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STUDENT REPORT

Evaluation of simplified models for checking compliance with building regulations

Prediction of thermal comfort in dwellings

2013

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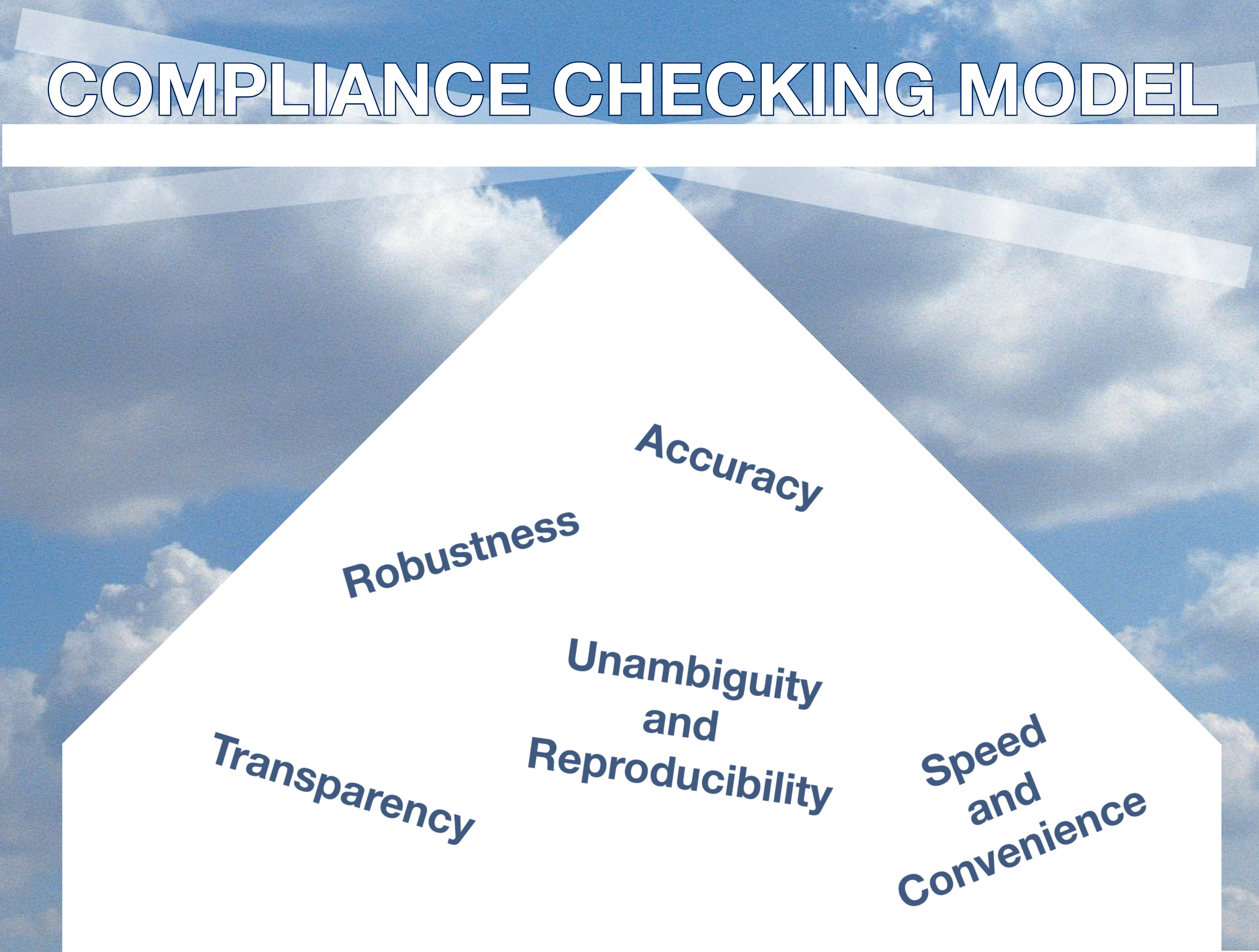

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STUDENT REPORT

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Evaluation of simlified models for checking compliance with building regulations

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Synopsis:

The main purpose of the present thesis was to evaluate simplified models intended for checking compliance with Danish Building Regulations regarding summer thermal comfort.
A survey among companies initially specifies the necessity of a simplified in the preliminary design phase in order to predict how a building design will influence of risk of overheating in residential buildings. A simplified model developed by the Danish Building Research Institute intended for such preliminary estimation and for checking compliance with Danish building Regulations has been evaluated. Prior to the evaluation of this simplified model two additional methods to predict excessive operative temperatures in building are compared according to their implementation and usage of boundary conditions and input data. Thanks to sensitivity analysis the most important input parameters was revealed which made it possible to focus on improvements and select the most favourable boundary conditions.
Subsequently, by implementing similar boundary conditions and input data for each of the considered simplified models an evaluation solely based on model calculation procedures was conducted by usage of changing input parameters and consider their impact in model output. In the end simplified models varying by difference in level of complexity in user input and calculation procedure are evaluated based on aspects of quality. This is based on five real buildings.

Resumé

Design af nye bygninger er i særdeleshed påvirket af de seneste årtiers øget fokus på at mindske bygningers energiforbrug, hvilket især omfatter passive tiltag, såsom forøget lufttæthed af bygningen samt yderligere udnyttelse af solenergi ved at placere store sydvendte vinduespartier. Dette har dog ofte en negativ effekt på det termiske indeklima i sommerperioderne, da bygninger til tider vil blive ude af stand til at overkomme de termiske belastninger, hvilket resulterer i overtemperaturer indendøre. Dette har medført at flere europæiske lande i seneste år har indført anbefalinger eller ligefrem krav til det termiske indeklima. Danmark indfører i det kommende bygningsreglement 2015 for første gang specifikke krav til tilladte antal timer om året med overtemperaturer. Dette kræver dog, at det nuværende beregningsprogram af bygninger energibehov Be10, anvendt til myndighedsgodkendelse, videreudvikles i form af implementering af et forenklet program, i stand til at beregne indetemperaturer på timebasis for et enkelt rum for at kunne analysere det termiske indeklima samt dokumentere om kravene fra bygningsreglementet er opfyldte.

Dette forenklede program vil i nærværende afgangsprojekt blive evalueret og sammenholdt med øvrige forenklede metoder til bestemmelse af overophedning. Indledningsvist præsenteres en undersøgelse baseret på et spørgeskema udsendt til danske virksomheder, som vil indikere behovet for et forenklet program til bestemmelse af det termiske indeklima samt hvilke egenskaber det skal besidde. Senere separeres de betragtede forenklede metoder og modeller ved først at fokusere udelukkende på randbetingelserne samt input parametre. Ved hjælp af følsomhedsanalyser af input parametrene for de forenklede modeller fremhæves det vigtigste parametre, hvilket går det muligt at fokusere på forbedringer som udvælgelse af det mest favorable brug af input parametre og randbetingelser i modellerne. Dette gør det muligt at anvende ens randbetingelser samt input i alle de betragtede modeller og dermed udelukkende fokusere på beregningsprocesserne for det forenklede modeller.

Efter enkeltvis analyse af det forenklede modeller randbetingelser og input samt beregningsprocesser, evalueres det forenklede modeller i form af case study for enkelte parametre varieres og sammenholdes med deres indvirkning på resultatet. Afslutningsvist vurderes de betragtede forenklede modeller ud fra i hvor høj grad de besidder forskellige kvalitetsaspketer defineret i internationale standarder for forenklede modeller til bestemmelse af bygninger termiske ydeevne. Denne vurdering er baseret på fem reelle test bygninger med henblik på at opnå brugbare samt troværdige resultater.

Preface

This Master thesis is a documentation of the study concerning the evaluation of simplified models intended for checking compliance with Danish Building Regulations regarding thermal indoor environment in dwellings. The project was written during the period from September 2012 to June 2013 by two students in the Master of Science Programme at the faculty of Indoor Environmental Engineering at the School of Civil Engineering at Aalborg University.

The aim of the thesis is to obtain knowledge and perform theoretical calculation with regards to building thermal performances and thermal building simulations. Basic knowledge regarding passive energy technologies, thermal accumulation calculation methods and building evaluation through sensitivity and uncertainty analysis will be the prerequisites for reading the report.

Read guidance

The project is divided into two parts - a main report and appendix. In the main report methods, assumptions and results are presented with continuous references to the appendix, which should be read as an encyclopedia to the main report. The appendix contains additional calculations along with theoretical descriptions and entire data results. As a supplement to both the main and appendix is also attached an appendix DVD to the back of the report. This contains calculations, simplified models and other additional information regarding this thesis. References to the appendix DVD will have the name appendix A.

Chapters are individually numbered chronologically. All figures and tables are numbered according to the chapter. Thus, the first figure in Chapter 6, number 6.1, the second has the number 6.2, etc. Explanatory text for figures and tables can be found below the given figures and tables, and the source is indicated if the object does not have own production.

The report will contain references, all of which are collected in a bibliography at the very end of the report. Source citation is given by *Harvard method*, so a source in the text refers to [Surname, Year]. However, given norms and regulations with abbreviated names, for example [EN ISO 13790 2008], will be referred to by the given number of the standard. Furthermore, the source will be clarified by indicating section or part of the literature, e.g. [K. Thullner, 2010, p. 23]. If the source has more than one author, these are indicated by "*et al.*" Performs the same author several times, the surname will also be numbered alphabetically. The bibliography details books by author, title, edition and publisher, while websites are indicated by author, title, and download date. If a source is placed within a sentence before the dot, it refers to the sentence, whereas it refers to the entire section if it is placed after the dot.

Symbols and units

Symbols

A_{f}	Floor area of critical room	$[\mathrm{m}^2]$
$A_{\mathrm{f,tot}}$	Floor area of entire building	$[\mathrm{m}^2]$
A_{m}	Effective mass area	$[\mathrm{m}^2]$
A_{tot}	Total internal surfaces area	$[\mathrm{m}^2]$
A_{w}	Window area	$[\mathrm{m}^2]$
a, b	Lower/higher boundary for expected interval	[-]
b	Temperature factor	[-]
C_{m}	Thermal capacity	$[\mathrm{Wh}/^{\circ}\mathrm{C\,m}^2]$
c_{p}	Specific heat capacity	$[\mathrm{J}/\mathrm{kg}\,^{\circ}\mathrm{C}]$
d	Thickness of internal layer	[m]
d_{T}	Effective thickness	[m]
d_1	Window distance from edge	[m]
d_2	Window offset from ground level	[m]
d_3	Distance between windows	[m]
f_{c}	Shading factor	[-]
f_{g}	Glazing area fraction	[-]
$f_{\mathrm{si,f}}$	Dimensionless ratio between internal surfaces and floor area	[-]
f_{sh}	Shadow factor	[-]
f_{hor}	Partial shadow factor for horizon	[-]
f_{ov}	Partial shadow factor for overhangs	[-]
f_{fin}	Partial shadow factor for side fins	[-]
f_{wc}	Partial shadow factor for wall cavity	[-]
f_{w}	Angle factor	[-]
g	Solar energy transmittance for perpendicular solar incidence	[-]
g_{dif}	Solar energy transmittance for diffuse solar radiation	[-]
g_{dir}	Solar energy transmittance for direct solar radiation	[-]
g_{gl}	Solar energy transmittance of transparent part of collective element	[-]
H	Building height	[m]
H	Specific heat transfer	$[\mathrm{W}/^{\circ}\mathrm{C}]$
H_{adj}	Specific heat exchange with adjacent rooms	$[\mathrm{W}/^{\circ}\mathrm{C}]$
H_{sa}	Specific heat flow between internal surfaces and room air	$[\mathrm{W}/^{\circ}\mathrm{C}]$
H_{tr}	Specific heat transfer by transmission	$[\mathrm{W}/^{\circ}\mathrm{C}]$
$H_{\mathrm{tr,adj}}$	Specific heat transfer by transmission from adjacent rooms to external conditions	$[\mathrm{W}/^{\circ}\mathrm{C}]$
$H_{\mathrm{tr,em}}$	Specific heat flow between external air and thermal mass	$[\mathrm{W}/^{\circ}\mathrm{C}]$
$H_{\mathrm{tr,ms}}$	Specific heat flow between thermal mass and internal surfaces	$[\mathrm{W}/^{\circ}\mathrm{C}]$
$H_{\mathrm{tr,opa}}$	Specific heat transfer by transmission through opaque construction	$[\mathrm{W}/^{\circ}\mathrm{C}]$
$H_{\mathrm{tr,tot}}$	Specific heat transfer by transmission for entire building	$[\mathrm{W}/^{\circ}\mathrm{C}]$

Symbols

$H_{tr,w}$	Specific heat transfer by transmission through windows	$[W/°C]$
H_{ve}	Specific heat transfer by ventilation	$[W/°C]$
I_{dir}	Direct solar incidence	$[W/m^2]$
I_{dif}	Diffuse incidence	$[W/m^2]$
$I_{gl,h}$	Hourly global solar radiation	$[W/m^2]$
$I_{gl,m}$	Monthly global solar radiation	$[W/m^2]$
I_{net}	Transmitted solar radiation through the glazing element	$[W/m^2]$
I_{ref}	Reflected solar incidence	$[W/m^2]$
I_{sol}	Total solar incidence	$[W/m^2]$
k	Number of input parameters	[-]
L	Building length	[m]
L^{2D}	Thermal coupling coefficient	$[W/m\,°C]$
L_w	Length of window	[m]
l	Linear thermal length	[m]
N, n	Number	[-]
P	Probability	[-]
p	Angle-dependent factor depending on different types of coatings	[-]
Q	Annual electricity consumption	$[kWh/year]$
q_i	Volumetric infiltration air flow rate	$[l/s\,m^2]$
q_{50}	Leakage at 50 Pa pressure difference	$[l/s\,m^2]$
q_{ve}	Volumetric ventilation air flow	$[m^3/s]$
$q_{ve,daytime}$	Maximum ventilation rate during daytime	$[m^3/s]$
$q_{ve,evening}$	Maximum ventilation rate during evening	$[m^3/s]$
$q_{ve,night}$	Maximum ventilation rate during night	$[m^3/s]$
R	Thermal resistance	$[m^2\,°C/W]$
R_s	Surface resistance	$[m^2\,°C/W]$
R_{se}	External surface resistance	$[m^2\,°C/W]$
R_{si}	Internal surface resistance	$[m^2\,°C/W]$
r	Number of elementary effects per design parameter	[-]
T	Temperature	[°C]
T_{air}	Room air temperature	[°C]
T_{adj}	Adjacent room temperature	[°C]
T_{ctr}	Control temperature	[°C]
T_e	External air temperature	[°C]
T_f	Floor temperature	[°C]
T_m	Thermal mass temperature	[°C]
T_{op}	Operative temperature	[°C]
T_{prop}	Proportional band	[°C]
T_{si}	Internal surfaces temperature	[°C]
T_{sup}	Supply temperature	[°C]
$T_{ve,set}$	Ventilation set-point temperature	[°C]
U	Opaque construction thermal transmittance	$[W/m^2\,°C]$
U_{ms}	Accumulation layer thermal transmittance	$[W/°C\,m^2]$

Symbols

U_w	Window thermal transmittance	$[W/{}^{\circ}C\,m^2]$
V	Building volume	$[m^3]$
x	Input parameter	[-]
y	Output	[-]
W	Building width	[m]
α	Thermal diffusivity coefficient	$[m^2/s]$
α	Overhang angle	[°]
α_{cr}	Critical overhang angle	[°]
α_{conv}	Convective heat transfer coefficient	$[W/{}^{\circ}C\,m^2]$
α_{rad}	Radiative heat transfer coefficient	$[W/{}^{\circ}C\,m^2]$
α_{tot}	Total heat transfer coefficient	$[W/{}^{\circ}C\,m^2]$
α_s	Solar altitude angle	[°]
β	Solar incidence angle	[°]
γ_s	Solar azimuth angle	[°]
γ_s'	Solar pseudo azimuth angle	[°]
δ	Earth's declination angle	[°]
δ	Variation coefficient	[%]
δ	Periodic penetration depth	[m]
ε	Hemispherical emissivity of the surfaces	[-]
η	Utilisation factor	[-]
κ	Areal thermal capacity of building element	$[J/{}^{\circ}C\,m^2]$
λ	Thermal conductivity	$[W/{}^{\circ}C\,m]$
μ	Mean value	[-]
$\mu*$	Mean value	[-]
ξ	Ratio of material thickness to penetration depth	[-]
ρ	Density	$[kg/m^3]$
σ	Standard deviation	[-]
σ	The Stefan-Boltzmann constant	$[W/{}^{\circ}C^4\,m^2]$
τ	Time step	[h]
τ_0	Time constant for thermal zone	[h]
τ_s	Solar time for specific location	[h]
Φ_{air}	Thermal load affecting room air	[W]
$\Phi_{HC,nd}$	Heating/cooling need	[W]
Φ_{int}	Internal heat gains	[W]
Φ_m	Thermal load affecting thermal mass	[W]
Φ_{mtot}	Thermal load coefficient	[W]
Φ_{si}	Thermal load affecting internal surfaces	[W]
Φ_{sol}	Solar heat gains	[W]
Φ_{loss}	Thermal loads transmitted to external air	[W]
ϕ	Latitude	[°]
χ	Point thermal transmittance of point thermal bridge	$[W/{}^{\circ}C]$
ψ	Linear thermal transmittance	$[W/{}^{\circ}C\,m]$
φ	Horizon angle	[°]
ϖ	Hour angle	[°]
φ_{cr}	Critical horizon angle	[°]

Acronyms

BR	Building Regulation
CEN	European Committee for Standardization
DS	Dansk Standard (Danish Standard)
EPBD	Energy Performance of Building Directive
ISO	International Standardization Organization
PHPP	Passive House Planning Package
PD	Percentage Dissatisfied
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
SBi	Statens Byggeforskningsinstitut (Danish Building Research Institute)
SA	Sensitivity Analysis
UA	Uncertainty Analysis

Table of contents

Chapter 1

Introduction

This chapter will introduce global building energy and indoor environmental related problems along with their solutions with respect on the European Union and Denmark in particularly. As one of the initiatives, recently entered into force building regulations regarding energy consumption will be discussed here.

