode consists in an ON/OFF controller for the heating, cooling and ventilation systems, and a two-position controller for lighting and shading device with pre-set positions for daytime and night-time. The "Smart" control mode consists of a PI (Proportional and Integral) controller for each of the five HVAC systems. Finally, the "Perfect" control is a model-based control that calculates the exact needs for ventilation rate, heating, cooling, lighting and shading position to compensate for the current deviation between the three process variables and their respective setpoint. These adjustments to the HVAC systems operation are applied at the next time step. However, this "Perfect" controller does not take into account the change of boundary conditions at the next time steps: it is not a model predictive controller.

Conclusion

This article has presented GEENIE, an interactive video currently used to introduce a university course about control of HVAC systems in buildings. This video game has been found to be very effective at engaging the students with the main topics of the course. The players are competing for the highest score by manually controlling the intensity of different HVAC systems to maintain the best IEQ possible with the minimum energy use in a simulated building. This classic game mechanics engages the players and trigger their curiosity to learn more about the topics of building thermodynamics, IEQ, and control systems. It also enables the supervising teachers to exchange with the players about the relationships between the different HVAC systems and their impact of the IEQ parameters, and the common issues and mistakes occurring in building automation. In addition, the players are invited to observe the game being run in "automated" mode in which the computer regulates automatically the HVAC systems. The game is purposely designed to be difficult for human players. Therefore, the automated control largely outperformed the latter in achieving optimum IEQ with the lowest energy use possible, emphasizing the importance of building automation, the course's main topic.

Discussing daylight simulations in a proposal for online daylighting education

Federica Giuliani[1*], Mandana Sarey Khanie[2], Natalia Sokół[3], Niko Gentile[4]
[1]Università Niccolò Cusano, Rome, IT
[2]Technical University of Denmark: Kgs. Lyngby, DK
[3]Gdańsk University of Technology, Gdańsk, PL
[4]Lund University, Lund, SE
* *corresponding author: federica.giuliani@unicusano.it*

Abstract

There is increasing interest concerning daylighting in the building sector. However, such knowledge is difficult to penetrate the curricula of architects and designers as existing educational programmes often do not provide sufficient training on BPS. This also leads to superficial use of daylight simulations.

This paper presents a proposal for a needs-based education package on daylighting design, that mixes modular eLearning and an intensive summer school, called NLITED.

The NLITED model includes modules on daylight simulation whose implementation (in eLearning key) can trigger a constructive discussion and receive valuable feedback from the Nordic community of BPS specialists.

Introduction

Daylight is strategic in building design.

- It improves mood and well-being through visual and non-visual processes (Stevens *et al.*, 2007; Solt *et al.*, 2017; Amundadottir *et al.*, 2017). Given its impact on human circadian rhythms, it is also a fundamental resource to design healthy indoor environments, which proves to be essential in the course of recent worldwide events with an increased spread of infectious diseases and their high chance of reoccurrence (Dietz *et al.*, 2020; Hobday and Dancer, 2013; Horve *et al.*, 2019).
- It impacts thermal loads (solar thermal gains), playing a crucial role in both winter and summer energy-saving strategies. For this reason, the importance of daylight in buildings starts to be recognised in building regulations and practice, like in the new European standard on Daylight in Buildings (EN 17037:2018) or the updated EN 15193-1:2017 - *Energy performance of buildings. Energy requirements for lighting*.
- It is a quality lighting that enhances the visual perception and visual comfort in space. It promotes attention, interaction and communication with effect on our psychological (Heschong, 2002; Veitch, 2001) and physiological responses (Sarey Khanie *et al.*, 2016).

Nevertheless, some research indicates that many designers tend to rely on simplified calculations, experience, and rules-of-thumb (Reinhart and Fitz, 2006; Galasiu and Reinhart, 2008; Reinhart and Lo Verso, 2010). Professionals are lacking knowledge about daylighting design, retrofitting, and skills associated with energy performance (Dubois *et al.*, 2015).

Authors' previous investigation revealed that students of nine European architectural schools demonstrated limited knowledge about daylighting (Giuliani, 2017, 2018, 2019), which may result in likewise limited professional expertise. Approximately 2/3 of respondents stated that they had participated in daylighting lessons and knew at least one indicator or metric of daylighting. However, only 1/5 of them used daylight modelling in their design projects. The most known and used indicator remains the Daylight Factor. The responders form all nine countries experienced problems in correctly identifying light units or pointing out daylight simulation tools. In brief, the daylight skills learned in the classrooms seem to remain at a theoretical level and have a limited application in the design projects via advanced software tools and metrics (Giuliani, 2019).

Besides, advanced simulation tools have made it difficult for students to use them unsupervised due to inaccurate input or limited understanding of the results obtained. The main issue is arguably the lack of widely accessible, coherent, and structured pedagogical offer for education in all aspects of daylighting design and simulation.

The *New Level of Integrated TEchniques for Daylighting education* (NLITED) is a proposal for a new education project with the following objectives:

1. filling existing knowledge gaps by introducing a comprehensive blended learning model for knowledge and better integration of daylight into architectural projects, starting from theory to state-of-the-art daylight simulation,
2. raising awareness and knowledge among experts in the field on shortcomings of knowledge transfer in BPS realm.

The concept of NLITED has been developed by a partnership of four European universities: the Danish *Technical University of Denmark* (DTU), the Italian *Niccolò Cusano University* (UNICUSANO), the Polish *Gdansk University of Technology* (PG) and the Swedish *Lund University* (LU). The project has just been funded by the European Community and will be activated by the end of 2020.

This paper describes how NLITED is conceptually structured, how the teaching of daylight simulation is thought for this eLearning setting and, finally, illustrates what the authors believe to be the expected impact of the educational proposal.

The NLITED concept

The Educational Package (EP)

The EP is structured in several teaching modules to cover different aspects of multidisciplinary of the daylighting field. Teaching modules include an eLearning Platform and an Intensive Study Program (ISP) in the form of a summer school.

The ePlatform will contain theoretical knowledge, while the ISP will be used for in-depth applied training, as shown in Figure 1.

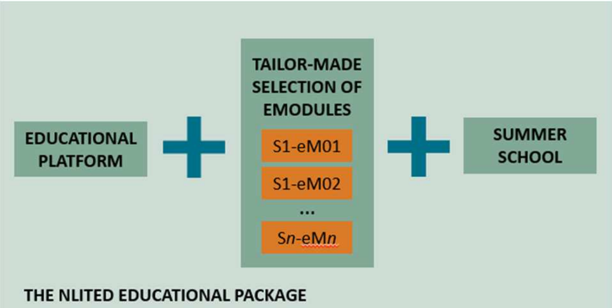

Figure 1: The NLITED educational package. It consists of an educational platform offering modular teaching combined with a summer school. The ePlatform and eModules offer the theoretical part of learning while the summer school enables practical application.

The EP is designed for three different types of learners:

- Traditional learners. University students mainly from the faculties of architecture, civil engineering and environmental sciences that can supplement online training credits for their curricula.
- Part-time learners. Student-workers who can benefit from a distance and modular learning.
- Non-traditional learners. Building professionals who wish to follow only a few modules to improve their knowledge.

The training paths

A prior-knowledge test (input test) will assign learners to the didactic eModules needed to fill the individual knowledge gaps (Figure 4). The learner will carry out a final exam (exit test) on the assigned eModules. ECTS credits (students) or certificates of attendance (professionals) are recognised for each eModule. Students willing to deepen their knowledge can enter a selection for joining the ISP. The ISP is a summer school which includes lectures, hands-on sessions and peer discussion. All participating students will receive extra ECTS credits or certificates of participation. Scholarships are provided for travel and accommodation to ensure students' participation in the ISP.

Choice of partners

The four partners involved in the implementation of the education package represent three distinct European geographical areas facing different challenges in daylighting design.

- **Northern Europe countries** (Denmark and Sweden) face daylight design challenges in terms of significantly changing availability of daylight during the year and low solar angles, increasing, e.g. risk of glare.
- **Central Europe countries** (Poland) must deal with the often-cloudy sky and constantly changing weather conditions.
- **Southern European countries** (Italy) face challenges in terms of excessive solar heat gains during some months.

In addition to the main academic partners, a **local network of stakeholders** has been built for each participating country.

Their role is to ensure that the training proposal can have a real impact on the social context of the territories involved. They have been included as associated partners and divided into five categories:

- Universities
- Building Associations
- Building Companies
- (day)Lighting Associations
- Dissemination sector as trade journals, professional magazines (Figure 2).

Associated partners are involved in defining educational needs, recruiting learners, and publicising the proposal and its results.

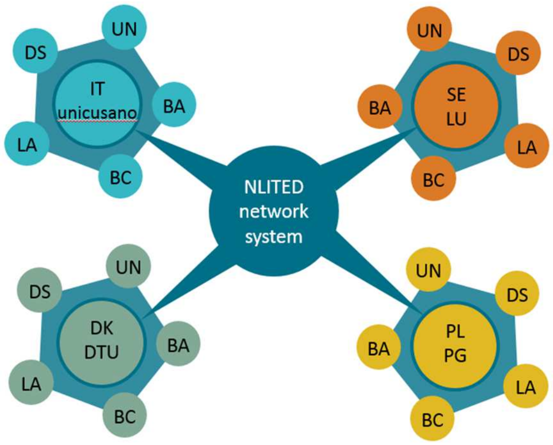

Figure 2: The NLITED network includes associated national partners. They are other Universities (UN), Building Associations (BA), Building Companies (BC), (day)Lighting Associations (LA) and bodies from the Dissemination Sector (DS).

Content of eModules

NLITED is planned with a pre-proposal of six subjects organised in 24 eModules (Figure 3). They cover main daylighting design areas like daylight cultural aspects, non-visual aspects of light, energy implications of daylighting design, simulation methods, daylighting evaluation and daylighting design. The first part of NLITED, which lasts one year, aims at defining the exact content of eModules. This is done in cooperation with the associated partners. The purpose is to create a demand-oriented, yet robust and comprehensive, EP which can have a real impact in the professional world. The ISP summer school takes up the themes of the platform but makes them applicable through a whole project of integrated daylighting.

The eModules on BPS accounts for nine eModules in two subjects (Figure 3).

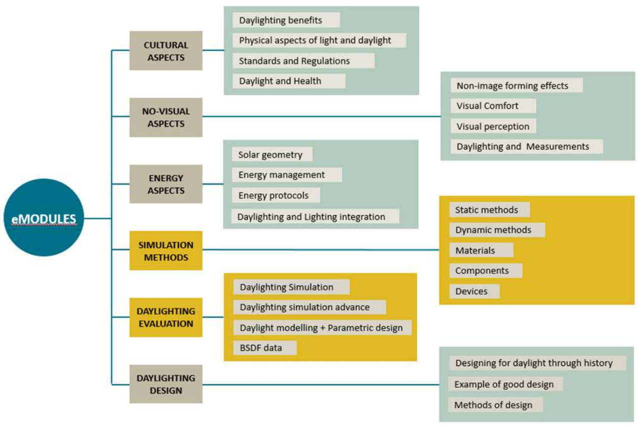

Figure 3: The NLITED organisation of the modules in the training proposal. The modules dealing with daylight simulations are highlighted in yellow.

Daylight simulations in NLITED

Daylight simulation as a topic in itself

Daylight simulations are highly recommended to be performed at the early design stage when many design elements are yet to be defined. This calls for many assumptions about input values, which will significantly affect outputs and call for careful expert interpretation (Ochoa *et al*., 2012). For example, the choice of surface reflectance can result in ±60% differences in output for some daylight metrics, even if the choice is within appropriate ranges as defined by building codes (Brembilla *et al*., 2018). Also, the choice of simulation technique has an impact on outcomes. For example, Brembilla *et al*. (2018) found ±15% difference in results by using different Radiance-based techniques. Training daylight simulations is, thus, not an easy appendix to daylight theory, rather a discipline itself. It requires a deep understanding of input and their impact on daylight metrics. It also requires knowledge of theory and methods used by lighting simulation software in order to understand, for example, why a radiosity technique may not be appropriate for glare assessment, or why the same simulation may provide slightly different results when carried out with different software. For such reason, NLITED is planned with specific and extensive modules on daylighting simulations. The choice is also justified by the fact that NLITED target students are also part-time and adult learners, for which a simple module structure with focus on assessments seems to be more effective (Youde, 2019).

Content of the simulation eModules

As main learning objective, the simulation eModules aim at training the "daylight simulation 'expert'"; namely, a professional with a comprehensive understanding of the scientific domain, rather than someone with simple knowledge of software operation (Alsaadani and Bleil De Souza, 2019).