1.1 European building regulations regarding energy consumption

The energy performance of buildings has become an important issue because of the increasing strains on fossil energy resources and thus the increasing awareness of the environment. Holding in mind that fossil fuels make up a bulk of carbon emissions, efforts are necessary here in order to achieve reduction of greenhouse gases and subsequently stop global warming. Even since the Kyoto Protocol entered into force in 1997, where the European Union (EU) acceded as the leading force and committed to reduce the CO_2 emissions, it has been highlighted to strive for primary energy consumption reduction. This is vital bearing in mind that energy consumption in buildings is an important factor that contributes to an increase in global warming of the Earth and accounts for 40% of the total energy use in Europe, [Thullner 2010, p. 1].

The long-term solution is to eliminate the use of fossil fuels by developing low-energy buildings, which includes a combination of using energy conservation, passive techniques and renewable energy. Besides contribution to global warming process, fossil fuels reduction will lessen EU dependence on energy from politically unstable regions. The ambition of the European Union is that their member states should collectively reduce their emissions of greenhouse gases by 60% to 80% by 2050, [The Danish Ministry of Climate and Energy 2011].

As an aid to achieve the energy targets of the Kyoto Protocol, the EU Directive on the Energy Performance of Buildings (EPBD) was introduced in 2002 and brought into force in January 2003 by the European committee. This is a common legislation for member states of EU with regards to energy performance of the buildings, which was later supplemented with European Committee for Standardization (CEN) standards, [Thullner 2010, p. 1].

Since 2005 many countries in Europe have strengthened energy requirements for buildings, and EPBD recommends these strengths to happen at least each fifth year. Various countries established long-term roadmaps with detailed goals towards nearly zero energy buildings, to improve energy performance of the new buildings, [EU Energy Policy 2012]. Some examples of good implementation of EPBD are requirements for applying renewable energy in Germany, strongest requirements for specific building elements in Norway and strict framework in Denmark. Furthermore, several

European countries have already established governmental low-energy building definitions and non-governmental (NGO) passive house definitions. The latter is mainly based on on German definition issued by the Passivhaus institute, [Atanasiu 2011, p. 9]. Definitions of low-energy buildings can be seen in appendix B.

1.2 Danish building regulations regarding energy consumption

Building energy requirements in Denmark for the first time occurred in 1961, where it provided only specific requirements for thermal insulation and airtightness of dwellings. Later in the 1970's these specific energy requirements were tightened mostly because of the oil crisis and the establishment of the Danish Energy Authority. The global climate changes caused by emissions of greenhouse gases were initially highlighted in the 1990's due to demonstrations from environmental organizations in order to achieve international agreements to further reduction. This was achieved by strengthened requirements in the Danish Building Regulations (BR) 1995 as well as due to Kyoto Protocol. On the basis of EPBD, the energy requirements introduced in Danish BR in 2006 require 25% lower consumption than the previous from 1995.

It is the vision of the Danish Government that Denmark in the future will be completely independent of fossil fuels. This will of course contribute to maintaining secure, stable and independent energy supply, which will be a key challenge in the future. The vision is brought forward by including the low-energy building concepts, namely the voluntary low energy class 2015 and especially building class 2020 in the current Danish BR (BR2010). This implies a reduction compared to the situation in 2006 of minimum 25% for energy use for new buildings in 2010, 50% for energy use for new buildings in 2015 and finally 75% for new buildings in 2020, [The Danish Ministry of Climate and Energy 2011, p. 1]. Figure 1.1 illustrates this historical reduction of the continuously more stringent energy requirements.

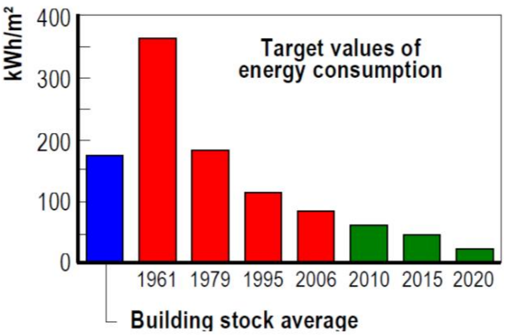


Figure 1.1: *Danish roadmaps towards nearly zero energy buildings [Kurnitski 2012b, p. 13].*

With talks about energy performance in buildings, indoor environmental quality should also be mentioned, as the buildings are created to accommodate human beings and provide healthy and comfortable conditions for them. It is furthermore included in BR2010 that buildings should be constructed so as to avoid unnecessary energy consumption for building services while providing healthy conditions [Danish Energy Agency 2010, section 7.1(1)]. Nevertheless, with all benefits of strengthening energy performance requirements negative consequences more distinctly began to appear, such as deteriorated thermal comfort and indoor air quality in new low-energy buildings accompanied with residents dissatisfaction. These issues are reviewed in following section.

1.3 Indoor environment associated problems in European and Danish buildings

The design of new buildings is significantly influenced by considerations of energy consumption and production, which may have negative effect on the thermal conditions and indoor air quality. For example large windows areas are often placed in southern room to increase solar gains during winter and thereby reduce heating demand, though these actions promote overheating in houses during summer period. Problems, associated with thermal comfort are well-known, but are more distinct in low-energy houses, because their increased airtightness and low building thermal capacity of the buildings facilitate quicker heating of the spaces, [Larsen 2011a, p. 36]. This experience emphasizes, that more attention should be attached to the indoor environment.

This trend is reported in an occupants' satisfaction survey for low-energy buildings constructed in Denmark between 2007 and 2010. There is a significant occupants' dissatisfaction regarding thermal comfort, i.e. 68% of respondents experienced too warm temperatures in summer and 27% claimed too cold during winter period [Kurnitski 2012a, p. 14]. The survey underlines a significance of preventing overheating in low-energy buildings compared to insufficient heating during winter period.

Report *The Comfort Houses*, [Larsen et al. 2012e, p. 66], states that measured excessive temperatures do not correspond to those, which were calculated. In five out of eight houses excessive temperatures, i.e. operative temperatures above 25°C, were experienced during longer time than required by passive house standard, i.e. longer than 10% of the operation time. The author declares that the calculations do not reflect the house behaviour in reality by using average house temperature. However, in real life the indoor temperature varies between different rooms. In addition to thermal comfort an assessment of the indoor air quality (IAQ) was executed, based on measurements of CO_2 level and relative humidity. Assessment showed that CO_2 level is the most critical and there were experienced considerable violations in bedrooms and nurseries, while in living rooms CO_2 level excess was not critical.

With introduction and implementation of EPBD through national legislation the focus have shifted to energy calculation, neglecting indoor environmental issues. Until 2008 indoor environmental issue was dealt differently in different European countries, for example by setting up requirements for ventilation rates or penalties for excessing temperatures, which is a part of global energy performance of a new building [Thomsen et al. 2008, p. 22]. However, the problems with overheating in low-energy buildings, which were described above, forced several countries to implement summer indoor temperature limits in national regulations. These are specified in table 1.1.

Country	Regulation	Binding requirements for summer thermal comfort
Finland	D3 2012	27 °C (25 °C in non-residential) cannot exceed between June 1 and August 31 no more than 150 degree hours, simulated with TRY.
Denmark	BR2010	for class 2015 and 2020, 26°C must not exceed by more than 100 hours and 27°C for more than 25 hours compared to DRY.
Estonia	2007 VVm 258	27 °C (25 °C in non-residential) cannot exceeded Between June 1st and August 31st no more than 150 (100 in non-residential) degree hours, simulated with TRY.
Germany	EnEV 2009	Cannot exceed temperature 25, 26 or 27 °C depending on the climate region for more than 10% of the time of presence.
UK	-	Not included in the regulation, recommendations in CIBSE Guide A (2006).

Table 1.1: *Summer thermal comfort requirements implemented in national regulations in different European countries, [Kurnitski 2012a, p. 16]. Summer thermal comfort is referred to indoor temperature limits in buildings mainly during summer period.*

Bearing in mind anticipated tightening of building national energy requirements in many countries, cf. section 1.1, it is obvious that indoor environment associated problems will demand higher attention in future. Foregoing existing and in future applied thermal comfort requirements create a need to develop tools intended for building thermal comfort evaluation and national building regulations compliance.

Chapter **2**

Problem description

In this chapter the problem considered in the current master thesis is formulated based on an analysis of the indoor environmental challenges regarding thermal comfort and indoor air quality. Furthermore the scope of the project is delimited by introducing different restrictive conditions as well as main focus points. Finally, a project structure is introduced by means of flowchart in order to facilitate understanding of project material.

2.1 Problem analysis

Although indoor air quality associated problems take places in new European and Danish dwellings, a summer thermal comfort in dwellings becomes of increasingly higher importance, cf. chapter 1. An implementation of summer indoor temperature limits in BR of several countries reveals a need for a compliance model capable of evaluating summer comfort in dwellings, while still be attractive for the users by incorporating simplicity and convenience.

2.1.1 Thermal building simulation tools

To prevent overheating in summer periods it is substantially beneficial to alleviate the excessive temperatures in dwellings during the preliminary design phase of a building project, because it is less expensive and difficult. Based on this statement, Erhvervs- og Byggestyrelsen (the Danish Enterprise and Construction agency) introduces in 2015 a requirement for the low-energy buildings regarding control and documentation of excessive temperatures only in the critical rooms. This documentation should include result of thermal indoor environment analysis accomplished by appropriate software, which for dwellings can apply simplified calculation methods. [Erhverv- og byggestyrelsen 2011, p. 22]

The lack of this software is highlighted in *The Comfort Houses*, [Larsen et al. 2012e], where it is emphasized that Be10, building energy calculation tool [SBi 2011], is suitable during the design phases for energy calculations yet not for indoor environmental analysis. While being limited on single zone calculations, Be10 does not reveal thermal comfort problems of south facing rooms with large area of windows. It is emphasized that there is a need for a simplified simulation tool suitable for summer thermal comfort analysis, which unlike Be10 program will not be restricted with single zone monthly calculations and related to them uncertainties. [Larsen 2011a, p. 37]

It should be noted that Danish Building Research Institute (SBi) is currently in progress of a new Be10 version development, which will incorporate a model intended for calculation of summer temperatures in dwellings. This model, [SBi 2013*], was given a name of "SBi simplified model" in the current project. This models is based on EN ISO 13790 simple hourly calculation method specified in European standard and intended for energy calculations. Another well-known in Denmark, simplified energy calculation method - Bo Adamson method, which was later edited by Bo Andersen.

PHPP is a simplified thermal building simulation tool, which is widely used in Europe and is capable of predicting overheating temperatures and thus judging summer thermal comfort. This tool is developed by the Passive House Institute and evaluates proposed building design regarding the Passive House design standard. Due to its relative simplicity it has weaknesses, especially regarding thermal comfort analysis [Larsen et al. 2012e, p. 66]. For example it performs calculations at a building level, by neglecting multizone behaviour, what is not consistent with dwelling behaviour in reality. Furthermore for boundary conditions monthly averages of climate data are used. Therefore PHPP gives an approximation of how the building may behave, but not predicts the performance at the extremes of a local climate.

BSim, [SBi 2004a], is an integrated simulation software for analysis of building, developed by SBi since the middle of the 1980's. It is capable of predicting thermal conditions on an hourly basis by taking into account both the outdoor and indoor climatic data and thus perform a documentation of excessive temperatures. The indoor temperatures and corresponding heat balances are determined for thermal zones, which can consist of one or more physical space. The thermal mass of the building components is likewise considered making the simulations able to take into account the heat exchanged between spaces and structures.

BSim together with another detailed building performance simulation software IES VE, [IES 2012], are currently the only sophisticated thermal simulation software on the Danish market, making them the obvious choice to perform the required thermal indoor environment simulations. However, with upcoming thermal comfort regulations in mind and the necessity of complying them, the complexity of the model should be rather limited for the sake of encouraging the use of it by building designers and architects. In addition, indoor environmental and energy specialists could also benefit of using a tool of limited complexity, because of reduced costs of establishing the model for particular building.

In general, building simulation tools/models may be distinguished by having different complexity, accuracy and required time for establishing the model. Unfortunately, the complexity and accuracy of a tool are often linked to each other due to an increased awareness of the building details, which imply a higher level of input. Additionally, a tool can have a complexity at such an extent that it is incomprehensible, which implies that different actors will achieve different results for the same building and simplified tools with limited input become more preferable. Therefore different aspects should be considered for establishing the model intended for compliance with BR requirements and all of the aspects should be satisfied in order to obtain a balanced model.

2.1.2 Aspects of simulation model used in context of building regulations

As one of the objectives of EPBD is to improve energy performance of buildings, it promotes an establishment of simplified calculation procedures for energy calculations, [EU Energy Policy 2012,

p. 1]. These methods can as well be used for thermal comfort calculations. In order to establish a favourable simulation model, a balance between several aspects contributing to the quality of the compliance model should be obtained. These are important in context of building regulations and are illustrated in figure 7.1.

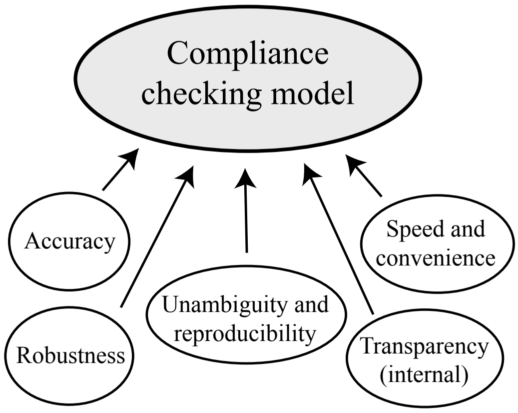


Figure 2.1: *Aspects contributing to the quality of the compliance model. Redrawn from EN ISO 13790 [2008, p. 128].*

Model intended for compliance with BR requirements should provide reasonably accurate result, where accuracy should be balanced with other benefits of the model. With regards to robustness, the model is responsible for providing result with a certain level of accuracy for a wide application. This is especially important for a compliance model, which should be applicable for buildings with all kind of complexity. Unambiguity and reproducibility defines model ability of giving the same or similar output when different users set up the model for the same building and is strongly correlated with input data. Speed and convenience are essential for the user; simple calculation procedure and limited input require minimum time and thus reduced costs to acquire and learn as well as to set up the model. Internal transparency characterises the model ability to be tracked for each time step by the person responsible for calculation procedure. This is achieved when the calculation procedure is based on physical rules and clearly described by set of equations with limited number of parameters containing values without "unknown background". As more transparent the model is as more robust it is and in case if some failures in models performance are detected it is easier to track the calculation procedure and find the possible errors. [EN ISO 13790 2008, p.129-130]

Taking into account above listed aspects of the compliance model, it can be concluded that the compliance model in context of BR should be simplified and transparent with balanced accuracy and robustness, where input should be unambiguous and reproducible. In this case the user is protected from a wrong use and is insured that the result is accepted without a discussion, while saving time on setting up the model and understanding its usage, [EN ISO 13790 2008]. Furthermore, as the compliance model is getting constantly improved, it is also important to provide transparency and limited complexity for the model developers.

2.1.3 Uncertainties in building simulation

Problems regarding deviations between predicted and actual building performance are often caused by occupants behaviour, among these are in particular increased room heating temperature set-point, unpredictable opening of windows for room venting and use of solar shading. Furthermore, climatic conditions and building constructions related uncertainties may lead to an exceedance of the presupposed design criteria and requirements for the actual building.

The more buildings become energy efficient the more uncertain they will become, because the minor factors may have a considerable importance. If these are not considered with caution the actual building conditions may very well exceed the predicted building thermal conditions, [Landing 2011, p. 19]. The calculations will most likely be theoretical and extremely sensitive. This calls for uncertainties consideration within the thermal comfort simulations in dwellings.

Current calculations of the building performance are based on deterministic input causing an uncertain deterministic output. In order to take into account in a simplified way these different kind of uncertainties in prediction of the building performance, their input distribution should be included only for the most uncertain parameters. But this depends on a subjective assessment, which is why the balance between accuracy of the received output and the speed of obtaining result is important.

2.2 Problem formulation

Increasing focus on indoor environment in low-energy buildings is anticipated in future. This is confirmed by including summer temperature limits in various national building regulations. With this in mind, there is a wish for a model intended for checking compliance with building regulations requirement regarding summer thermal comfort. It should incorporate several aspects, which determine the quality of the model and be attractive for the users and developers. An example of such a model is an upcoming simplified hourly model to calculate summer temperatures in dwellings, i.e. SBi simplified model. As this simplified model will be employed within the Danish construction industry and thus responsible for insurance of acceptable thermal comfort in Danish low-energy dwellings the following will be investigated:

- *Is it possible to achieve results at a reasonable high level of accuracy and quality by means of the simplified model?*
- *What are the advantages and disadvantages of SBi simplified model comparing to other existing simplified models capable of predicting summer thermal comfort in dwellings?*
- *Could the features of SBi simplified model regarding aspects of compliance model with Danish BR2015 requirement be modified in order to obtain further balance and attractiveness?*

Another issue which takes serious nature is dealing with uncertain input parameters in low-energy building simulations. Without taking this into account it will be difficult to obtain a reliable result of building thermal performance. Therefore uncertainty analysis should be conducted in the current work, while answering the questions:

- *How important is a role of the modeller in making reasonable estimations of input parameters and obtaining reliable result?*
- *How uncertain is model output?*

2.3 Delimitation

With the purpose of providing high quality of the current thesis it was decided to limit the areas of comprehension. First of all, only summer thermal comfort in buildings are considered for the output of simplified simulation models. Furthermore solely dwellings are investigated within the current thesis, as upcoming thermal comfort requirements in Danish BR are related for dwellings only. It means that only excessive indoor temperatures constitute the requirements for the thermal comfort evaluation in dwellings in current thesis. The application of simplified simulation models and compliance are only considered in Denmark and with Danish legislation respectively, as the Danish weather data is used for models boundary conditions. With this in mind the models are only applicable for dwellings without mechanical cooling.

2.4 Project structure

The main principle used in the project is a split of models into two components, namely models calculation procedures, which are introduced in chapter 4, and boundary conditions/input data, which receive a thorough analysis in chapter 5. The split is undertaken for the sake of isolating one component from each other, which allows to perform a thorough analysis of the models and their corresponding components.