In line with the NLITED plan, the BPS eModules are provided with the overarching topics for each subject. The exact content and adopted software will be defined in a number of workshops between the academic and the associated partners. The workshops will provide a stage for discussion and negotiation of demands coming from the scientific and professional worlds.

Open questions for the workshop can be, for example, which software should be adopted. The discussion would deal with what are – partially – still "academic" demands (as the ability to run advanced dynamic daylight simulations and the handle BSDF) versus professional demands (as the commercial spread of the software, ability to include the tool in existing workflows, the current normative requirements). Similar debates will consider, for example, the daylight metrics to be included in the curricula, the extent to which materials and their properties are implemented in the simulations, and more.

In any case, a comprehensive overview of existing simulation tools and the engines behind will be given. Both sunlight and daylit analysis tools for integration of them in the building design process will be explained. The participants will learn about:

1. daylight urban and architectural site planning analysis and modelling,
2. a computer-assisted architectural drawing or computer-aided design tools useful in sunlight analysis,
3. simulation and visualisation tools (computer or photography documentation) for daylight appraisal.

The acquisition of this knowledge will allow the future expert to conduct simulations as a series of experimental procedures to suggest better integration of them into building performance modelling. The idea is to build up an influential theory as a starting point. Physically-based rendering systems tailored to the demands of lighting and architecture allow for accurately rendering the flow of light in the space (Ward, 1994; Ward-Larson and Shakespeare, 1998). A core knowledge on rendering methods, e.g. radiosity, raytracing, etc. will deepen the understanding on how main principles of global illumination, reflected light is equivalent to emitted light and the principle of direction are met to realise a physically-based rendering. Such deepened knowledge will strengthen the simulation basis, geometrical assumptions, the definition of optical properties of materials, and the shortcomings of the obtained results for a more conscious design decision making.

Implementation of rendering methods in different software and tool is the following step. Through inductive methods and providing several examples, tool, metrics and parameters will put in test and demonstration to increase the learning level. Inductive methods, through real examples, will link the simulation theory, the knowledge of the software and the daylighting theory for better understanding of the building performance itself.

A teaching framework for the simulation eModules

Training the daylighting experts requires a training ladder where knowledge is built with an increasing level of difficulties (Alsaadani and Bleil De Souza, 2019).

One possible way to frame this training ladder is provided by the learning spiral theorised by Beausoleil-Morrison (2019), an adaption of the theory of experiential learning by Kolb (2014) to the teaching of building performance simulation. The learning spiral provides continuous feedback between the study of theory, real experience, and phases of reflection and conceptualisation. Each spiral account for a part of teaching curricula and connects to the following learning spiral in seamless grow in complexity. The model seems useful to train building simulation experts (Beausoleil-Morrison, 2019; Gentile *et al.,* 2019), and it can be easily implemented in eLearning, where the real experience is computer-based by definition.

A well-fitting example has been recently provided by Mendes and Mendes (2019). The authors proposed and successfully tested, instructional design to promote e-learning in the field of education in building energy simulations. The educational offer included theory of building physics and practical exercise run via a specific software, which accounted for the study theory and concrete experience as defined by Kolb's theory of experiential learning. Also, the authors used cooperative problem-based learning where students could have an asynchronous written discussion on teaching. The authors argued that the collaborative environment could trigger reflections and conceptualisation (Mendes and Mendes, 2019).

It is essential to underline that online teaching comes with several additional challenges for learners. Kebritchi *et al.* (2017) identified learners' expectations, readiness, lack of sense of community, and passive participation as commonly reported issue in online teaching. Such issues are likely to occur in a diverse learners' community like the one in NLITED, which attracts a different type of students, with different pre-knowledge and possibly different goals. To address the issue of expectations, the curricula will be built together by academic and associate partners, acting as representatives of the different types of students. This is extremely important for the simulation part, which should always be updated in the tools, extended in content, but not overwhelming. Also, NLITED is planned with a first-year trial followed by an evaluation by students and partners, which will shape the subsequent editions of the course.

The experience of Mendes and Mendes (2019) suggests that readiness and participation of learners can be minimised by creating a collaborative learning environment with stimulating teaching methods like problem-based learning. Also, daylight simulation offers a range of possibilities for introducing and testing appealing teaching methods that could work remotely in both synchronous and asynchronous communication, like learning by playing (Reinhart *et al.*, 2012).

Finally, as far as the sense of community is concerned, the use of interactive and collaborative learning methods for daylight simulation should build a close-knit learners' group and reduce drop-out (Croxton, 2014). Going beyond the online experience, NLITED is planned with the additional ISP, which is attended physically, and which would increase – hopefully – a sense of belonging.

Based on such considerations, the authors believe that online training of daylight simulation experts can be appropriate and effective. The learning spirals may shape the planning of modules. Several learning spirals may be used, starting from the theory of simulations, expanding to static and climate-based daylight simulations, and finishing with, for example, advanced glare assessment. Finally, some form of interactive peer collaboration should be included in the learning process.

Partners experience in teaching daylight simulation

At LU, about 25 students per year attend a course on daylighting. The course is divided into 24 hours of theoretical frontal lectures and 25 hours of simulation, including the theory of lighting simulations. The students work in groups of 2-3 students to a project report, which consists of daylight simulations of a real environment (static, climate-based, and image-based) where they propose some improvement of daylight for space. The simulation part is supported by video tutorials that are highly appreciated by the students. The simulation in the class consists mostly of tutoring. The format seems to work fine: course reports are of good quality and course evaluations are positive. A similar approach may be transferred online, maybe with synchronous tutoring at set times. However, this has not been tested yet and the author have neither experience nor feedback from online teaching of daylight simulation.

At the PG during the academic year of 2019/20, there are four courses with daylight analysis offered for BSc (15 hours) and MSc (30 or 60 hours) architecture students. The students are asked to participate in 5 or 6 theoretical lectures and then perform a solar analysis of the building of their design. The next stage includes a hand-on course on daylit interior simulations using one available software dedicated to daylight analysis. The participants are asked to evaluate daylighting within spaces in the buildings designed by them during their studies to comprehend the consequences of taken design decisions. In a spring term of 2020, all the courses are held online via eLearning platform due to Covid-19 pandemic's restrictions.