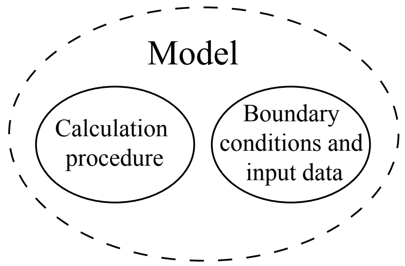


Figure 2.2: *Definition of model term.*

In order to facilitate understanding of project material a flowchart of project structure is made, cf. figure 2.3.

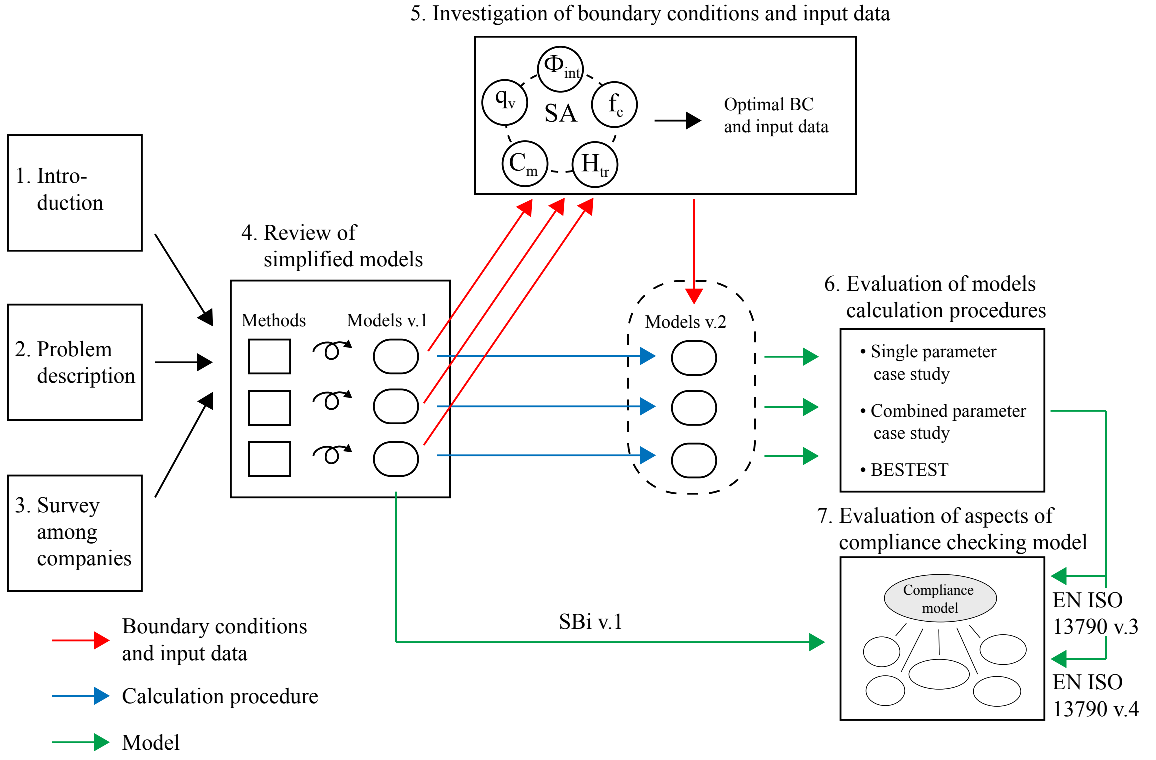


Figure 2.3: *Structure of current master thesis. Rectangles represent chapters in the main report.*

Chapters 1-3 are used for obtaining information regarding the wish for a simplified compliance model for summer thermal comfort simulations in dwellings and its desired features. Chapter 4 is a starting point where existing simplified models are established based on EN ISO 13790 and Bo Adamson calculation methods. SBi simplified model, which is based on EN ISO 13790 hourly calculation method, was received by authors of the current thesis from SBi. Afterwards, models become separated into calculation procedures based on resistance-capacitance schemes and boundary conditions/input data. The latter are investigated separately in chapter 5 by means of sensitivity analysis and later by using BSim, statistics and EN ISO 13786 detailed thermal capacity calculation method for evaluation and comparison. When only one optimal set of boundary conditions and input data is selected, it is applied to models calculation procedures. Usage of the same boundary conditions and input data allows to compare calculation procedures in the same conditions and evaluate them in chapter 6 through single and combined case studies as well as Building Energy Simulation TEST (BESTEST). Since upcoming SBi simplified model is the model, which soon will be employed for compliance with Danish BR2015 requirement, it was thus investigated, whether it is possible to modify this simplified model in order to increase its complexity and hence the accuracy, while still be attractive for all interested parties. Based on models evaluation two simplified models are established with different complexity of RC scheme and boundary conditions and input data (v.3 and v.4). These simplified models together with original SBi simplified model (v.1) are chosen in chapter 7 for comparison and selection of the most favourable simplified model according to aspects of the compliance checking model used in context of Danish BR2015.

Chapter 3

Demand of the market regarding simplified compliance tool

The present chapter serves investigation results regarding the performance of indoor environmental calculation in the Danish companies along with a needs assessment to clarify the demand of the market regarding a simplified tool for analysis of the indoor environment. In addition, the estimation of uncertainties and their importance are included.

3.1 Survey among companies

The survey is based on a questionnaire forwarded to 30 Danish companies in November 2012, of which 22 companies responded. These constitute a sample of representative companies in Denmark who are involved in indoor environmental calculations and hence relevant for assessment of the demand of the market for a simplified compliance tool. These are selected from a predefined composition which comprises 14 consulting engineering companies, five contracting companies and three manufacturing companies, of which the former is divided according to size by means of table 3.1, which is specifying criteria for different-sized enterprises. The questionnaire used in the survey can be found in appendix D together with a list of participated companies and data results.

Company category	**Staff headcount**	**Annual turnover**	**Annual balance sheet**
Large	≥ 250	> €50M	> €43M
Medium-sized	< 250	≤ €50M	≤ €50M
Small	< 50	≤ €10M	≤ €10M

Table 3.1: *Criteria for different-sized enterprises, [European Commision 2005, p. 14].*

It has been emphasized in the survey that the respondents are anonymous, thus it has been necessary to remove the persons names in the report. Likewise, all comments from the Danish companies have been translated into English. For all the results, a mean value along with a standard deviation have been calculated and will be visually presented in the following figures.

3.2 Indoor environmental calculations

There are strict requirements for building energy consumption, where indoor environmental parameters, especially concerning thermal comfort, are not well defined. Bearing in mind that nowadays only a satisfying CO_2 concentration in schools and daycare institutions is necessary to obtain authority approval, [Danish Energy Agency 2010], companies were queried about the frequency of performing indoor environmental calculations.

As illustrated in figure 3.1, large consulting engineering companies perform indoor environmental calculations more often than others. This was expected, as they usually deal with more complex buildings, for which it is important to provide a satisfying indoor environment in order to achieve either authority approval or client's satisfaction. The following category is contractors, as they in some cases are responsible for performing indoor environmental calculations, whereas consulting engineering companies, who are responsible for design, establish the conditions for them, [Brohus 2012-2013]. Another interesting fact is a conduction of indoor environmental calculations by manufacturers. This can be explained by that some manufacturers have advanced departments for dealing with analysis of indoor environmental results due to the interest they have to sell their production, [Brohus 2012-2013]. It should be emphasised that conclusions of result should not solely rely on mean values as relative high standard deviations are experienced for each category.

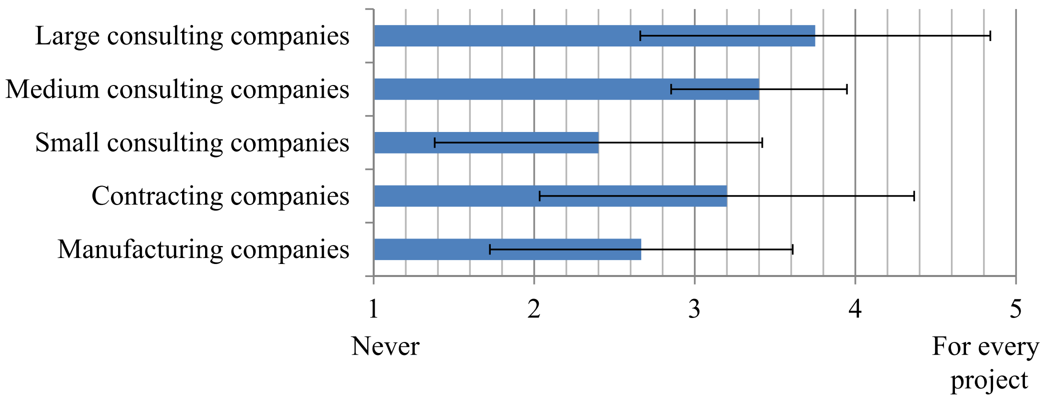


Figure 3.1: *Distribution of answers from participated companies regarding how often they perform indoor environmental calculations. Results are presented as mean values along with ± standard deviation.*

The purpose to perform indoor environmental calculations was investigated among companies, where the main trend is domination of analysis, whereas design of building and its components is following. An authority approval is the least common reason for large consulting companies, equals to the design purpose for medium and small companies and is out of interest for manufacturers. The aforementioned trend is only not valid for contractors, who has a high interest in authority approval purpose, i.e. in 80% of cases it is one of the reason of executing indoor environmental calculations.

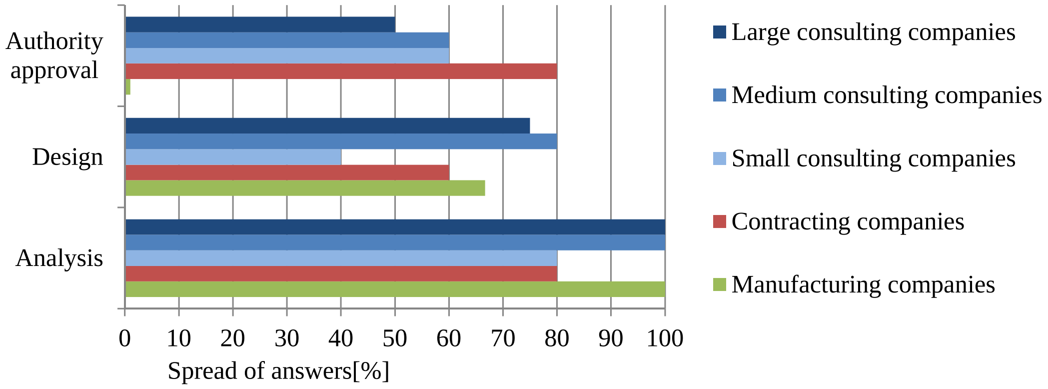


Figure 3.2: *Distribution of answers from participated companies regarding their purpose of performing indoor environmental calculations.*

In order to investigate the complexity of the tools used for indoor environmental calculations a list of software was proposed for companies, comprising BSim and IES VE. Although energy calculation tools like Be10 and PHPP are not applicable for accurate predicting of indoor environment, as emphasised in section 2.1, it was decided to include them in the questionnaire, bearing in mind that some companies might use them for checking thermal conditions in buildings on preliminary design stage of building projects.

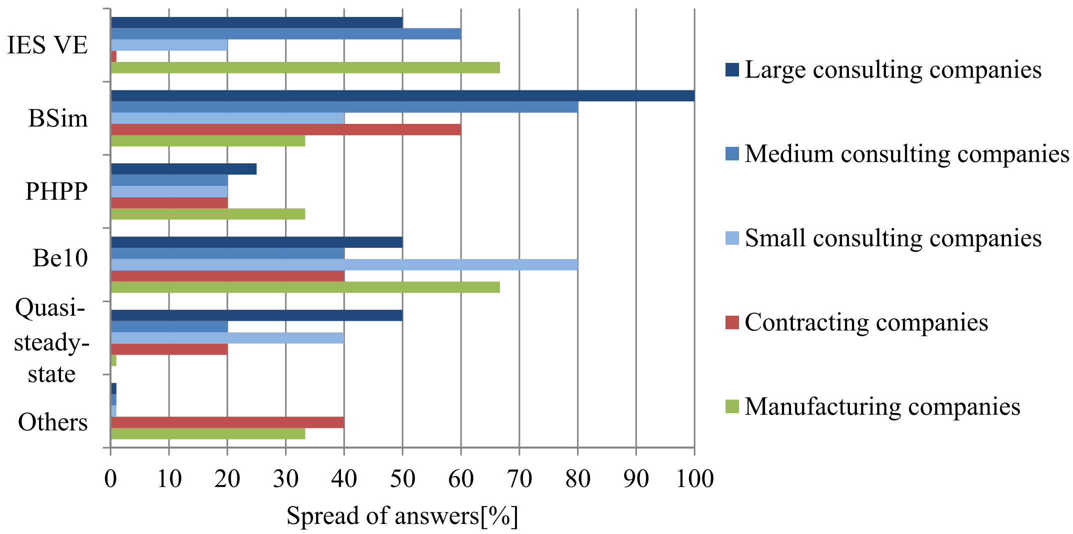


Figure 3.3: *Distribution of answers from participated companies regarding which tools they use to perform indoor environmental calculations.*

According to the participated companies, BSim is the most commonly used tool for documentation of thermal indoor environment in Denmark, as it contains an illustrative and detailed presentation of results and is often demanded from the client. According to comments from the questionnaire, even though IES VE comprises more possibilities and rather detailed results than BSim, this tool is further expensive. In general, complex tools as BSim and IES VE are time consuming and hence expensive which is making them less suitable for rough estimations in the preliminary design phase, where the uncertainties are large and numerous parameters have not yet been defined.

3.3 Assessment of demand for a simplified tool

The need of a simplified tool among the participated companies is strongly dependent on whether high accuracy or limited simulation time is most preferable. The answers from participated companies on the latter question are illustrated in figure 3.4, where for large consulting engineering companies the accuracy dominates, whereas the rest of companies prefer golden mean between speed and accuracy. Accurate calculations are often required to the design and analysis of rather complex types of building such as hospitals, schools and office buildings etc. On the other hand, for dwellings the calculations will be more based on authority approval for which a limited simulation time is preferable.

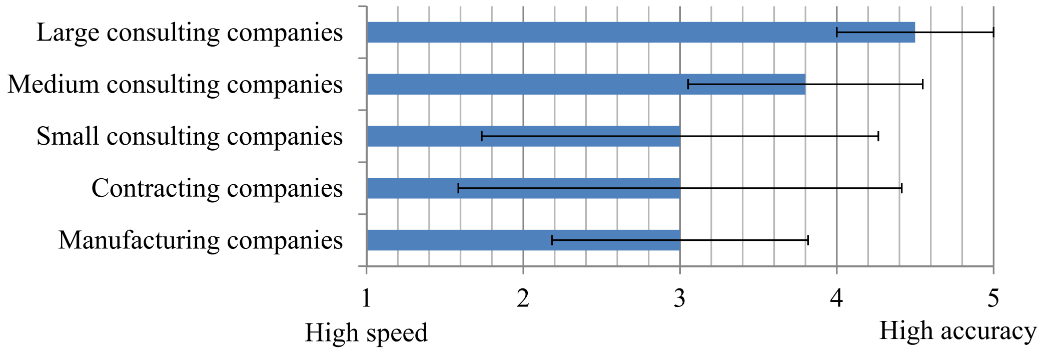


Figure 3.4: *Distribution of answers from participated companies whether they prefer speed or accuracy in indoor environmental calculations. Results are presented as mean values along with ± standard deviation.*

In general, it can be stated that a simplified tool for indoor environmental calculation purposes is needed among the participated companies, cf. figure 3.5. However, according to the comments received within a survey, for different types of buildings the need is rather different, i.e. the companies involved in dwellings design have the highest need, whereas for non-domestic buildings there is a restricted need.

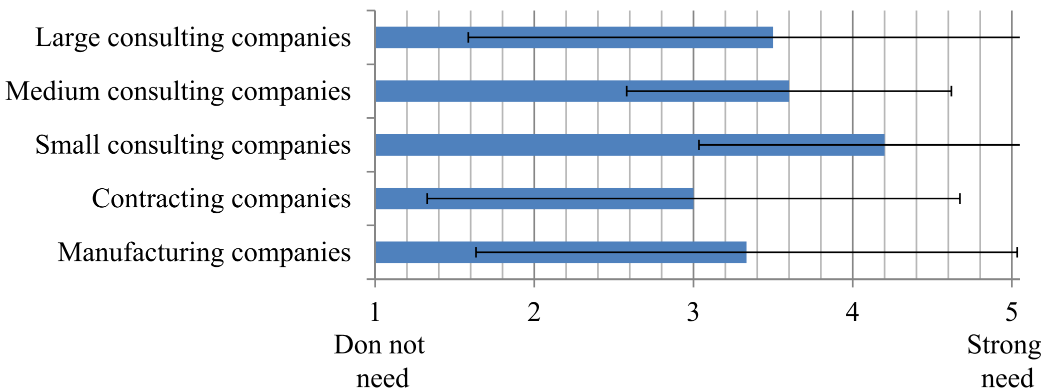


Figure 3.5: *Distribution of answers from participated companies regarding their need of a simplified tool. Results are presented as mean values along with ± standard deviation.*

The need of a simplified tool is more significant among consulting engineering companies as some of the participated contracting and manufacturing companies only deals with rather accurate calculations. The majority of the participated companies was having a need(4) or strong need(5) for a simplified tools. The six companies who have a restricted need(2) or even do not have a need(1) for a simplified tool explain, that accuracy is significantly important in order to achieve reliable results, which a simplified tools is not capable of in complex buildings.

The indoor environmental calculations should be performed rather quickly in order to have an influence on the design of the building otherwise experience is often used. Thus, a practically usable and simplified tool, with a limited simulation time, is needed only for rough estimations in the preliminary design phase by the majority of the companies. Accuracy is needed mainly for simulations in the detailed design phase. However, the majority of the companies already perform complex indoor environmental calculations by means of either BSim or IES VE, cf. figure 3.3. Thus, the need of an accurate tools is rather insignificant.

The demands from the companies are important to specifically determine in order to define the features of this simplified tool. Because of the upcoming requirements in the Danish Building Regulation regarding thermal comfort in dwelling, all the participated companies are mainly interested in number of hours above certain temperature and consider a determination of the risk of overheating as an important feature of the simplified tool, cf. figure 3.6. However, rather detailed information regarding the thermal indoor environment, described by the PMV- and PPD-indexes, is rather unnecessary for a majority of the companies, especially the small consulting engineering companies and contracting companies.

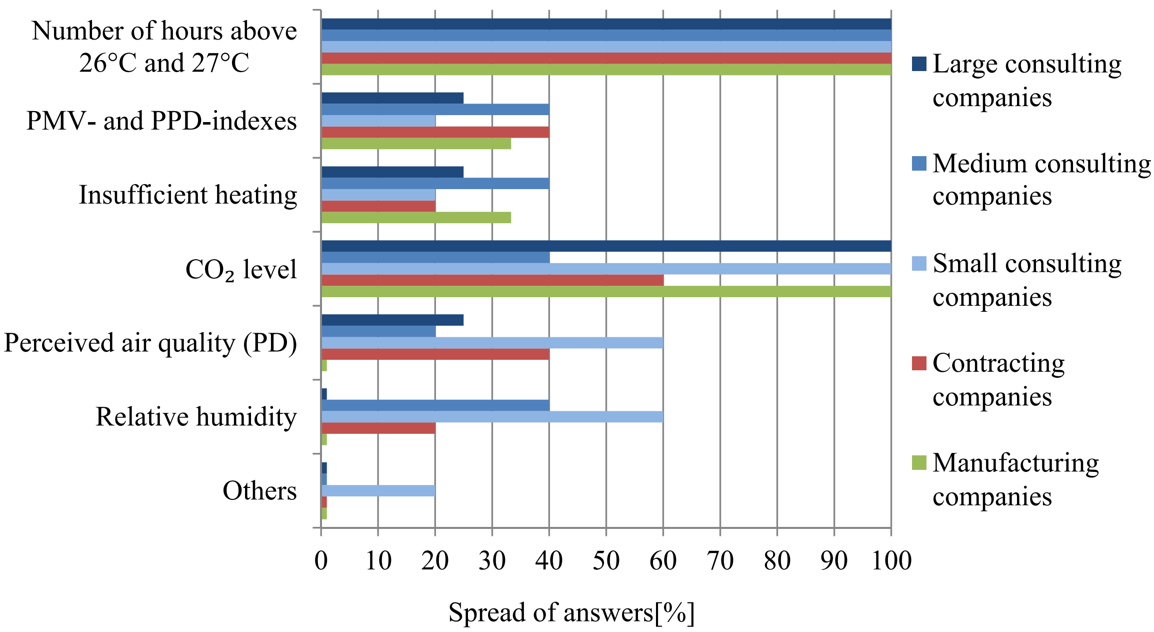


Figure 3.6: *Distribution of answers from participated companies regarding the features of a simplified tool.*

The CO_2 level is preferred for almost every company except a few medium consulting engineering companies and contracting companies. Bearing in mind the requirements of IAQ in schools and daycares from the Danish Building Regulations, this output parameter was expected to be desired, despite the fact that only dwellings are related to the current thesis. Even though any requirements for IAQ are related to dwellings, the CO_2 level is practically usable as an indicator of the IAQ in dwellings as well as any other type of building. The perceived air quality (PD) is less desired than an actual CO_2 level, although it is desired by the small consulting engineering companies, who is not interested in any indexes for the thermal environment. The moisture as an output parameter is desired only for a small part of the participated companies, mainly the medium and small consulting engineering companies. In addition to the predefined features of the simplified compliance tool, one small consulting engineering company stated a wish for having distribution of daylight as a feature.

Since the indoor environment is coherent with the energy consumption of the building, it is important to investigate whether the participated companies perform either stand-alone indoor environmental calculations for analysis of the building or combine them with building energy calculations. Since Be10 is required for building energy calculations in order to obtain authority approval, [*REF*], another software is necessary for performing indoor environmental calculations as Be10 is not applicable for this, at least not without the forthcoming expansion. Thus, a trend among the participated companies for performing mostly stand-alone indoor environmental calculations is revealed in figure 3.7.

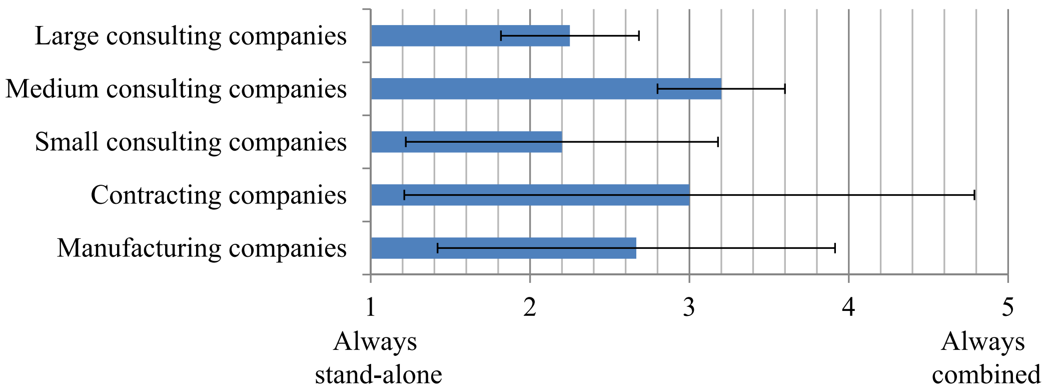


Figure 3.7: *Distribution of answers from participated companies whether they perform stand-alone indoor environmental calculations or combine them with energy calculations. Results are presented as mean values along with ± standard deviation.*

Five of the surveyed companies were stating that they performed indoor environmental calculations evenly(3) as stand-alone and combined with energy calculation, but did not use neither BSim nor IES VE. Hereby their so-called indoor environmental calculations are mainly based on penalties calculated by Be10 based on excessive temperatures in a building.

3.4 Consideration of uncertainties in calculations

The answers for each company regarding estimation of uncertainties in indoor environmental calculations are rather distributed along the scale. In general, the different categories of companies estimate the uncertainties rarely(2) or sometimes(3), except small consulting engineering companies who estimate the uncertainties often(4), cf. figure 3.8. The latter can be explained by the fact that some of the small consulting companies are either very specialised in indoor environment calculations or have lack of knowledge with regards to parameter variations.

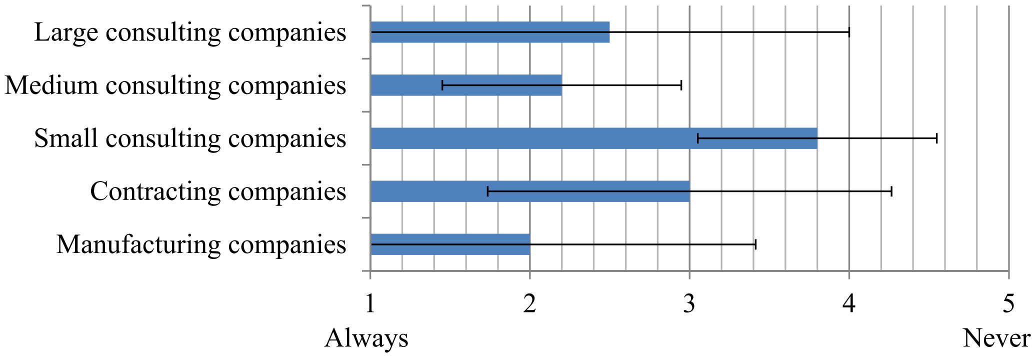


Figure 3.8: *Distribution of answers from participated companies regarding how often they consider uncertainties in indoor environmental calculations. Results are presented as mean values along with ± standard deviation.*

It is necessary nowadays to handle uncertainties, as performance of modern buildings becomes very stochastic. Almost all companies are aware of this, but treat uncertainties in different ways. According to the comments received within current survey only five of the surveyed companies estimate the uncertainties by parameter variation, others are just informing the clients about the uncertainty based on subjective and empirical estimation. It is therefore very common that engineers are aware of the uncertainty solely based on the previous experience, whereas the specialised analysis, like parameter variation is rarely conducted. Besides, there are also engineers who pays more attention on the assumptions they do during set up of the simulation model in case of complex buildings. According to their opinion it is more important to be aware of consequences due to these assumptions.

An assessment of the need regarding performance of sensitivity analysis (SA) and uncertainty analysis (UA) in the simplified indoor environmental tool was conducted among the participating companies, and is shown in figure 3.9. In general, no company was having a strong need(5) to implement sensitivity and uncertainty analysis, as the preconditions are rather essential compared to the uncertainty of the calculation procedure of the tool.

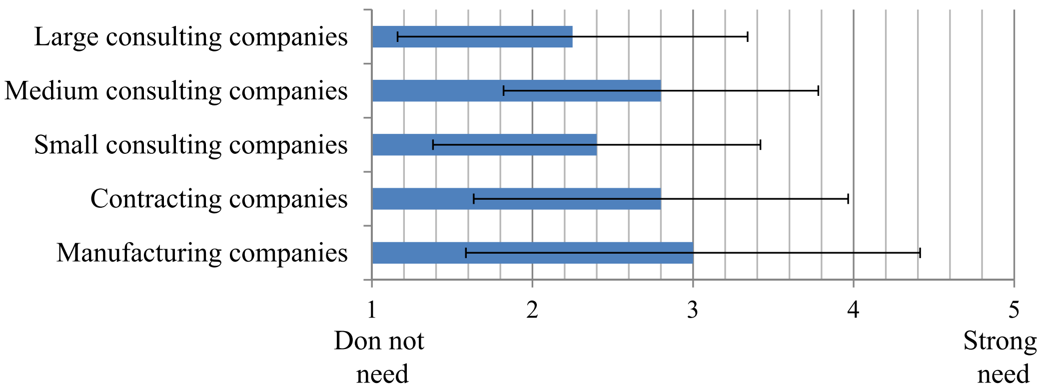


Figure 3.9: *Distribution of answers from participated companies regarding their need of including uncertainty analysis in the simplified tool. Results are presented as mean values along with ± standard deviation.*

However, whether the companies need to implement sensitivity and uncertainties analysis correlates with their already estimation of uncertainties, which explains why figure 3.9 an 3.8 are comparable for most of the companies. Though, small consulting engineering companies have a less need compared to what extent they already estimate uncertainties. In contrast, manufacturing companies have a higher need compared to what extent they already estimate uncertainties, as they find it necessary in the future. In general, SA and UA are neither strongly necessary nor out of interest for the companies. However those companies, which carry out parameter variation, have both higher frequency of uncertainties consideration in buildings design and stronger wish of uncertainty analysis implementation in simplified tool.

3.5 Consideration of occupants behaviour in calculations

The companies consider the importance of occupants behaviour differently, as the results of the survey were scattered, although there is no significant difference between categories, cf. figure 3.10.

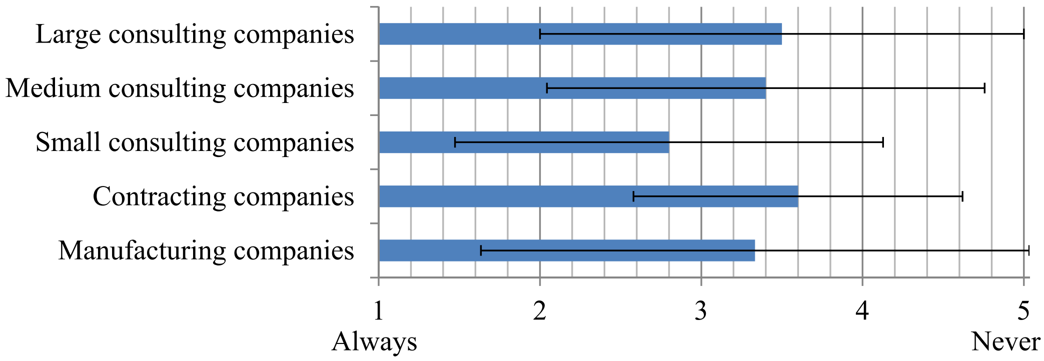


Figure 3.10: *Distribution of answers from participated companies regarding to what extent they consider occupant behaviour. Results are presented as mean values along with ± standard deviation.*

Half of the companies considers occupants behaviour as much as they find it important, the second half finds occupants behaviour much more important than what they already do. Hereby, the importance of considering occupants behaviour among the companies is much higher than the current extent, cf. figure 3.11.

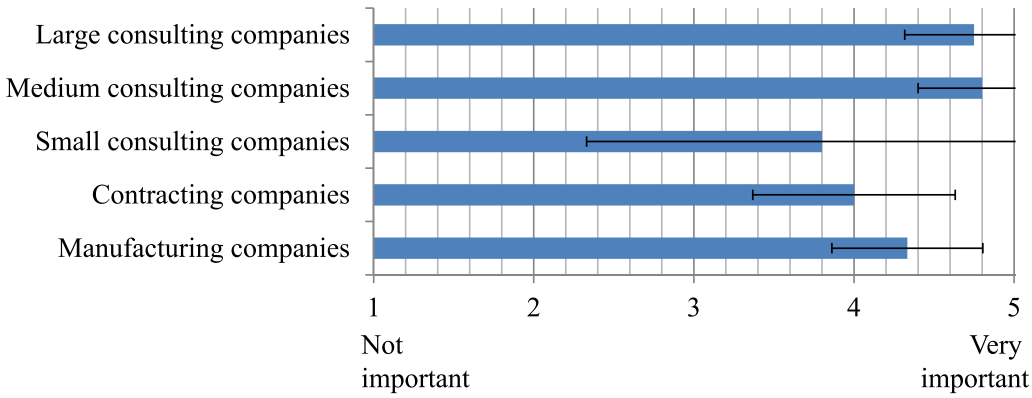


Figure 3.11: *Distribution of answers from companies regarding to what extent they find it important. Results are presented as mean values along with ± standard deviation.*

3.6 Discussion

It is not a surprise that nowadays in the design of buildings a more dependent on energy consumption rather than on indoor environment not least due to absence of strict requirements for the latter one (exceptions are school buildings and daycare institutions). Therefore it is only a client who can choose how good should be thermal and air quality conditions, based on recommendations and guides from European standards. This leads to the situation when indoor environmental calculations are not performed for every building project, because for small ones the analysis is sometimes being neglected.

Regarding remarks given by companies rough calculations or tools intended for energy calculations are common for estimation of the thermal environment in the preliminary design phase of the complex building design project. For the so-called rough calculations, quasi-steady-state calculations are often applied, but they are slightly inaccurate as well as they do not consider neither heat accumulation nor hourly peaks of thermal loads in a sufficient manner. Thus, the majority of the surveyed companies have a certain need for a simplified tool using at least hourly methods, but only for rough estimation in the preliminary design phase as complex indoor environmental tools usable in the detailed design phase are already on the marked.

According to the participating companies, the most wanted features the simplified tool should be capable of calculating are the risk of overheating and CO_2 level. It is a reasonable choice regarding the upcoming overheating requirements in buildings and the fact that these to parameters represent analysis of both thermal comfort and indoor air quality.

The majority of companies are aware of importance of uncertain parameters in the buildings, but not many of them yield an uncertainty analysis with parameter variations. In turn, it is a common practice among companies, especially small and medium ones, to either implement safety factors by considering the results worse than they were calculated or to inform the client about how the different factors like occupants behavior can deviate the calculated results.

Surprisingly, the need for estimation of uncertainties in indoor environment simulations is rather weak than strong. It is explained by the fact that for the companies which deal with small and not complex projects the estimation of uncertainties is rather unnecessary, whereas the companies which are involved in complex projects use respectively complex software where the focus lies on uncertainties in assumptions at building up the model. Notwithstanding, the companies performing specialised uncertainty analysis, i.e. 5 out of 22, have a strong need for simplified tool to possess uncertainty analysis, in order to avoid them doing it by means of another tool.

3.7 Summary

The thorough analysis of current chapter outlines the number of findings, which are presented below:

1. Contracting companies and especially large consulting companies perform indoor environment analysis more often than other participants of the survey, i.e. in around 60% and 80% of projects respectively.

2. The analysis of thermal comfort and IAQ is a dominating reason for indoor environmental calculations execution, comparing to design and compliance.

3. The BSim and IES VE are the two most common tools for analysis of indoor environment used by companies. Although BSim is more preferable nowadays, some of the companies mentioned that they are planning to change to IES VE, due to its higher functionality.

4. Taking into account remarks given by surveyed engineers the majority of them are aware of Be10's and alike tools' weaknesses and inability of giving proper results of indoor environment calculations. However some of the engineers use Be10 to get an indication of thermal conditions on preliminary design phase of building projects.

5. The demand for a simplified tool is strongly dependent whether high accuracy or limited simulation time is most preferable, which in turn is based on the type of buildings the company is dealing with. For dwellings the simplified tool is very wanted, whereas for more complex buildings, like hospitals, schools and offices it is unnecessary.

6. The risk of overheating, i.e. the number of hours above the certain room temperature and the CO_2 level are the two most preferable output parameters, the companies would like the simplified tool to possess.

7. Most of the companies perform indoor environmental analysis by means of BSim and IES VE, however while doing energy calculations in Be10 and PHPP the companies often check thermal conditions in these tools on earlier stages of building design. Therefore the dominating decision among companies is performance of indoor environmental calculations by using both stand-alone and combined tools in equal proportions.

8. The answers about consideration of uncertainties in buildings design and the wish of uncertainty analysis being implemented in the simplified tool are very correlated. In general there is a restricted need for uncertainty analysis implementation in the simplified tools as there is no a big necessity in it. However the companies, which make uncertainty analysis by doing input parameter variation have all in all both higher frequency of uncertainties consideration in buildings design and stronger wish of uncertainty analysis implementation in simplified tool.

9. Occupants behaviour is of high importance for 90% of surveyed companies, however the extent to which the companies consider it is lower, than the extent of its importance.

Chapter 4

Review of simplified models

This chapter introduces a review of simplified models, based on some existing calculation methods intended for thermal comfort simulations, in order to emphasise their different features regarding calculation procedure and determination of boundary conditions and input data.

4.1 Thermal indoor environment in a thermal zone

The thermal environment in a thermal zone depends on a complex interaction between the building construction, its thermal loads and the outdoor climate, all of which make up a heat balances for the thermal zone, [Danvak ApS 1987, p. 93]. The simplified models utilise the fundamental theory behind the heat balance to establish simplified central difference equations. This takes into account the dynamic heat exchanges between the room air, internal surfaces and the external air accompanied by the thermal capacity of the constructions and affect of thermal loads. The elements which are affecting the thermal environment in a thermal zone are shown in figure 4.1.