At DTU, up to 80 students attend the daylighting and lighting course each year from mainly civil and architectural engineering study paths. The course is a 5 ECTS course held over 13 weeks with learning objectives on evaluation level according to g to Bloom's taxonomy level (Adams, 2015). To promote deep and constructive learning, the course has been revised in recent years with several formative assignments, summative assessment methods based on poster session in connection with industry done in groups of four and a final individual exam. The training assignment and group work are based on accessible building measurements and simulation to access the reality of the environment.

The experiences of the partners show that the simulative aspects are well integrated into architectural design, but it is necessary to understand better the differences between the various techniques that can be used online teaching.

Expected impact

Validation of the methodological approach

The educational model is designed to be implemented in three years:

- year one for the creation of the educational material and the dissemination system (modules and platform);
- year two for the launch of a trial version of the EP;
- year three for implementing feedback and for the realisation of the final version of the EP.

The full implementation is planned to be supervised by monitoring and evaluation activities, which allow at the end of the process to have a validated model, ready to be launched as an educational proposal on an eLearning platform. The relationship between outputs and validation phases during all three years of activity is shown in Figure 5.

The validation process of the educational model is necessary to produce an educational package that meets the real needs of designers. The validity of the teaching framework is expected to be evaluated with survey and interviews with both learners and associated partners.

Expected outcomes

The following outcomes are expected from the NLITED project and related daylight simulation eModules.

- A defined, need-based, demand-oriented daylight educational curricula, based on input from the associated partners in the countries involved.
- The proposed educational system, thanks to the eModules database combined with an entry test system, will allow each student to take advantage of a tailor-made training offer, adapted to their needs and aimed at active and non-dispersive learning. This will enable students and professionals to make better use of daylight in their architectural designs, reducing design errors (thermal overloads, electricity consumption) and improving their awareness of environmental sustainability.
- Useful lessons learned for future pedagogical approaches to the teaching of daylight theory and simulation in the building sector.

Elements of innovations of NLITED

Considering the state of the art of daylight training, the NLITED educational project possesses strong elements of innovation.

- **The Topic.** Despite the current knowledge on the effect of light and daylight on human health and the undeniable importance of daylighting in terms of indoor environmental quality and energy-saving, the study of daylighting still has neither its educational visibility nor the recognisable professional evidence it deserves because of its complexity. Through the NLITED project, we will facilitate a close connection between European daylighting research centres, which will benefit from each other's experience, transferring expertise that is hardly available in one single country.
- **The strategic partnership.** The choice to have a partnership based on countries of the three main European latitudes. This will guarantee to respect all the different points of view of the design problem.
- **The supranational network.** Stakeholders will not be involved on a one-off basis, but will become an integral part of the partnership creating a double system of cooperation at the local and supranational level is implemented.
- **The methodological approach.** NLITED project combines a variety of study modes (modular learning + distance learning + intensive study programme) for a diversity of learners (traditional, part-time and non-traditional students) through a flexible and tailor-made methodological approach adaptable to the different users. Such an approach prepares designers more concrete. Design teaching always requires debating with mentors and peers, as through workshops or summer schools.
- **The ICT tool.** Since daylighting design and simulation is a specialist preparation, having an audience interested in the subject in one country can be difficult. A platform can allow having a more widespread but also motivated audience. Through the eLearning platform, one can reach students who are motivated but physically located in contexts where there is little teaching tradition for this subject.
- **BPS modules innovation**
  The deep learning approach provided through the BPS module will ensure an educational framework that can train practitioners and future daylight professionals with a more in-depth knowledge and connection between the virtuality of the simulation environment and the real environment. Through inductive methods, several examples from real buildings and real problems, the intention is to

advance the learners skills not only on the appropriate and proper use of the tools but accurate and realistic interpretation of results.

Conclusion

The training proposal presented in these pages illustrated the concept of an educational package for daylight theory and simulation blending eLearning and a summer school. The package is suitable for teaching specialised but also strongly multidisciplinary subjects. The programme is thought for need-based, demand-oriented teaching. The use of ICT will improve the technical training offer going beyond the national scale and reaching students from other European countries. This will help to train qualified designers on sustainable design and to raise the cultural level of the debate on environmental issues. Besides, specialist eLearning models show that they are best suited to respond to conditions of high uncertainty such as the one we are experiencing now due to the COVID-19 pandemic.

In this paper, we proposed the general content and a teaching framework to introduce daylight simulations in this eLearning educational package. However, the teaching framework is based solely on existing literature and the authors' own experience. It is the authors' wish to discuss and share the experience with the experts of the IBPSA Nordic community to improve this framework. We are persuaded that their constructive feedback would much improve the quality of NLITED.

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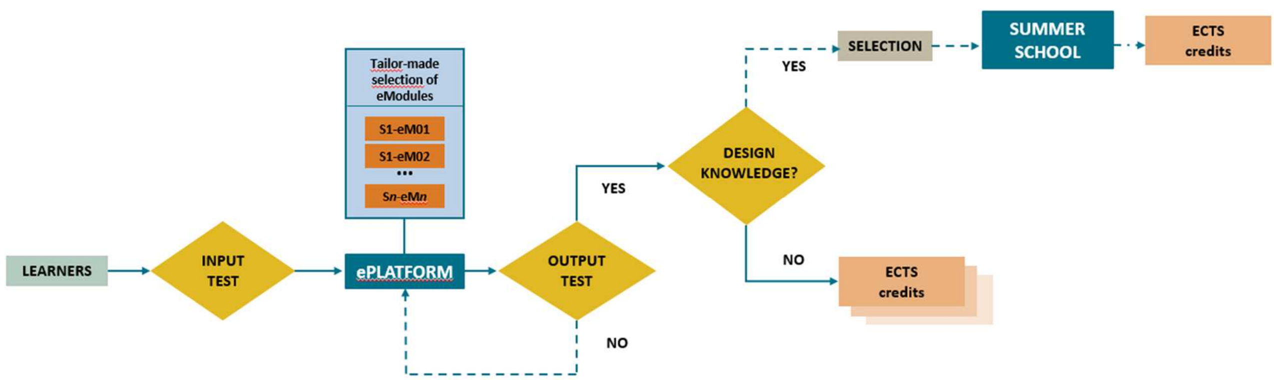

Figure 4: The NLITED training path. A prior-knowledge test (input test) will point to the eModules that should be taken up to fill the knowledge gaps. The final exam (output test) is a summative assessment to verify the learning outcomes. The students will receive ECTS credits for each passed module. Participation in the ISP (summer school) is not compulsory but is an in-depth study concerning applied daylighting design and simulation for real-world problems.