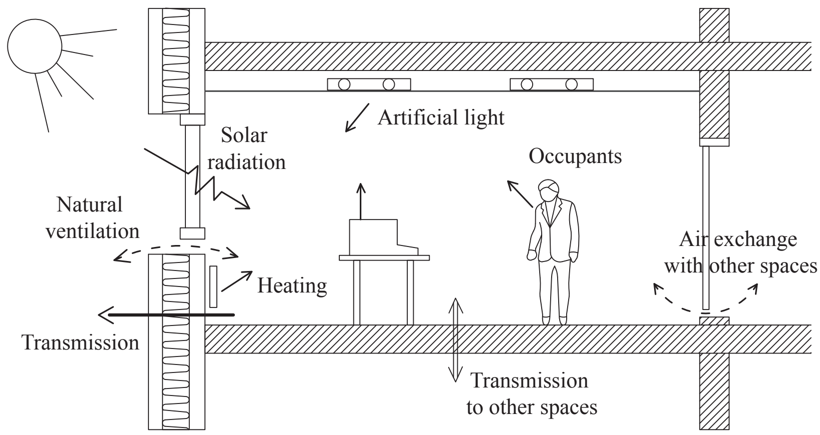


Figure 4.1: *Elements affecting the thermal indoor environment in a thermal zone. Redrawn from Danvak ApS [1987, p. 93].*

Some important factors are the thermal loads from the solar radiation, appliances and people, whereas the two latter imply significant uncertainty due to their unpredictable behaviour in dwellings. The heat gains affect the thermal zone differently in time depending on the heat transfer modes, i.e. radiation and convection. Radiant heat transfer affects the building construction, whereas convective heat influences the room air and hereby implies higher temperature fluctuations as the energy is directly transmitted. [Danvak ApS 1987, p. 94]

Each of the simplified models makes a distinction between room air and internal surface temperatures, which makes it possible to use them for prediction of thermal comfort in the critical room, [EN ISO 13790 2008, p. 24]. The operative temperature is used as a fictive internal temperature, with the purpose of simplify the description of the thermal environment.

The excessive operative temperatures in dwellings should be calculated on room level for the so called critical room of the building, [Danish Energy Agency 2010, sec. 7.2.1(13)]. Although, as the Danish BR2010 does not specify any approach for determination of which room should appear as the critical one, SBi recommends to manually select the critical room according to the highest occurring solar heat gains, [Mortensen 2012], even though the SBi simplified model does not provide an opportunity for such calculations.

Another approach is to chose the critical room based on the largest occurring thermal loads during daytime determined by a steady state calculation, [Larsen 2011b, p. 27]. However, this approach could be time consuming and quick estimations becomes allowable in order to facilitate the determination. It is thus suggested, that the critical room is determined according to the room with high occupancy during daytime and large window areas facing south.

4.2 Models calculation procedures

All three simplified models are capable of quasi-steady-state calculation on hourly basis valid for single-zone calculations, which is sufficient for the Danish BR2010 requirement regarding number of hours allowed over a certain temperature. As opposed to a monthly calculation procedure, these simplified models are capable of using hourly patterns, e.g. user schedules, heating and ventilation systems etc., cf. appendix C.

Due to delimitation of the current thesis, simplified models are applicable only for dwellings without mechanical cooling. In addition, the calculation of heating need is neglected as the main purpose of reviewed simplified models is to determine risk of overheating. Thus, during the heating period when heat supply is necessary, indoor temperatures are simply substituted with 20°C temperature, which corresponds to the lowest limit of category B, [EN 15251 2007, p. 31].

The simplified models utilise the lumped capacitance method, which deals with transient conduction problems, see detailed description of the lumped capacitance method in appendix E. All elements in this method are treated as they are concentrated or, in other words, lumped. Since there is no distinction between internal surfaces, they are represented by the mean radiant temperature (MRT). According to the electrical-thermal analogy, simplified models consist of resistance and capacitance schemes. The number of resistances varies within the level of complexity for different simplified models, while the capacitance is normally represented as one total element. Bearing in mind that the heat transfer is inverse proportional to heat flow resistance, i.e. $H \propto 1/R$, for convenience all resistances are substituted with specific heat transfers.

The calculation of heat balances is based on energy conservations. To avoid simultaneous calculation and use of matrices, a non-iterative approach of sequential solution of equations is performed. Thanks to lumped capacitance method, approximation of transient heat transfer process within the thermal zone is simplified into an ordinary differential equation, which implies use of time step.

4.2.1 EN ISO 13790 simplified model

This simplified model is a modification of the simple hourly method from EN ISO 13790 standard, though it solely differs by excluding the heating and cooling demand. A simplified tool, which is established in Microsoft Excel and based on this simplified model, is attached at CD-appendix A.2 - *EN_ISO_13790_simplified_model_v.1.xlsx*.

The lumped capacitance method employs five resistors and one capacitance for the EN ISO 13790 simplified model, and is hence based on a 5R1C scheme as shown in figure 4.2. A thorough description of the calculation procedure including distribution of thermal loads and calculation of unknown temperatures appears in appendix F.

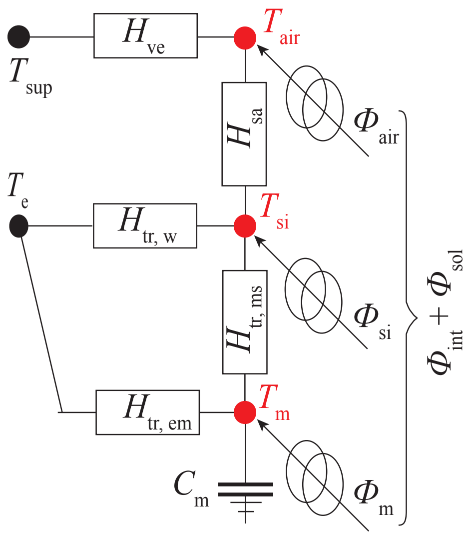


Figure 4.2: *EN ISO 13790 simplified model based on a 5R1C scheme visualized in thermal-electric analogy. Redrawn from EN ISO 13790 [2008, p. 90].*

The specific heat transfer between unknown temperature nodes is based on fixed heat transfer coefficients (HTCs) and area of all surfaces facing the thermal zone and an effective mass area as described in section F.1 in appendix. The area can either be determined by calculation or by using simplified approaches provided in the standard.

4.2.2 Bo Adamson simplified model

The simplified model presented in this section is a modification of Bo Adamson calculation method. A simplified tool, which is established in Microsoft Excel and based on this simplified model, is attached at CD-appendix A.2 - *Bo_Adamson_simplified_model_v.1.xlsx*.

The lumped capacitance method employs four resistors and one capacitance for the EN ISO 13790 simplified model and hence it is based on a 4R1C scheme as shown in figure 4.3. A thorough description of the calculation procedure including distribution of thermal loads and calculation of unknown temperatures appears in appendix G. Calculation of temperatures in the adjacent rooms requires multizone calculation. Nevertheless, as the simplified models are only applicable for single-zone calculation, the current simplified model differs from the Bo Adamson calculation method by excluding the transmission heat transfer between the critical room and adjacent rooms, by assuming that the adjacent rooms and the critical room have similar thermal conditions.

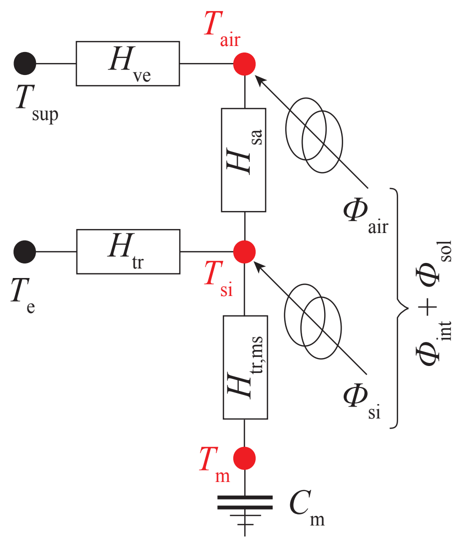


Figure 4.3: *Bo Adamson simplified model based on a 4R1C scheme visualized in thermal-electric analogy. Inspired by EN ISO 13790 [2008, p. 90].*

The specific heat transfer between unknown temperature nodes is based on heat transfer coefficients and area of all opaque surfaces facing the thermal zone as described in section G.1 in appendix. As the surface heat transfer coefficient incorporates convective heat exchange, a distinction is made between walls, ceilings and floors, as the convective heat exchange depends on the direction of the flow, i.e. upwards, horizontal and downwards. For the transmission heat transfer coefficient between internal surfaces and thermal mass, detailed thermal properties of the thermal mass are incorporated, cf. section 4.2.4.

As the application of reviewed simplified models is to check compliance with building regulations, they should possess limited input data, in order to keep attractiveness for the users. To use the possibility of limited input in Bo Adamson model a simplified surface heat transfer coefficient was developed by means of surface-to-floor dimensionless ratio equal to 4.5 taken from EN ISO 13790 [2008, p.26]. Simplified surface heat transfer coefficient is equal to 2.67 $^{W}/_{°C \cdot m^2}$, cf. table 4.1.

	α_{tot} $[^{W}/_{°C\cdot m^2}]$	**Proportion** $[-]$	**Weighted** α_{tot} $[^{W}/_{°C\cdot m^2}]$	**Simplified** α_{tot} $[^{W}/_{°C\cdot m^2-floor}]$
Floor	2.5	1.0	2.5	
Ceiling	2.0	1.0	2.0	**2.67**
External wall	3.0	2.5	7.5	
Total		4.5	12	

Table 4.1: *Calculation of simplified surface heat transfer coefficient, α_{tot}, for Bo Adamson simplified model by means of surface-to-floor dimensionless ratio equal to 4.5.*

Calculation of heat transfer coefficient between internal surfaces and thermal mass is more complicated and requires use of additional parameters, cf. table **??**. Therefore it was decided to implement the algorithm of calculation specific heat transfer between internal surfaces and thermal mass from EN ISO 13790 standard, cf. equation (F.4), by use of fixed heat transfer coefficient.

4.2.3 SBi simplified model

The fundamental elements behind this simplified model appear from the simple hourly method in EN ISO 13790 standard and is initially created by SBi as an extension in the forthcoming version of Be10. A simplified tool, which is established in Microsoft Excel and based on this simplified model, is attached at CD-appendix A.2 - *SBi_simplified_model_v.1.xlsx*.

The lumped capacitance method employs three resistors and one capacitance for the SBi simplified model and hence it is based on a 3R1C scheme as shown in figure H.1. A thorough description of the calculation procedure including distribution of thermal loads and calculation of unknown temperatures appears in appendix H.

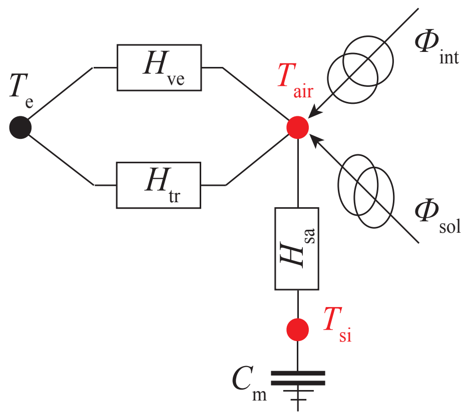


Figure 4.4: *SBi simplified model based on a 3R1C scheme visualized in thermal-electric analogy. Inspired by EN ISO 13790 [2008, p. 90].*

In order to simplify the SBi simplified model further from EN ISO 13790 simplified model, several assumptions were being applied, [Mortensen 2012, p. 8].

- Temperature difference between the thermal mass and internal surfaces is assumed negligible;
- Heat supply from thermal loads is assumed to be allocated only in the room air;
- Heat transfers between external and internal environments influence solely the room air.

By assuming an insignificant thermal resistance of the thermal mass, the temperature difference between the thermal mass and internal surfaces is negligible. As the thermal mass can not include thermal insulation, [EN ISO 13786 2007, p. 12], this assumption can be considered as reasonable. Subsequently, only two unknown temperature nodes are considered in SBi simplified model, whereby it becomes the internal surfaces of the construction which interacts with the room air.

By allocating the heat supply from thermal loads solely in room air, the thermal loads do not have a direct influence on the internal surfaces temperature. It is explained that, although there is an error when sun is directly shining onto internal surfaces, in case of internal solar shading the solar heat gains are absorbed by solar shading device and then released indoors via convection, by influencing room air temperature.

In addition, the heat transfer by transmission is assumed not to have directly influence neither the temperature of the internal surfaces nor thermal mass, [Mortensen 2012, p. 8]. This slows down the cooling process of the building mass, containing thermal capacity during the nights in warm periods, when a passive cooling is an effective way of cooling the building down. As the goal of the simplified model is to determine overheating problems and ensure that the building will not violate the requirement, then this assumption has the purpose to work as a safety factor.

The specific heat transfer between room air and internal surfaces temperatures assumes that thermal zone contains furniture and is calculated by using a surface HTC with a fixed value of 20 $^{W}/_{°C\,m^2}$ of heated floor area, which incorporates a fixed relation between floor area and all internal surfaces area of the critical room.

4.2.4 Number of input required in simplified models

Specific heat transfers between internal surfaces and room air, H_{sa}, and between internal surfaces and thermal mass, $H_{tr,ms}$ see figure 4.5, are varying for each particular thermal zone, depending on geometry of the thermal zone as well as materials properties of construction elements.

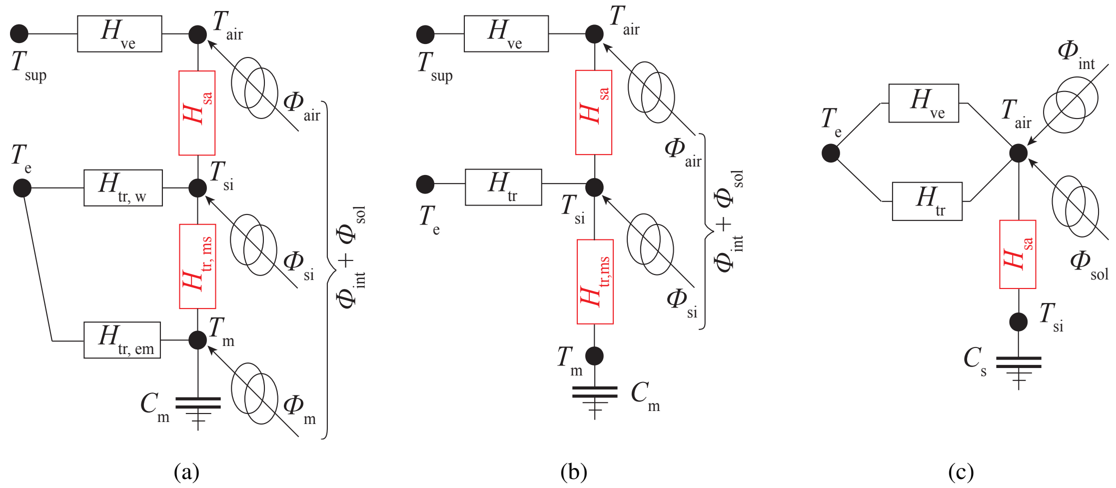


Figure 4.5: *RC schemes of EN ISO 13790 (a), Bo Adamson (b) and SBi (c) simplified models. Red colour indicates specific heat transfer between internal surfaces and air, H_{sa}, and between internal surfaces and thermal mass, $H_{tr,ms}$.*

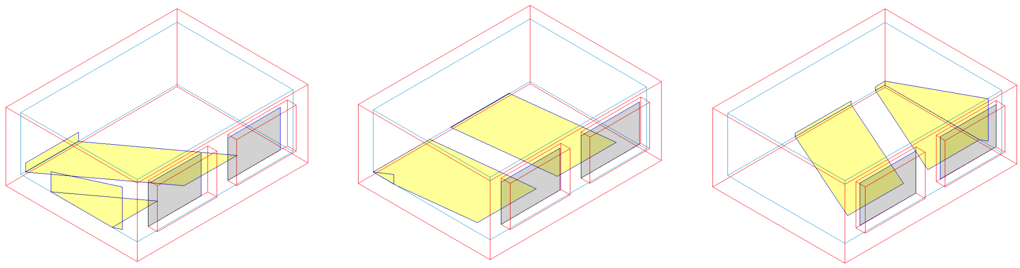
There are two ways of determining specific heat transfers, either using limited input data and corresponding simplified coefficients, which are distinct for different models, or using detailed information regarding areas and building constructions. However, by using detailed information, which may influence output precision, number of input data increases substantially. Since SBi simplified model, which possesses only limited input in order to minimize the efforts for set up the model, is in priority in the current thesis, it was decided to distinguish simplified models by complexity of input data. Simplified models with only limited input will pay highest attention further in the thesis, as the simplified models for checking compliance with Danish BR2015 are in focus, which require limited input amount to be attractive for the users. Furthermore, according to the survey among companies, presented in section 3.3, there is a wish of the Danish construction industry to receive a tool with as limited input as possible.

4.2.5 Shortwave and longwave radiation treatment

Simplified models reviewed in the current chapter are based on lumped capacitance method, in which building construction elements, namely external walls, ceiling, external and internal walls are lumped with corresponding lumped thermal capacity, cf. appendix E. This simplification influences the treatment of shortwave (SW) and longwave (LW) radiation in the thermal zone.

Shortwave solar radiation

The accurate modelling of solar transmission through the transparent surfaces implies prediction of internal surfaces position relative to the solar incidence beam, which is a function of site longitude and latitude, thermal zone geometry and time of the day/year, [Clarke 2001, p. 11]. Furthermore shadows from surrounded objects and constructions as well as building components should be taken into account. Such an algorithm is implemented in XSun tool, which is a part of BSim tool, see figure 4.6. After the solar incidence beam is transmitted indoors, it strikes some internal surfaces, where opaque surfaces absorb and reflect radiation, transparent surfaces absorb, reflect and transmit (outside or to another zone) radiation. Absorbed heat flux from radiation is later transfered to the air via convection, to other surfaces via LW radiation or/and to the thermal mass via conduction. Due to detailed modelling of solar radiation transmission inside the thermal zone, thermal mass of particular construction elements, such as floor and, in lower degree, walls has higher importance than thermal mass of ceiling, as the solar radiation primarily strikes these construction elements.