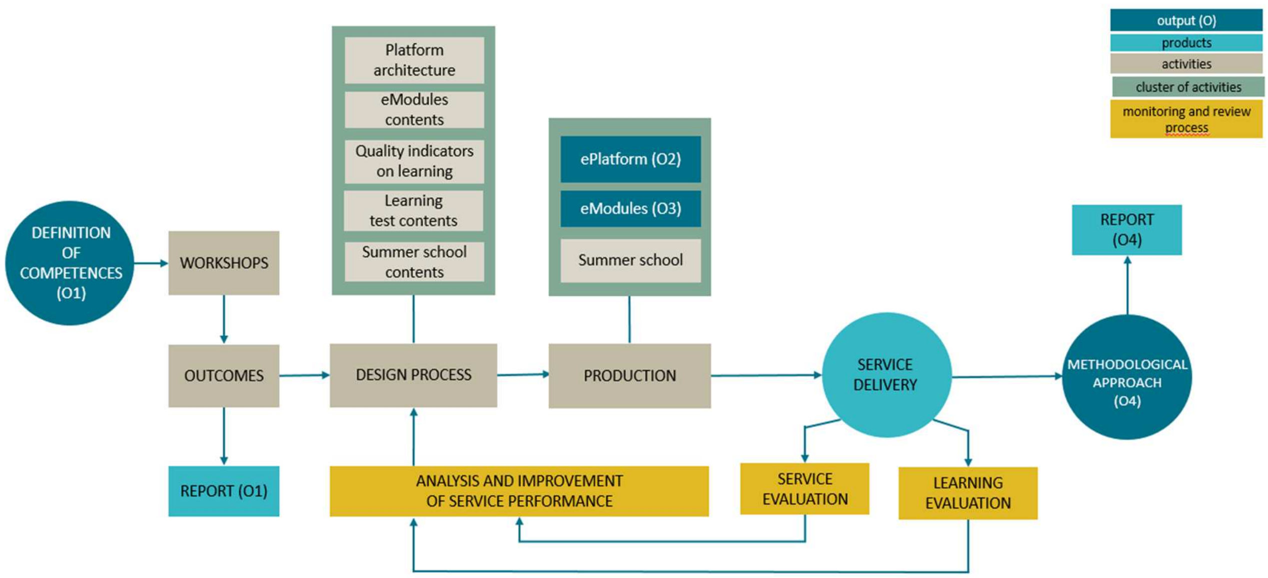

Figure 5: The validation of the NLITED methodological approach. The creation of the educational package is based on mutually related activities. The "Definition of competence" is the starting activity/output for the creation of the eModules. Once the ePlatform is activated, the monitoring and evaluation process will lead to a revision of the educational proposal after the first trial year. The results obtained, corrections made, and new results will be collected for the validation of the educational model.

Update of a living building-simulation tool

Ole Michael Jensen*, Kim B. Wittchen, Chrisitian Grau Sørensen, Jesper Kragh, Jørgen Rose, Nanna Dyrup Svane, Karl Grau Sørensen

Aalborg University, Denmark
corresponding author: omj@sbi.aau.d

Abstract

In the early 1980s, researchers at the Danish Building Research Institute (SBi) created a successful building simulation tool called tsbi, since year 2000 BSim with a full 3D geometry model and Windows compliant. At that time, C++ was a new promising programming language and BSim and its extensions was based on this technology.

After almost two decades, the researchers, together with the programming team, decided to rebuild BSim. It was acknowledged that it needed a new platform for compatibility reasons and a new user interface to meet users' requests. A special challenge on the doorstep of this rebuilding was how to make the new BSim ready for online simulation and to establish an API (Application Programming Interface) while maintaining the existing BSim simulation core in operational stage.

This paper deals with the researchers' analyses of BSim concerning functionality, user interface, performance etc. Moreover, it deals with the smooth transformation from the old to the new BSim. The programming team dealt with this transformation by implementing a "parasite" into BSim and establishing a manager that is able to control the old BSim. The team created the parasite as 'tentacles' designed in C++. This enables the team to build a new BSim core by use of Rust programming language. At first, the new interface will only be a thin layer around the old BSim, interacting via this parasite. Gradually, the thin layer will be more elaborate, and at the end replacing the old BSim, but without loss of functionality and speed of simulation.

This way the paper demonstrates how a dated IT program can be recycled and boosted without disturbing the users in order to conserve a highly appreciated simulation tool for future use.

Introduction

Since the 1980s, the dominating thermal building simulation program in Denmark has been BSim and its predecessor, tsbi3. It has been used by building designers and engineers for indoor climate analyses especially in non-residential buildings. The strengths is its flexibility and relative simple approach to simulating technical buildings systems. It can easily be used in the early design phases to analyse indoor climate and control strategies for technical building systems.

The weaknesses are its old-fashioned user interface, simple 3D drawing ability, limitations in import of building geometry from CAD tools, and the use of the outdated Microsoft Foundation Classes (Microsoft, 2019).

From the start, the Danish program received high ranking in international validation exercises of building energy performance simulation programs. In 1997, the predecessor tsbi3 demonstrated its capability of accurate simulation of the energy demand in an international empirical validation exercise (Lomas et.al., 1997). Later on, in a study contrasting the capabilities of building energy performance simulation programs, Crawley et al. (2008) points out that "BSim provides user-friendly simulation of detailed, combined thermal simulations of buildings and constructions". Last but not least, BSim has a large number of users expecting regular updates and the occasional offer of new simulation features.

All in all, this calls for a much needed update of BSim to have a role in future Danish building design and to sustain its high international standard.

Since this realisation, the discussion among the developers has been vacillating between building a new program from scratch and gradually rebuilding BSim on a new IT platform with a smooth transition. The first approach requires support and maintenance of the existing source code as a separate program in parallel with creating the new tool.

Finally, it was decided to design a new BSim while the legacy BSim is still at work. In other words, the old BSim still has to be maintained and extended using the new Rust platform while the new BSim is under development, but as one integrated new tool. The solution found by the developers is clear: A new BSim Manager must be created that simultaneously is able to run the legacy BSim and the new BSim during the creation process. This solution must include an all new code able to run on multiple platforms, like Windows (Microsoft, 2020) and Linux (Linux Foundation, 2020), although MacOS (Apple, 2020) must be supported as well. Finally the solution must include accessibility on the web, at least as a simulation engine.

This paper has two parts. The first part is an account of the evolution of the legacy BSim starting from the origin in the early 1980s. This includes the story of a simulation tool continuously being reconstructed, transformed and extended. The second part is an account of the development of a new generation simulation tool. This includes an explanation of the components that make up the new BSim and its IT platform.

The history

The origin of BSim can be dated back to the so-called TEMPFO4 (Andersen, 1974) program. It precedes the first thermal building simulation program tsbi and was released in 1974. Details are unknown except that it was programmed in the FORTRAN language (Control Data Corporation, 1972) and built to be run on mainframe computers.

After TEMPFO4 came tsbi designed to run on “micro-computers” or PC’s. It was an initial scientific model developed in cooperation with Bo Andersen, Crone & Kock A/S. Karl Grau, researcher at Danish Building Research Institute (SBi) did the programming in Pascal (Jensen and Wirth, 1974). The building model in the first tsbi was a single zone model (Grau et al., 1985). In 1987, researchers at SBi launched the third generation simulation-program tsbi3 (Johnsen and Grau, 1994). By a new design, this tool was able to simulate multi-zone building models. This was a total rewrite of the source code in C programming language (Schildt, 1995) for PC’s under MS DOS.

tsbi3 was a stand-alone program dedicated engineers and building design offices carrying out indoor climate and energy flow analyses in buildings. However, in 1990 the SBi developers, Johnsen, Grau and Rode participated in The EU JOULE COMBINE projects (Augenbroe, 1992). This was the first international project with relevance for the building simulation and neutral data exchange to adopt the ISO STEP standard (ISO 10303-1, 1992). The scope of the phase 1 COMBINE projects was to develop prototypes of an Integrated Building Design System, where data integration between architectural and engineering design tools facilitates a more efficient and fault tolerant exchange of data.

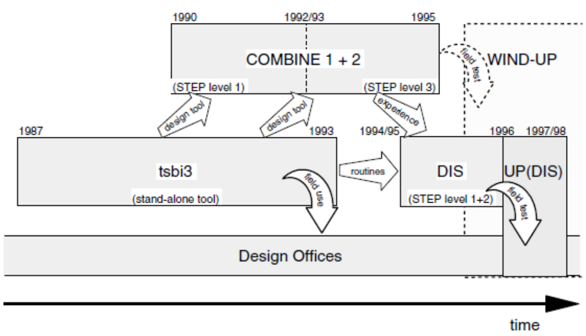

Figure 1. Evolution of a building energy simulation tool from the stand-alone program (tsbi3), over a design tool (DIS) in an advanced integrated building design environment (COMBINE 1+2) (Rode and Grau, 1996).

In second phase the COMBINE projects succeeded in developing and demonstrating the functionality of integrated building design systems (Augenbroe, 1994). In this phase, the Danish developers succeeded to combine the original tsbi3 stand-alone tool with a number of other design tools (Rode and Grau, 1996), the final product was called DIS (See Figure 1).

The design tool BSim

The forerunner of BSim was the so-called DIS system. DIS was the first Danish integrated thermal simulation system. From the very beginning it consisted of a number of design tools and utilities, all based on a common data-model. The design tools were implemented as separate Windows programs each with their own user interface. Physical STEP files transferred data for a building model between the programs.

This was also implemented in BSim and here the modules are DisView (editor for visualisation of the building model and common user interface for many modules), SimDXF (a tool for extracting information from 2D CAD drawings saved in DXF format), building model export to Be18 (Aggerholm, 2018), which is a compliance checking tool in accordance with the Danish Building Regulation’s requirements, SimLight, (a simple daylight calculation tool), tsbi5 (the 5th generation tool for dynamic hygro-thermal building simulation) and SimDB (a building components and materials database user interface). See Figure 2.

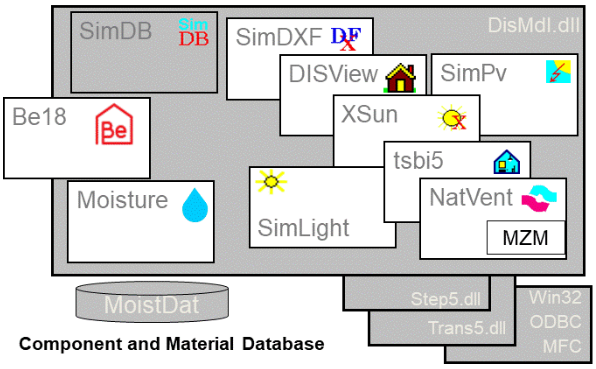

Figure 2 The architecture of BSim combines a number of design tools like a visualization tool (DisView), a simulation tool (tsbi5) and a building components and materials database (SimDB).

BSim, and its predecessors, were all to a large extend programmed by one single person, Karl Grau. The current BSim source code is written in C++ (Stroustrup, 1997) and exceeds 1 million lines of code. It is thus not straight forward to take over the programming task and therefore a step-vise transformation is deemed most fail-safe.

The data-model

The core of BSim, is a common data model shared by the majority of the design tools. The data-model consists of five sub-data models

1. A 3D Geometry/topology model for overall layout of a building described as Cells, Faces, Face Sides, Edges and Vertices.
2. A Space model describing the space objects (Ground and Rooms) having the Cells as geometry/topology representations,
3. An Enclosure model, describing enclosing elements (Constructions, Windoors and Holes) that have the Faces as geometry/topology representations. 'Windoor' is a common description for windows and doors. In addition the enclosing elements have a description of the two Finishes that have the Face Sides as representations,
4. A Building Component model describing standard building components and materials. The model describes the physical properties of the enclosing elements.
5. System model describing various HVAC systems and their control.

Model editor

From the very beginning, the model editor DisView was a central tool in BSim. It is used for the creation, editing and visualisation of the building model, and for the activation of the design tools in the BSim program package (Wittchen et al., 2000-2019).

The user interface (Figure 3), is organised in a left and right view. The right view is split up in four panes showing the building graphically. The lower left pane shows a plan view of the building. The two upper panes shows the elevations, and the lower right pane shows a 3D parallel projection. The left view is a representation of the building as a hierarchical tree.