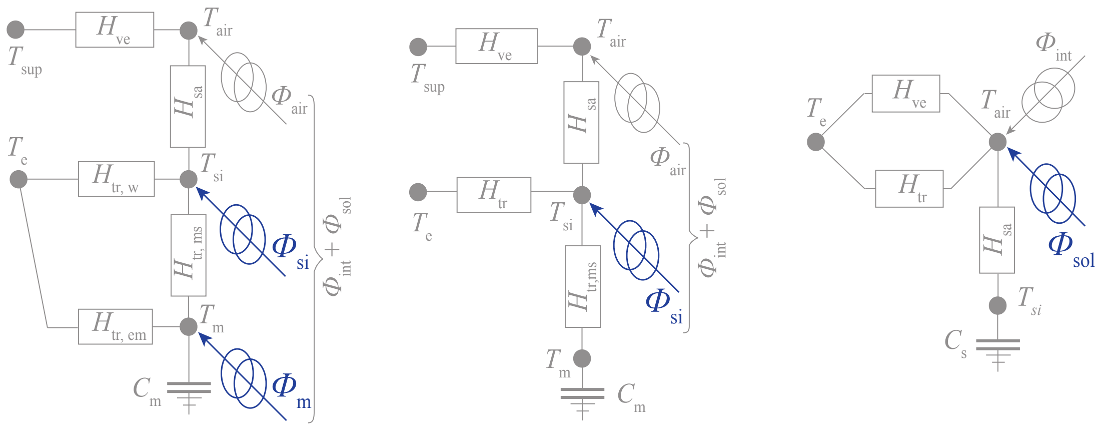


(a) (b) (c)

***Figure 4.6:** Demonstration of XSun solar distribution on 12th February at: 10:00 (a), 12:00 (b), 14:00 (c).*

In the absence of detailed modelling of solar incidence beam there are suggested solar fractions valid for the particular surfaces. For example, in BESTEST solar fractions are presented, where the dominating fraction of solar radiation belongs to the floor and the magnitude of all fractions depends on the absorptivity of internal surfaces, [Judkoff and Neymark 1995, table 1-9].

SW solar radiation in simplified models is treated differently from above mentioned "physical behavior" and differently from each other, cf. description of thermal loads distribution in subsection 4.2.6. Although, due to lumped internal surfaces it is not possible to implement accurate modelling of solar incidence beam in simplified models, all transmitted solar radiation should first affect internal surfaces temperature, according to Clarke [2001, p. 11], as it functions in Bo Adamson simplified model. However EN ISO 13790 and SBi simplified models use another treatment of solar radiation flowpaths, via proportions of solar heat gains utilised by construction internal surfaces and thermal mass and air respectively, cf. figure 4.7. Different treatment of solar SW radiation flowpaths among simplified models is investigated in appendix P.



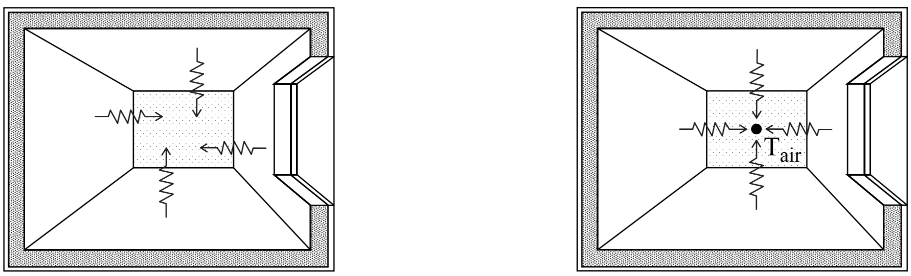
(a) (b) (c)

Figure 4.7: *Simplified models represented by their RC schemes: EN ISO 13790 simplified model (a), Bo Adamson simplified model (b) and SBi simplified model (c). Blue colour indicates heat fluxes, which contain solar heat gains (SW solar radiation). Explanation of Φ_{si} and Φ_m can be found in appendices F and G for EN ISO 13790 and Bo Adamson simplified models respectively.*

Longwave radiation in the thermal zone

LW radiation inside the thermal zone appears as a radiation exchange between internal surfaces and it occurs when there is an internal surfaces temperature asymmetry. Therefore LW radiation tends to establish a temperature equilibrium by cooling hot and heating cold surfaces. LW radiation is a function of internal surfaces temperatures, emissivities and view factors, meaning how the surfaces are in visual contact with each other, [Clarke 2001, p. 10]. There are two cases for modelling LW radiation among internal surfaces, [ASHRAE 2009, p. 29.21]:

1. Room air is completely transparent and not participating in LW radiation exchange, figure 4.8(a);
2. Room air absorbs all LW radiation from internal surfaces, figure 4.8(b).



(a) (b)

Figure 4.8: *Two approaches of LW radiation modelling in the thermal zone: room air is completely transparent to LW radiation (a), room air completely absorbs LW radiation (b).*

The first case represents physical nature of LW radiation and room air interaction and is often used in energy modelling. The second case is attractive due to its simplicity and ability of treating LW radiation by means of radiative HTC, [ASHRAE 2009, p. 29.21]. Even though it is not consistent with physical behaviour of LW in the thermal zone, which is a non-linear process, it can be utilised in simplified energy simulation models.

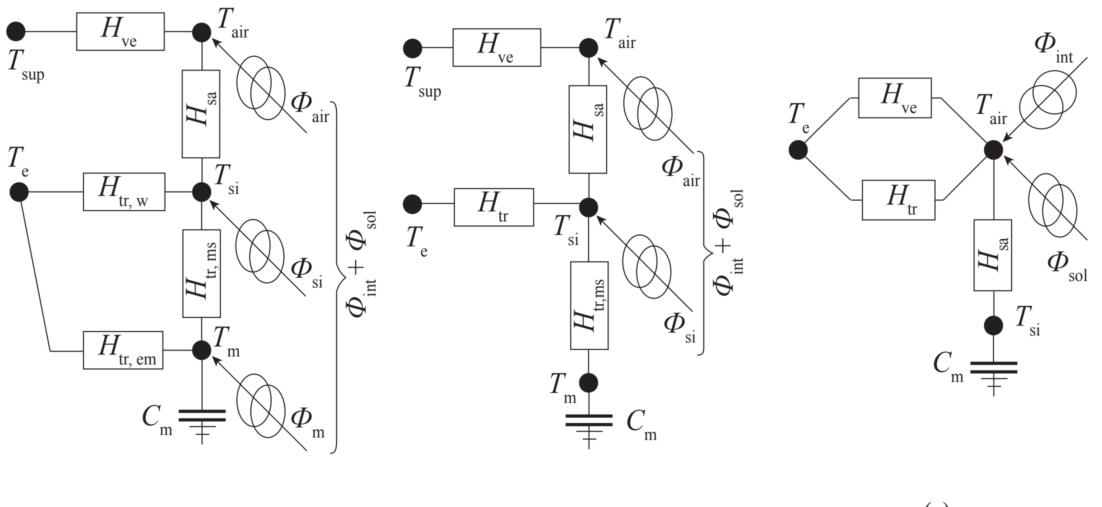
In currently reviewed simplified models building constructions elements are lumped, thus there is no internal surfaces temperature asymmetry and only mean radiant temperature (MRT) is utilised. Although first approach of LW radiation modelling is not applicable for these simplified models, second approach can be realised by combining radiative and convective surface HTCs in the total one, α_{tot}. It is not specified in simplified models descriptions whether implemented surface HTCs are only convective or both convective and radiative. However, comparing with surface HTCs from EN ISO 6946 standard cf. table 4.2, surface HTCs of simplified models are likely responsible only for convective heat exchange, therefore omitting LW radiation between internal surfaces.

	α_{tot}, $\left[{}^{W}/_{°C\ m^2}\right]$		
	Ceiling	**Wall**	**Floor**
EN ISO 6946*	10.14	7.64	5.84
EN ISO 13790 simplified model	3.45	3.45	3.45
Bo Adamson simplified model	2.00	3.00	2.50
SBi simplified model	4.44**	4.44**	4.44**

Table 4.2: *Comparison of surface HTCs in simplified models and EN ISO 6946 standard. Methodology from EN ISO 6946 standard is described in appendix M.3. *Radiative HTC was calculated for temperature 20°C and emissivity 0.9. **In SBi simplified model is valid for floor area, was converted for internal surfaces area by means of $f_{si,f}$ = 4.5, [EN ISO 13790 2008, p. 26].*

4.2.6 Comparison of models calculation procedures

Different simplified models utilise different RC schemes, where the most sophisticated RC scheme is possessed by EN ISO 13790 simplified model, while SBi simplified model carries the most simplified scheme. EN ISO 13790 and Bo Adamson simplified models have RC schemes with three unknown temperature nodes, while SBi simplified model consideres only two unknown temperature nodes in the RC scheme due to the assumption that internal surfaces and thermal mass temperatures are similar, [Mortensen 2012, p. 8].



(a) (b) (c)

Figure 4.9: *Simplified models represented by their RC schemes: EN ISO 13790 simplified model (a), Bo Adamson simplified model (b) and SBi simplified model (c).*

Flowpaths of heat losses

In Bo Adamson and SBi simplified models a heat loss through opaque constructions occurs without direct influence on thermal mass temperature and, subsequently, thermal capacity of the thermal zone. This decreases the passive cooling effect of thermal mass at nights during warm periods. In other words, the temperature of thermal mass can be decreased only due to heat transfer between thermal mass and internal surfaces or, as in SBi simplified model, between internal surfaces and room air. Thus, the risk of overheating is expected to increase and consequently a demand for design increases not to violate the upcoming overheating requirement.

In EN ISO 13790 simplified model the distinction between transmission heat losses through windows and opaque constructions is realised in a more realistic way, where the former are connected with internal surfaces temperature node due to negligible thermal capacity and the latter influences the thermal mass temperature.

Flowpaths of thermal loads

EN ISO 13790 simplified model has the most sophisticated distribution of thermal loads among temperature nodes, assuming that convective part of internal heat gain affects the room air, whilst radiative part of internal and solar heat gains is apportioned among internal surfaces and thermal mass temperatures. The latter is apportioned in such a way that heat is transfered from internal surfaces into mass layer by transmission. However, not all thermal loads can be transfered, as windows unlike opaque constructions have negligible thermal mass and therefore thermal loads through internal surfaces of external windows get transfered to external air and become the heat loss. The occurrence of this heat loss is not taken into account neither in Bo Adamson nor in SBi simplified model.

Bo Adamson simplified model has nearly the same flowpaths for the thermal loads, except that the thermal mass temperature does not receive any part of the thermal loads - entire portion of radiative thermal loads is utilised within internal surfaces.

In contrast, by allocating all thermal loads in room air temperature node, the SBi simplified model looses the feature of distinct convective and radiative heat flows. Such approach is explained by the fact that solar shading usage leads to utilisation of absorbed solar radiation by room air and subsequently to the increment of its temperature, [Mortensen 2012, p. 8].

Numerical method

Unlike the Bo Adamson and SBi simplified models, which employ forward (explicit) Euler method for treatment of thermal capacity of the thermal zone, EN ISO 13790 simplified model uses Crank-Nicolson method, which is based on central difference only in time. In every simplified model the heat balances for all temperature nodes are handled by using sequential approach in order to avoid simultaneous calculation and use of matrices. The time step of one hour is implemented in all simplified models as they are intended for simulation on hourly basis and there is no instructions provided for time step variation.

Specific heat transfer between internal surfaces and room air

Specific heat transfer between internal surfaces and room air is calculated by multiplying surface HTC with areas of surfaces exposed to the thermal zone.

Surface HTC is predefined in a different way among the simplified models, cf. subsection 4.2.4. In case of limited input in EN ISO 13790 and Bo Adamson simplified models a factor of 4.5 is used for converting specific heat transfer valid for internal surfaces area into one, which is valid for floor area, see table 4.3. Specific heat transfer in SBi simplified model was already adjusted to be valid for floor area only in order to minimise number of input data. However, it is noticeably higher than corresponding specific heat transfers in other simplified models as it was manually adjusted taking into account furniture presence in the thermal zone, [Aggerholm 2013].

	Limited input			Detailed input				
	EN ISO 13790	Bo Adamson	SBi	EN ISO 13790	Bo Adamson			SBi
					Floor	Ceiling	Wall	
α_{tot}, $[{}^{W}/_{^\circ C\, m^2}]$	3.45	2.67*	4.44**	3.45	2.5	2.0	3.0	-***

*Table 4.3: Comparison of predefined values of surface HTC between internal surfaces and room air for limited and detailed input in simplified models. *Established in table 4.1. **Was converted from only floor to all internal surfaces application by means of $f_{si,f}$ = 4.5. ***Is not developed for SBi simplified model.*

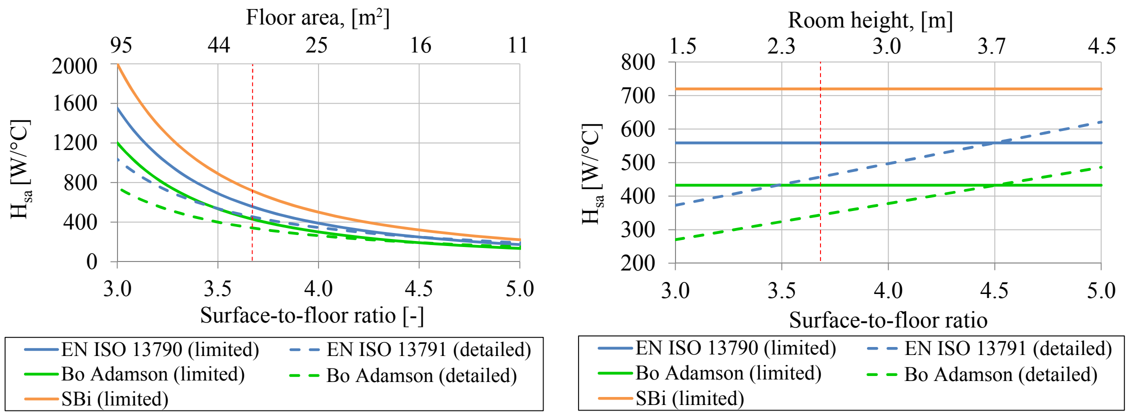
Taking into account the above mentioned differences among simplified models, it is decided to calculate specific heat transfer between internal surfaces and room air for different simplified models by means of two cases, namely case A, illustrated in figure 4.10(a), where the height of the room is constant while width and length are varying, and case B, illustrated in figure 4.10(b), where only height of the room is varying.

(a) (b)

Figure 4.10: *Different layouts of thermal zone: case A (a), case B (b).*

A surface-to-floor ratio equal to 3.7, which corresponds to dimensions of room equal to [6m x 6m x 2.5m] for [L x W x H] is assumed to be a typical one for rooms in dwellings. According to figure 4.11(a) simplified models algorithms for calculation of specific heat transfer between internal surfaces and room air are significantly varying for different surface-to-floor ratios. For rooms with a large surface-to-floor ratio the spread of results is close to each other, whereas for rooms with small surface-to-floor ratio the result can be as twice as different as for SBi and Bo Adamson simplified models. It is important to point out that simplified input is increasing specific heat transfer between internal surfaces and room air. It can result in lower operative temperatures, since ventilation is removing heat from the air and thus it will take shorter time to decrease surfaces temperature, which is incorporated in operative temperature.

Unlike the previous figure, figure 4.11(b) reveals a drawback of limited input implementation in simplified models. Within the range of room height variation 2.3-3.0 m a change of approximately 20% is obtained in models using detailed input.

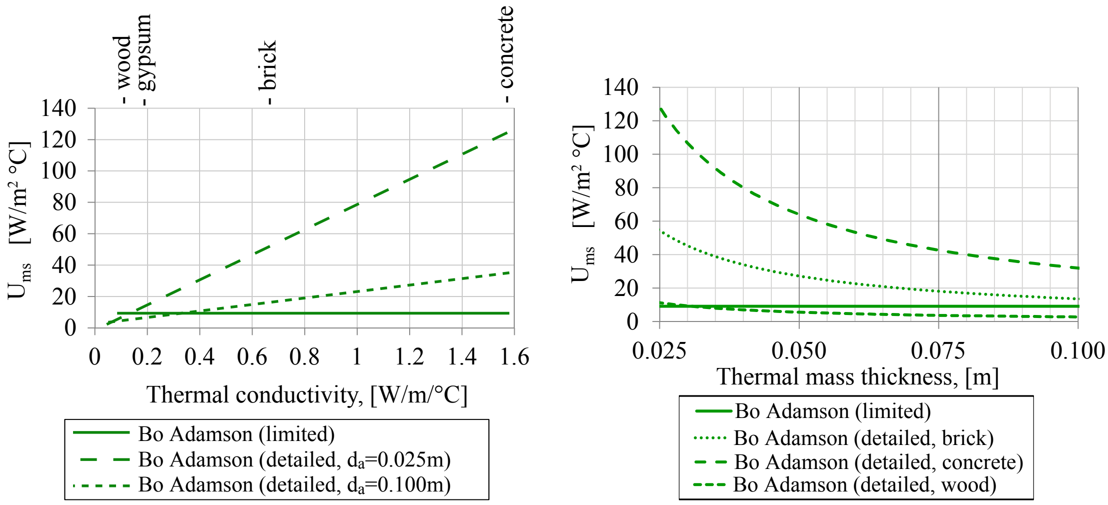


(a) (b)

Figure 4.11: *Comparison of different simplified models according to specific heat transfer between internal surfaces and room air: case A (a), case B (b). Dashed red line indicates an assumed typical surface-to-floor ratio.*

Transmission heat transfer between internal surfaces and thermal mass

Heat transfer between internal surfaces and thermal mass is implemented in EN ISO 13790 and Bo Adamson simplified models and is indicating the rate of building thermal capacity behaviour. With high values of aforementioned heat transfer, thermal capacity is able to accumulate higher portions of heat and vice versa. Note, that both limited and detailed input are available in aforementioned simplified models, cf. subsection 4.2.4. In EN ISO 13790 simplified model a difference between limited and detailed input is in consideration of different areas, i.e. either internal surfaces area or effective mass area. The latter is determined by taking into consideration different thermal capacity of different areas, which results not in significantly diverse specific heat transfer. Unlike EN ISO 13790 model there is a significant difference in specific heat transfer calculation in Bo Adamson model for limited and detailed input. The former utilises a fixed HTC, 9.1 $^{W}/_{m^2\,°C}$ taken from EN ISO 13790 [2008, p. 66], which is also implemented in EN ISO 13790 model with limited input. The latter is taking into account material properties of thermal accumulation layer, i.e. thermal conductivity and thickness of thermal mass layer. Two different investigations are conducted in order to figure out how thermal conductivity of materials as well as thickness of various materials influence the value of HTC, U_{ms}, see figure 4.12. In figure 4.12(a), two thermal mass thicknesses are utilised, i.e. d_a=0.025 m and 0.100 m. It is expected that in typical future low-energy building thermal mass thickness will be within that range. In figure 4.12(b) thermal mass thickness, in turn, is varying, whereas thermal conductivity is fixed for three materials, namely concrete and wood.