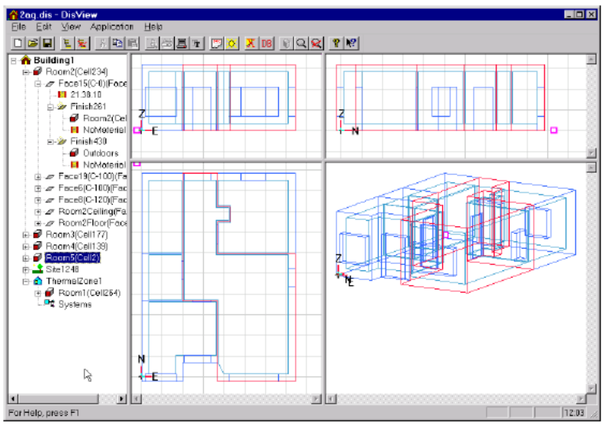

Figure 3. The model editor DisView showing a building model in 4 wire-frame drawings and a tree structure giving access to modify inputs for all parts of the model on all levels.

Through dialog boxes the user can enter attributes associated with any selected object in the building model from the tree structure. In addition the automatically calculated properties, i.e. areas of walls and volumes of rooms are shown in the dialogues.

An ambition already in 1995 was direct integration and use of CAD models made by the architects and engineers so that the design model and the simulation model was based on the same data model. In that case the analyses could be performed immediately on the common digital model of the building project (Augenbroe, 1995).

Most CAD systems however, have their own data model. Therefore, data transfer between tools has to be performed manually or by a one-to-one tailor-made program mapping data between the different data models. This process is risky because of misinterpretation, or even impossible, because concepts in one model do not exist in the other model. Introduction of IFC (Industry Foundation Classes) aim at standardising the data structure of Building Information Modelling (BIM) and hence ease exchange of data (ISO 16739-1:2018). It is though still not straightforward to import data from a CAD tool to a building simulation model (Dessel et al., 2019). Therefore, in parallel to the reconstruction of BSim a method for Semi-automatic geometry extract from Revit (Svane et al. 2020) is being carried out. This will ease the way for data import from a BIM model to building performance simulation tools.

The thermal simulation tool

The thermal simulation tool tsbi5 is the central tool of BSim. tsbi5 is an acronym for Thermal Simulation of Buildings and Installations, 5th generation. Thus, tsbi5 is an enhanced Windows version of the known DOS program tsbi3 (Johnsen and Grau, 1994). The major enhancements in tsbi5 were:

1. Full 3D geometry and view of the model in a Windows user interface,
2. Implementation of combined heat and moisture (optional) transfer model in materials (Rode and Grau, 2001),
3. Windows compatible export of results (graphics and numbers) through a module with possibility of manipulating graphics,
4. Possibility to use 2D CAD drawings saved in DXF format as base for creation of 3D BSim model geometry,
5. Drag and drop model editing facilities,
6. One common building data model for several tools.

The fully developed tsbi5 is capable of performing transient hygro-thermal simulations of all, or part of the rooms in a global building model (Wittchen et al., 2000-2019). The heat transmission internally in the constructions is described as transient. The constructions are automatically divided into several control volumes. Heat transmission from a neighbouring volume is calculated on the basis of Fourier's heat transmission equation with the approximation that the temperature sequence between the nodal points of these two control volumes is the same as in a stationary situation.

Next generation development

In 2020, after serious considerations and discussions of the future for BSim, the researchers together with the programming team, decided to rebuild BSim. It was acknowledged that BSim needed a new platform for compatibility reasons and a new user interface to meet user requests.

Several challenges faced BSim. Firstly, the foundation of BSim (Microsoft Foundation Classes, MFC) was a legacy library long deprioritized by Microsoft. Secondly, the code was locked to Microsoft and Windows when contemporary IT programming is moving to other platforms. Thirdly, users' expectations for the user interface were increasing and we needed new technology to get there.

On the doorstep of rebuilding BSim several challenges arose: 1. How to make the legacy BSim, all the design tools included, available on a new platform from day one. 2. How to create a new BSim that along the design phase will be able to support the old BSim with new features and new user interfaces and 3. How to implement the new BSim, while still maintaining and extending the legacy BSim. The programming team dealt with the first challenges by creating a "parasite" able to control the legacy BSim fitted with C++/MFC "tentacles".

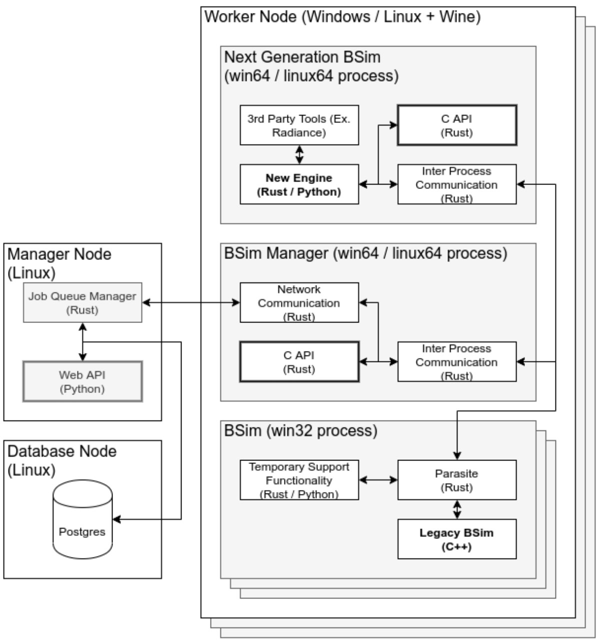

Figure 4. Diagram showing the overall functionality of key nodes of the BSim under development. The pivotal component of the worker node is the BSim manager able to control the legacy BSim (bottom) and the next generation BSim (top) simultaneously

The second challenge was dealt with by gradually designing a new next generation BSim engine compatible with the new goals set. The third challenge was dealt with by creating a new BSim Manager able to simultaneously control both the legacy BSim and the next generation BSim.

Finally, the developers decided that all new code should be written for execution on multiple platforms. The primary is Windows and Linux, but Mac OS will be supported as well.

The legacy BSim can only run on a 32 bit Windows environment. Therefore, a temporary solution must be found, such as running the legacy BSim via Wine (Wine, 2020). Wine is a Windows emulation layer that allows Windows applications to run unmodified on a 64 bit Linux platform (REF_A, 2020). See Figure 4.

Parasite control of the old BSim

The legacy BSim does not have any API for external control. The parasite was created to implement this, by injecting itself into the legacy BSim code.