(a) (b)

Figure 4.12: *Comparison of different simplified models according to specific heat transfer by transmission between internal surfaces and room air: for varying thermal conductivity (a), for varying thermal mass thickness (b).*

For various materials and their thicknesses the difference between calculated HTCs can be substantial. According to figure 4.12(a) as higher is thermal conductivity of material as bigger is the difference between limited and detailed input in Bo Adamson simplified model. For thermal mass thickness, in turn, this relation is inverse, i.e. as larger becomes the thickness as smaller the difference between models. According to figure 4.12(a) if brick or concrete is chosen for thermal mass with thickness of 50 mm then difference in HTC and subsequently in specific heat transfer, $H_{tr,ms}$, between limited and detailed input becomes three times and six times larger respectively. Unfortunately, it is not stated in EN ISO 13790 standard how the fixed value of 9.1 $^{W}/_{m^2\,°C}$ is determined and for which range of materials it is applicable.

Calculation of operative temperature

Operative temperature in all three simplified models is used for determining the number of hours above 26°C and 27°C, indicating the overheating problems in dwelling.

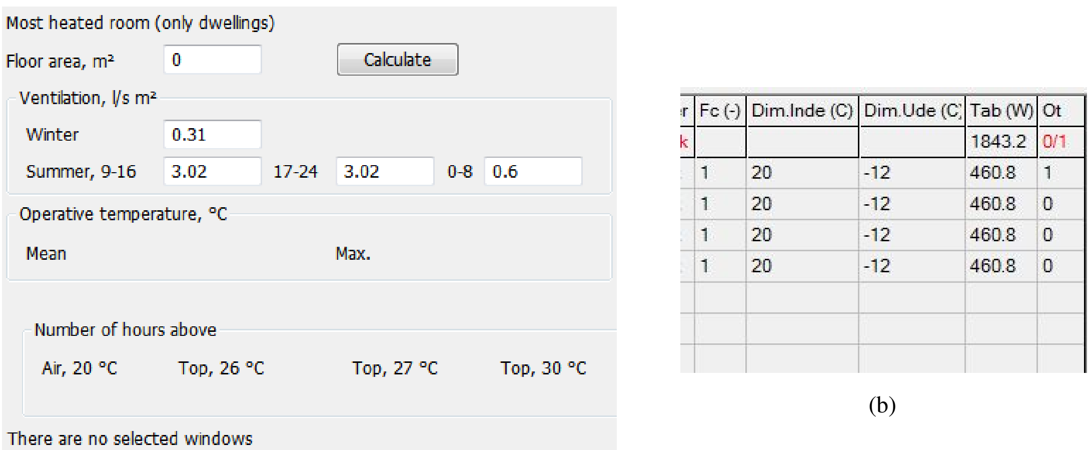
Unlike the common practice where equal coefficients are used for both room air and internal surfaces temperatures, the operative temperature in EN ISO 13790 simplified model is calculated by utilising 0.3 and 0.7 for room air and internal surfaces temperatures respectively. This is due to the fact that internal surfaces temperature is a combination of air and mean radiant temperatures weighted by the internal surfaces convective (3/8) and radiative (5/8) coefficients. In other simplified models equal coefficients, i.e. 0.5, are used for both room air and internal surfaces temperatures.

4.3 Models boundary conditions and input data

In this section the second component of simplified models, namely boundary conditions and input data utilised among simplified models are briefly introduced and more important compared to each other. They include determination of building thermal capacity, internal and solar heat gains, transmission and ventilation heat transfers together with control system for ventilation and solar shading.

As SBi simplified model v.1 appears as the only developed tool for prediction of summer thermal comfort, and thus have attached boundary conditions and input, only these will be introduced in the main report, whereas boundary conditions and input data applicable for EN ISO 13790 and Adamson simplified model v.1 appears in appendix L - O for each particular component along with associated theoretical descriptions. Nevertheless, it is worth to mention that description of boundary conditions and input data for EN ISO 13790 simplified model is based on EN ISO 13790 standard and for Bo Adamson simplified model it is based on Danvak grundbog.

In order to comply with upcoming requirements from Danish BR2015 concerning thermal comfort in new dwellings, a simulation should be performed using Danish Reference Year (DRY) for climatic boundary conditions, [Danish Energy Agency 2010, sec. 7.2.1(13)]. Therefore DRY is used for climatic boundary conditions in all simplified models in the report.



(a) (b)

Figure 4.13: User input data for SBi simplified model in forthcoming version of Be10 software with default values for ventilation rates (a) and implementation of window properties (b). Default values will be changed when the model will get released on the market.

Due to the fact that SBi simplified model will be implemented in the forthcoming version of Be10, most of the model input parameters are beneficially linked to the input parameters of that software. Except the windows, which should simply be selected in windows tab in Be10 to be applied for the critical room, cf. figure 4.13(b), the rest input data for SBi simplified model are illustrated in figure 4.13(a). Note, that the heated floor area corresponds to the gross floor area, [SBi-anvisning 213 2008, p. 74].

4.3.1 Thermal capacity

The thermal capacity of a building zone is not calculated in Be10. Hereby, it is the user's responsibility in Be10 to set the thermal capacity of the thermal zone. However, there is a guide providing thermal capacity and corresponding description of the building construction elements, cf. table L.2 in appendix. The specified thermal capacity is applicable for both the entire building and the critical room. Hence a similarity between thermal capacity of the entire building and critical room is assumed.

To avoid additional input parameters for description of building envelope constructions in order to calculate thermal capacity, predefined thermal capacities for different building descriptions are often preferable, as is the case for EN ISO 13790 and SBi simplified models. It should be noted that SBi simplified model employs values used in Denmark for checking compliance with energy frame in buildings. In addition, for energy calculation a utilisation factor is implemented, which is not used in SBi simplified model applicable for prediction of excessive operaitve temperatures.

The calculation algorithm for thermal capacity utilised in En ISO 13790 an Bo Adamson simplified models does not differ significantly from each other. Basically, the difference is related to the determination of the thickness of the thermal mass, which is more detailed explained in appendix L.

4.3.2 Solar heat gains

The solar heat gains are determined by means of Be10, which solar calculation algorithm is derived from the calculation algorithm described in appendix O. By summing up computed solar heat gains for all chosen facades, which the critical room possesses, Be10 provides monthly values. Accordingly, the monthly values are distributed among hourly values by use of global solar radiation on a horizontal surface according to DRY, cf. equation (4.1).

$$\Phi_{\mathrm{sol,h}} = \frac{I_{\mathrm{gl,h}}}{I_{\mathrm{gl,m}}} \Phi_{\mathrm{sol,m}} \tag{4.1}$$

$\Phi_{\mathrm{sol,h}}$	Hourly solar heat gains, [W]
$\Phi_{\mathrm{sol,m}}$	Monthly solar heat gains, [W]
$I_{\mathrm{gl,h}}$	Hourly global solar radiation on a horizontal surface, $\left[{}^{\mathrm{W}}/_{\mathrm{m}^2}\right]$
$I_{\mathrm{gl,m}}$	Monthly global solar radiation on a horizontal surface, $\left[{}^{\mathrm{W}}/_{\mathrm{m}^2}\right]$

The above mentioned transportation of monthly to hourly solar heat gains bring uncertainty to the final result, i.e. orientation of facades is ignored. However, the calculation of solar heat gains performed in Be10 does account, though in aggregate way, for orientation of facades, shading of windows and shadow from obstructions. In other words, daily distribution of solar heat gains has the same pattern for all buildings, independently of their windows orientation. The calculation of solar heat gains by mean of SBi simplified model is further investigated in section 5.3.2.

4.3.3 Internal heat gains

As only for EN ISO 13790 and SBi simplified models there are specified internal heat gains, Bo Adamson simplified model is not mentioned in this comparison. Both EN ISO 13790 and SBi simplified models possess different internal heat gains treating algorithms. Although the simplified models utilise hourly calculations, it is only EN ISO 13790 simplified model which uses daily occupancy profiles, whereas in SBi simplified model no occupancy patterns are being implemented. For the latter the internal heat gains are set by means of Be10 for the critical room, where people and equipment loads are summed up together. Default values for dwellings are equal to 1.5 $^{W}/_{m^2}$ and 3.5 $^{W}/_{m^2}$ respectively for occupants and appliances. Although they can be varied for entire building for energy calculation, they are fixed for the critical room for excessive temperatures simulation, [Mortensen 2012-2013].

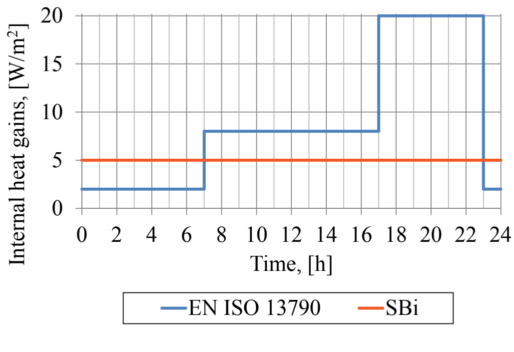
Furthermore, this value does not state about the occupancy level in particular room. For example, if for the critical room a bedroom has been chosen, then a permanent heat load occurs there all the day, despite the fact that, in reality, it is occupied mainly during the night. This leads to the increased risk of overheating, which subsequently requires an increased demand for the design. There are two different occupancy profiles mentioned in EN ISO 13790 [2008], i.e. for living room/kitchen and other rooms mainly intended for sleeping.

There is also a distinct approach in average values estimation among models. In EN ISO 13790 [2008] there is a specific value of 9 $^{W}/_{m^2}$ for living room/kitchen and 3 $^{W}/_{m^2}$ for other rooms, while 5 $^{W}/_{m^2}$ prescribed in SBi [2011] are applied for critical room, as reflected in table 4.4. For SBi model the internal heat gains are rather the average of heat gains in rooms intended for non-sleeping activities and rooms intended for sleeping activities.

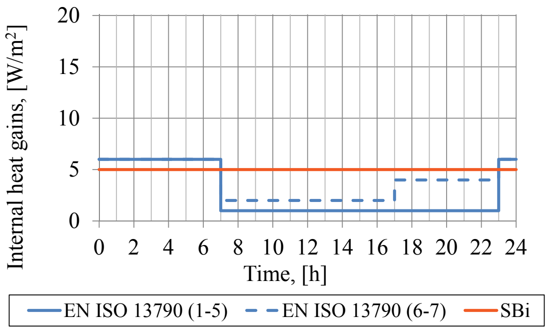
	EN ISO 13790		**SBi**
	Living room/kitchen	**Other rooms**	
	Q_{int}, $[^{W}/_{m^2}]$	Q_{int}, $[^{W}/_{m^2}]$	Q_{int}, $[^{W}/_{m^2}]$
Weekdays	9.0	2.67	5.0
Weekend	9.0	3.83	5.0
Weekly average	9.0	3.0	5.0

Table 4.4: *Average internal heat load applicable for different simplified models.*

The daily internal heat gains distribution can be seen in figure 4.14. For EN ISO 13790 model there is no difference in living room/kitchen occupancy between weekdays and weekend whereas it occurs for other rooms, where higher occupancy is applied during weekend.



(a)



(b)

***Figure 4.14:** Internal heat gains calculated by means of different models: for living room/kitchen (a) and other rooms (b). 1-5 represent weekdays, 6-7 weekend.*

Internal heat gains are dominating in SBi simplified model over EN ISO 13790 simplified model during period of low occupancy or even its absence in particular rooms, i.e. for living room during the night and for other rooms during the daytime. It means that there are additional unnecessary heat gains calculated by SBi model. On the other hand there are unexpected noticeable internal heat gains used in EN ISO 13790 simplified model for living room/kitchen during evening time, i.e. 20 $^{W}/_{m^2}$, which is investigated in section 5.3.3.

4.3.4 Specific heat transfer by ventilation

Both mechanical and natural ventilation are applicable in present simplified model, however supply air is always external air without preheating, [Mortensen 2012-2013]. Thus the supplied air is assumed bypassed a heat recovery unit in summer. For mechanical ventilation a basic ventilation rate is used, which is executed throughout the entire year and provides sufficient air exchange for acceptable IAQ. For natural ventilation summer ventilation rate is utilised, which intends to overcome overheating, see figure user input in 4.13(a). The latter can have different ventilation rates during three daily time periods, namely daytime, evening and night. Furthermore the ventilation rate should be specified by user and it is executed no matter what the capacity of ventilation system is. However, for natural ventilation it is not always possible to achieve desirable ventilation rates because of varying driving forces and more detailed analysis of natural ventilation rates potential is not executed in current simplified model.

For summer ventilation rate the control system implies proportional control, which depends on the control temperature, which, in turn, uses operative temperature for this purpose. The set-point for summer ventilation rate is set to a fixed value of 23°C and proportional band is set to a fixed value of 1°C.

4.3.5 Specific heat transfer by transmission

The specific heat loss by transmission through both opaque constructions and windows/doors is preliminary calculated for the entire building by means of Be10 software, which utilises the calculation algorithm described in appendix M. Hence, for the critical room this value is calculated simply by the ratio between the critical room and the entire building floor area, as it is shown in equation (4.2). Thus, the specific heat loss for the critical room is determined solely by specifying the heated floor area of the critical room.

$$H_{\text{tr}} = H_{\text{tr,tot}} \frac{A_{\text{f}}}{A_{\text{f,tot}}} \tag{4.2}$$

H_{tr}	Specific heat loss by transmission for critical room, $\left[\mathrm{W}/{}^{\circ}\mathrm{C}\right]$
$H_{\text{tr,tot}}$	Specific heat loss by transmission in entire building, $\left[\mathrm{W}/{}^{\circ}\mathrm{C}\right]$
A_{f}	Heated floor area of critical room, $\left[\mathrm{m}^2\right]$
$A_{\text{f,tot}}$	Heated floor area of entire building, $\left[\mathrm{m}^2\right]$

4.4 Summary

This chapter presents the description of three simple models intended for compliance with overheating requirement in Danish Building Regulations[Danish Energy Agency 2010], i.e. for calculation the number of hours when the room operative temperature is above 26°C and 27°C. For this reason all models utilise calculations on an hourly basis. However it should be noted that EN ISO 13790 model was established for energy calculation purpose, while SBi model was created with solely overheating calculation goal. In addition, SBi model is based on EN ISO 13790 model, though with further simplifications.

As it is stated in Danish Building Regulations the overheating should be calculated on room level, thus a term of critical room appeared, though without clear instructions how to identify it. As assumption of considering always a living room as critical one is implemented in Bo Adamson model based on general engineering experience. Another approach is used behind SBi model to select the critical room based on the highest solar thermal load in a room, however the model does not provide an opportunity for such calculations. All in all it was decided to consider living room as critical one, unless other methods are available.

The assumptions behind every model can be crucial and lead to differences between the models. These differences are reflected in lumped capacitance scheme each model is based on. At first, unlike the EN ISO 13790 and Bo Adamson models which are based on three building temperature nodes, SBi model employs only two building temperature nodes, assuming high heat transfer between the mass and internal surfaces of the building envelope and thus their similar temperatures. At second, in SBi model heat losses and heat gains affect only room air temperature, whereas other models imply more sophisticated heat flows, e.g.. the solar heat gains are absorbed by internal surfaces, transmission heat losses through opaque envelope elements affect thermal mass temperature, etc. At third, transient conduction is treated in different ways among models, i.e. either Crank-Nicolson method in EN ISO 13790 model or Euler forward method in Bo Adamson and SBi models are used.

Next chapter serves description and investigation of various boundary conditions and input data specified or recommended for reviewed simplified models.

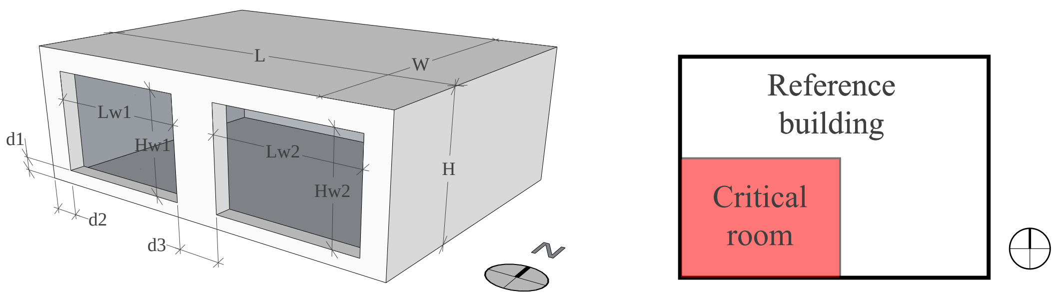
Chapter **5**

Investigation of boundary conditions and input data

This chapter outlines the boundary conditions and input data for three simplified simplified models reviewed in previous chapter. In the beginning a reference building is described, which is used throughout current chapter for investigation of boundary conditions and input data. Then boundary conditions and input data are reviewed followed by sensitivity analysis, which is executed in order to reveal the level of influence of different factors on thermal comfort. Finally, important boundary conditions and input data are deeper investigated.