The parasite was built in Rust and equipped with tentacles designed in C++ allowing it to manipulate everything in the legacy BSim code. The tentacles of the parasite needed programming in C++ to enable the internal manipulation of BSim.

To keep the parasite simple, it only works as a tool acting on others behalf. It is designed to be controlled either externally via inter process communication (IPC) or internally via the "temporary support functionality" module. External control has the advantage of the controller not being encapsulated in the legacy win32 process. Internal control has the advantage of higher bandwidth, and lower latency access to internals of BSim, because it does not need to go through the IPC channels.

Manager

The new BSim Manager was created to solve two problems. The first problem was, that our only way to escape the 32-bit windows process was running a new code in a separate process. Hence, we needed inter process communication and the BSim Manager became the other process. The second problem was utilization of all CPU cores. The legacy BSim was written when multi-core processing was rare and built under the assumption of running in one thread. After the fact, this problem cannot be fixed. Therefore, until a sustainable solution is found, several BSim instances each in their own process must run in parallel. This will not make the single simulation faster, but it will speed up simulation of a batch of projects. Already today, the new BSim Manager in the making handles this parallelization well.

Whatever simulation, single or batch, it must be emphasized that the calculation core is still the same. This means that validation and calibration of simulations carried out on the new BSim are not necessary. In other words, the manager operating the parasite, designed in

C++ will not be able to generate any new calculation or performance mistakes.

Next generation BSim

Concerning the engine of the new BSim simulation tool, the team has decided to use a combination of Rust and Python (Hetland, 2014) programming languages. Rust has the advantage of being able to reach the performance of C++ but is, in contrast to C++, equipped with added protection from "shooting oneself in the foot", i.e. making fatal programming errors. Python has the advantage of being simple, easy to learn and program development is fast.

Put otherwise, we attempt to deprecate the use of C++, mainly because it is rather easy to make mistakes in that code. At best, it leads to crashes and the like. At worst, it leads to bugs that only happen in rare instances. However the biggest problem is the security holes it can leave. Since BSim is increasingly used on the internet, this might pose growing problems.

Another challenge is that C++ contains a lot of heritage (for backward compatibility reasons). More recent standards give a lot of new features but in contract to old ways, allowing one to have code in the old and new styles at the same time. A complete rewrite of the code is necessary to use the newer features and then one can just as well choose a new language.

Since Rust does mitigate a lot of problems, we decided to use it as a replacement for C++. One disadvantage however, is that Rust is a young language hence having the risk of newer ones gaining a stable foothold in the developer mindshare. Nonetheless we concluded that in due time, the new engine should be able to handle the functionality supported in the legacy BSim (Figure 2).

The legacy BSim already supports co-simulation a couple of places, i.e. control of electric floor heating systems and heat/cool supply from heat pumps in the ventilation system. This functionality will be developed further in the rewriting of the code to facilitate inclusion of users' and students' own developments, preferably in the Python language, i.e. opening up BSim for users to develop their own controls, systems etc.

The web

Over time, many of our activities have moved to the web. Therefore, it is also time for BSim to be accessible there. Currently only web access to the calculation engine is implemented. Later on, also other features are planned to be accessible. Hence we created a Web API. The Web API allows a client to submit multiple models for simulation in BSim via the internet, have them simulated on our servers and retrieve the results. The Web API consist of one manager node and several worker nodes. The manager node consists of a web server, implementing the Web API, which in our case happens via "Representational state transfer" (REST) (See Figure 4).

A separate job queue manager ensures that jobs are processed from the database and results are stored there too. It controls several nodes, each running the BSim Manager.

Parallel computing

Already running the legacy BSim, parallel computing was introduced, in contrast to other simulation tools, not to improve the simulation speed for one building model. It was introduced to improve simulation speed for numerous models to be able to carry out myriads of parametric variations for building model optimization purposes (Østergård et al. 2020).

As computer performance increases, the use cases for BSim changes. Today, running thousands of simulations is becoming the new norm. Another aspect is that while computers continue to increase in performance, it is taken advantage of by being able to do more things in parallel instead of doing one thing faster, i.e. performance is improved significantly by having more CPU cores.

BSim is not able to use several cores for a single simulation but running one simulation per core is possible. The legacy BSim has a batch mode for this. The next generation BSim will use the BSim Manager for the same purpose.

Discussion and conclusion

It has proven possible to create a new user interface and a new IT platform to operate on several operating systems for the dated building simulation tool, BSim. This enables the possibility for gradually replacing the source code without the users experiencing performance issues. Additionally, use of a web API have already made it possible to use BSim for multiple, parallel simulations in order to carry out building model optimization by parametric variations.

Nonetheless, the new BSim has its limitations. Currently, only the simulation engine has become accessible via the web. The calculation code of the legacy BSim will not be improved until later. When this happens, a comprehensive inter-model validation procedure will be undertaken, comparing results from numerous models simulated in the old and the new simulation core. Carrying out this multi-model comparison is made simple because of the parallel simulation capability and automatic extract of results on a multi-core server. Finally, it is an obstacle that the legacy BSim still must run on a C++ 32 bits IPC.

The transformation of the legacy BSim has been decided. BSim is accepted as a competitive simulation tool and it is accepted to be a long journey for its modernization. Luckily, developers know where they come from as described in this paper, and they are full of ideas and visions of where we need to go. In this perspective the researchers together with the programming team are looking forward to the next international validation exercise of modern building energy performance simulation tools.

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Semi-automatic geometry extract from Revit for earlier and faster building performance simulations

Nanna Dyrup Svane[1,2*], Artüras Pranskunas[1], Lars Broder Lindgren[2], Rasmus Lund Jensen[1]
[1]Aalborg University, Aalborg, Denmark
[2]MOE A/S, Copenhagen, Denmark
** corresponding author: ndsv@build.aau.dk*

Abstract

The architecture, engineering, and construction (AEC) industry experience a growing need for building performance simulations (BPS) as a facilitator in the design process.

Inconsistent modeling practice and varying quality of export/import functions entail error-prone interoperability with IFC and gbXML data formats. Consequently, repeated manual modeling is still necessary.

In this paper, we present a coupling module for a semi-automated extract of geometry data from the BIM software Revit and a further translation to a BPS input file with the use of Revit Application Programming Interface (API) and visual programming in Dynamo. The module is tested with three test cases and shows promising results for fast and structured semi-automatic geometry modeling.