5.1 Description of a reference building

Throughout the report, a reference building is applied for investigation of simplified models with regards to their prediction of thermal comfort. The reference building, also referred to as case 0, appears as a dwelling, more specifically a recently built single-family house in Denmark. In order to promote the deteriorated thermal indoor environment, the reference building is assumed to have a low energy consumption, which implies thermal resistant and airtight construction elements. Due to the fact, that information regarding the entire building is necessary for the simplified models, the description contains of dimensions, thermal properties and application related to the entire building, although the main focus is aimed at the critical room. The dimensions of the geometry are given for the critical room in figure 5.1.



(a) (b)

Figure 5.1: *Visualisation of the critical room together with its geometry dimensions (a) and horizontal plan view of the entire reference building (b). Geometry of the critical room is taken from test building in BESTEST.*

The internal dimensions of the test building in Building Energy Simulation TEST (BESTEST), [Judkoff and Neymark 1995], are applied for the critical along with windows position. BESTEST is an analytical verification of building energy simulation programs and it is conducted in section 6.2 in order to validate the simplified models. The internal and external dimensions, namely net and gross, are listed in table 5.1. Note, that the internal heat gains and ventilation rate should be specified according to gross floor area, [Danish Energy Agency 2010, p. 74].

	Areas		**Room dimensions**			**Windows dimensions**		**Windows position**		
	A_f, [m^2]	V, [m^3]	L, [m]	W, [m]	H, [m]	L_{w1}, [m]	H_{w1}, [m]	d_1, [m]	d_2, [m]	d_3, [m]
Net	48.0	129.0	8.0	6.0	2.7	3.0	2.0	0.2	0.5	1.0
Gross	56.8	171.0	8.6	6.6	3.0					
Net	192.0	518.4	16.0	12.0	2.7					
Gross	227.3	684.0	17.2	13.2	3.0					

Table 5.1: *Dimensions of the critical room and its components along with the entire reference building.*

The building constructions have a relatively high thermal mass and building corresponds to construction class heavy (middel tung), [SBi-anvisning 213 2008, tab. 10]. The internal layers of constructions consist primarily of bricks and concrete except the ceiling, which consists of wood as the internal layer. The thermal characteristics of the building construction elements are listed in table 5.2. The methodology for calculating the thermal transmittances appears in appendix M.3.

Construction element	**Material layer**	**Dimension** [mm]	**Thermal conductivity** λ, [W/m°C]	**Thermal transmittance** U, [W/m^2°C]	**Linear thermal transmittance** ψ, [W/m°C]
Ceiling	wood	20	0.140	0.13	-
	Insulation	280	0.039		
	Roofing	10	0.048		
External walls	brick	108	0.680	0.15	-
	Insulation	242	0.039		
	Brick	108	0.680		
Internal walls	Brick	108	0.680	0.40	-
	Insulation	75	0.039		
	Brick	108	0.680		
Floor	Tiles	10	1.500	0.15	-
	Concrete	150	1.600		
	polystyrene fill	240	0.050		
Foundations	-	-	-	-	0.10
Windows	-	-	-	-	0.03

Table 5.2: *Thermal characteristics of the building construction elements applied for the reference building.*

The critical room contains two large windows facing South with the window properties listed in table 5.3. Although there is no shadow occurring on the windows from neither neighboring buildings nor overhang, the windows are provided with light curtains as shading devices, which are assumed to by either on or off.

Number	**Window area**	**Thermal transmittance**	**Solar energy transmittance**	**Glazing area fraction**	**Shading factor**
n, [-]	A_{w}, $[\mathrm{m}^2]$	U_{w}, $[\mathrm{W}/\mathrm{m}^2\,^\circ\mathrm{C}]$	g, [-]	f_{g}, [-]	f_{c}, [-]
2	6.0	1.20	0.60	0.92	0.65

Table 5.3: *Window thermal properties used in the critical room.*

In order to obtain sufficient IAQ and thermal comfort the minimum acceptable ventilation rates, according to BR10 are assumed to be in current critical room. The building has no mechanical ventilation system. However, as the critical room has openable windows, which are manually controlled, it is capable of utilising natural ventilation when high room air temperatures occur. As was mentioned before the air tightness of current dwelling is 1.0 l/s per heated floor area at a pressure of 50 Pa, then infiltration rate can be calculated using equation (5.1), which corresponds to infiltration rate during building usage time.

$$q_{\mathrm{i}} = 0.04 + 0.06 \cdot q_{50} \tag{5.1}$$

q_{i}	Volumetric infiltration air flow rate, $[\mathrm{l}/\mathrm{s\,m}^2]$
q_{50}	Leakage at 50 Pa pressure difference, $[\mathrm{l}/\mathrm{s\,m}^2]$

The infiltration rate is calculated to 0.10 $\mathrm{l}/\mathrm{s\,m}^2$ of heated floor area, which corresponds to maximum allowable value for building usage time according to Danish Energy Agency [2010] for energy class 2015. The basic ventilation rate is assumed to be 0.3 $\mathrm{l}/\mathrm{s\,m}^2$ of heated floor area resulting in 0.47 h^{-1}, which is a requirement for dwellings independently of the type of ventilation system used, [SBi-anvisning 213 2008, p. 59]. To cope with overheating in critical room the natural ventilation with ventilation rate of 2.4 $\mathrm{l}/\mathrm{s\,m}^2$ is assumed to be utilised by means of cross ventilation, resulting in 3.79 h^{-1}. This value is calculated from SBi-anvisning 213 [2008, p. 60] assuming area of effective opening equal to 2.27 m^2, which corresponds to 4% of the gross floor area of the critical room.

5.2 Sensitivity analysis

This section undertakes a sensitivity analysis (SA) of boundary conditions and input data for simplified models with the purpose to reveal the highest contributors to output uncertainty and hence investigate the most important parameters in order to enhance the knowledge base and therefore possibly reduce the output uncertainty. Not important input parameters, in turn, can be set to reasonable default values and thus reduce the number of input data, which is beneficial for the compliance model.

At the building preliminary design phase the use of SA is advantageous for making alternative solutions or optimising existing one. In this case the focus may lay on sensitive input parameters, which have a significant influence on the output, meaning that small changes in input brings a notable difference in output, [Hamby 1994, p.137]. Unlike such analysis, the current thesis is focused on performance prediction of already designed yet unbuilt buildings and thus on finding important input parameters, whose variability or uncertainty has large contribution to the output uncertainty, [Hamby 1994, p.137]. In the conducted survey among Danish companies, described in chapter 3 and appendix D, the respondents pointed out the most uncertain and important parameters regarding thermal building simulation:

- Occupants behaviour with respect to ventilation and solar shading control;
- Infiltration and natural ventilation with manual windows opening;
- Internal heat gains.

The screening technique proposed by Morris, i.e. Morris method, is used in current SA as it combines features of both local and global methods. Although one factor at a time (OAT) is varied in Morris method, like in local SA method, it is exploring interaction of input parameter with other parameters, which can be regarded as global measure, [Saltelli et al. 2004]. For description of entire approach used in the current SA see appendix J.2.

5.2.1 Input probability distributions

Prior to performance of a SA, it is essential to understand which input parameters are to be examined. In current thesis, simplified models intended to predict excessive operative temperatures in designed, but yet unbuilt dwelling are considered. Since for this type of simulations a designed weather data, i.e. DRY should be used, which includes weather variation in Denmark for 15 years and incorporates corresponding uncertainties, the only uncertainties which are investigated in the current SA are related to description of building itself, [Lomas and Eppel 1992, p. 29].

The input probability distributions were found by means of literature study, measurements, construction guidelines and, when necessary, assumptions. There are all together 31 considered input parameters presented in tables 5.4 - 5.7, which are expressed in terms of probability density functions (PDF) and are categorised into four main subgroups as shown below:

- Building geometry;
- Envelope thermal properties;
- Window solar properties;
- Occupants behaviour related parameters.

A confidence interval of 95% is used for all 31 input parameters to calculate the expected interval. Note that thorough description of input parameters probability distributions and their establishment can be found in appendix J.4.

It is important to mention that boundary conditions and input data of the simplified models, SBi model in particularly, consist of input parameters available for the user and those, which are hidden inside the so called "black box". In the current thesis first category of input parameters is denoted as user input and the second category is denoted as model input. The majority of input parameters is related to user input parameters, while several of them, which in fact are very dependent on occupants behavior are hidden inside the model, like internal heat gains, solar shading and ventilation set-points, proportional band for ventilation control. Although the user cannot modify them, they are varying from house to house in reality, which is reflected in input parameters probability distributions.

Uncertainties in building geometry occur because the building, once finished, will slightly differ from the one been modelled, even if it was built according to specifications, [Lomas and Eppel 1992, p. 29]. However, the building geometry related parameters are likely to be very close to those stated in specifications. The input parameter distributions related to building geometry are reflected in table 5.4, whereas their establishment is explained in appendix J.4.1.

Due to utilisation of limited input in simplified models, cf. subsection 4.2.4, transmission heat losses are related to the entire building and only heated floor area of the critical room should be specified, which converts building heat losses into ones related to the critical room. Confusion may arise when dealing with floor areas, since for transmission heat losses only net floor area is utilised, cf. appendix M.5, but ventilation rates and internal heat gains are related to the heated floor area, which is gross area, [SBi-anvisning 213 2008, p. 74]. Uncertainty related to the net (transmission heat losses) and gross (ventilation rates and internal heat gains) floor areas of the critical room are basically related to the same floor area. It was thus decided to use gross floor area of the critical room (parameter no. 4 in table 5.4) in SA, while implementing in the models a factor 0.85 in transmission heat losses calculation of the critical room to convert gross floor area to net.

No.	**Parameter**	**Unit**	**Type**	**Mean value** μ	**Standard deviation** σ	**Variation coefficient** δ	**Expected interval** *min* *max*
1	Ceiling area (building)	$[m^2]$	N	227.0	0.76	0.3%	225.5 - 228.6
2	External wall area (building)	$[m^2]$	N	170.4	0.50	0.3%	169.4 - 171.4
3	Net floor area (building)	$[m^2]$	N	192.0	0.70	0.4%	190.6 - 193.4
4	Heated floor area (critical room)	$[m^2]$	N	48.0	0.35	0.7%	47.3 - 48.7
5	Window area	$[m^2]$	N	6.0*	0.03	0.4%	5.95 - 6.05
6	Foundations linear thermal length	[m]	N	29.8	0.05	0.2%	29.3 - 29.3
7	Window linear thermal length	[m]	N	8.0*	0.02	0.2%	7.97 - 8.03
8	Orientation of windows	[°]	N	180	1.00	0.6%	178 - 182

Table 5.4: *Probability distributions of building geometry parameters. Following distribution type is used: N - normal. *Related to one window.*

Envelope thermal properties and window solar properties are more difficult to define as they are changing during their service life. Additionally, some of the building construction elements may have different properties from those stated by manufacturer, once they are implemented in building. In addition, such parameters as thermal capacity and shading factor require estimation from the engineer or any other person executing building simulation software, which can lead to the output uncertainty. The input parameter distributions related to the envelope thermal properties and window solar properties are reflected in tables 5.5 - 5.6, whereas their establishment is explained in appendices J.4.2 - J.4.3, respectively.

No.	Parameter	Unit	Type	Mean value μ	Standard deviation σ	Variation coefficient δ	Expected interval *min max*
9	External ceiling thermal transmittance	$[W/°C\,m^2]$	N	0.13	0.010	8.0%	0.11 - 0.15
10	External wall thermal transmittance	$[W/°C\,m^2]$	N	0.14	0.009	6.7%	0.12 - 0.16
11	External floor thermal transmittance	$[W/°C\,m^2]$	N	0.13	0.006	4.4%	0.12 - 0.14
12	Windows thermal transmittance	$[W/°C\,m^2]$	N	1.20	0.060	5.0%	1.08 - 1.32
13	Foundation linear thermal transmittance	$[W/°C\,m]$	N	0.10	0.004	4.4%	0.09 - 0.11
14	Window linear thermal transmittance	$[W/°C\,m]$	N	0.03	0.005	16.7%	0.02 - 0.04
15	Building thermal capacity	$[Wh/°C\,m^2]$	U	-	-	-	80 - 120

Table 5.5: *Probability distributions of envelope thermal properties parameters. Following distribution type is used: N - normal, U - uniform.*

No.	Parameter	Unit	Type	Mean value μ	Standard deviation σ	Variation coefficient δ	Expected interval *min max*
16	Horizon angle	[°]	U	-	-	-	0 - 30
17	Overhang angle	[°]	N	26.6	1.00	3.8%	24.6 - 28.6
18	Right fin angle	[°]	N	0	1.00	-	0 - 2
19	Left fin angle	[°]	N	0	1.00	-	0 - 2
20	Wall cavity in percentage*	[%]	N	2.5	0.25	10.0%	2 - 3
21	Solar energy transmittance	[−]	N	0.60	0.015	2.5%	0.57 - 0.63
22	Shading factor	[−]	N	0.65	0.075	11.5%	0.50 - 0.80

Table 5.6: *Probability distributions of window solar properties parameters. Following distribution types are used: N - normal, U - uniform. *Not applicable in EN ISO 13790 and Bo Adamson simplified models.*

The most important parameters of energy simulation in dwellings are often related to occupants behaviour, cf. [Brohus et al. 2010, p. 8], which are, in fact, very uncertain and very difficult to determine. The input parameters related to occupants behaviour considered in the current SA are reflected in table 5.7, whereas their establishment is explained in appendix J.4.4. Note that solar shading set-point distribution is not implemented in SBi simplified model as it implies monthly solar calculations and uses predefined tables for solar shading created by means of BSim tool. Another note is regarding ventilation set-point - mean value and standard deviation, 0.89°C and 0.45°C respectively are used solely to make shape of log-normal distribution with a peak at 1.99°C. However, when it is implemented in simplified models a value of 21.01°C is added to shift the peak into 23°C with interval of 22-27°C, cf. subsection J.4.4 in appendix. For internal heat gains in EN ISO 13790 and Bo Adamson simplified models a daily profile is implemented from EN ISO 13790 standard, cf. table N.1 and figure 4.14(a), whereas SBi simplified model utilises a constant profile.

No.	Parameter	Unit	Type	Mean value μ	Standard deviation σ	Variation coefficient δ	Expected interval *min* *max*
23	Internal heat gains from occupants	$[W/m^2]$	N	1.44	0.29	19.9%	0.86 - 2.01
24	Internal heat gains from appliances	$[W/m^2]$	N	3.06	0.38	12.3%	2.31 - 3.81
25	Ventilation set-point temperature	[°C]	L	0.89	0.45	-	22 - 27
26	Proportional band	[°C]	U	-	-	-	0 - 3
27	Basic ventilation rate	$[l/s\,m^2]$	N	0.3	0.10	33.3%	0.1 - 0.5
28	Daytime ventilation rate	$[l/s\,m^2]$	N	0.90	0.20	22.2%	0.50 - 1.30
29	Evening ventilation rate	$[l/s\,m^2]$	N	0.90	0.20	22.2%	0.50 - 1.30
30	Night ventilation rate	$[l/s\,m^2]$	N	0.90	0.20	22.2%	0.50 - 1.30
31	Solar shading set-point*	$[W/m^2]$	N	150	75	50.0%	0 - 300

Table 5.7: *Probability distributions of occupants related input parameters. Following distribution types are used: N - normal, L - log-normal, U - uniform. *Not applicable in SBi simplified model.*

5.2.2 Results

With 31 input parameters and maximum elementary effects (EE) of 10 a total number of executions is calculated to 320 via equation (5.2), [Saltelli et al. 2004, p.97]. As the computational requirements in Morris method are quite low, the maximum settings, e.g. eight levels, are chosen for the sample generation.

$$N = r \cdot (k + 1) = 10 \cdot (31 + 1) = 320 \tag{5.2}$$

N	Number of executions
r	Number of EE per design parameter
k	Number of input parameters

The result of SA is expressed with the mean value, μ, determining the degree of influence of input parameter on output variable and standard deviation, σ, determining interactions of input parameter with other input parameters and all nonlinear effects. The dotted wedge on the graphs is calculated based on relation between mean value and standard deviation, see equation (5.3), and indicating whether the input parameter has strong or low correlation with other input parameters and/or non-linear effect on the output.

$$\sigma = \frac{\mu\sqrt{r}}{2} \tag{5.3}$$

μ	Mean value
σ	Standard deviation
r	Number of EE per input parameter

The result of SA for EN ISO 13790 simplified model is illustrated in figure 5.2 and in table 5.8.

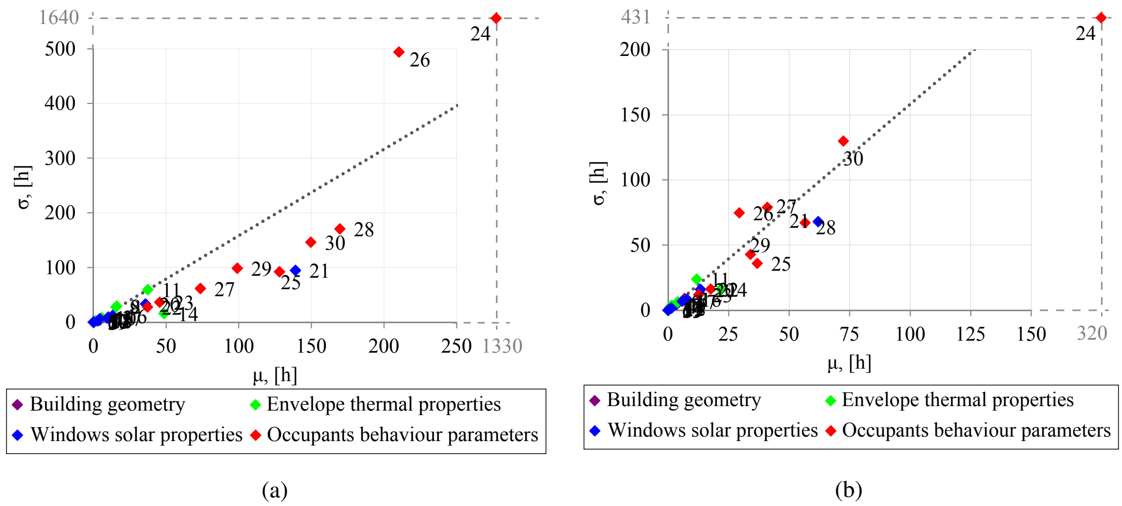
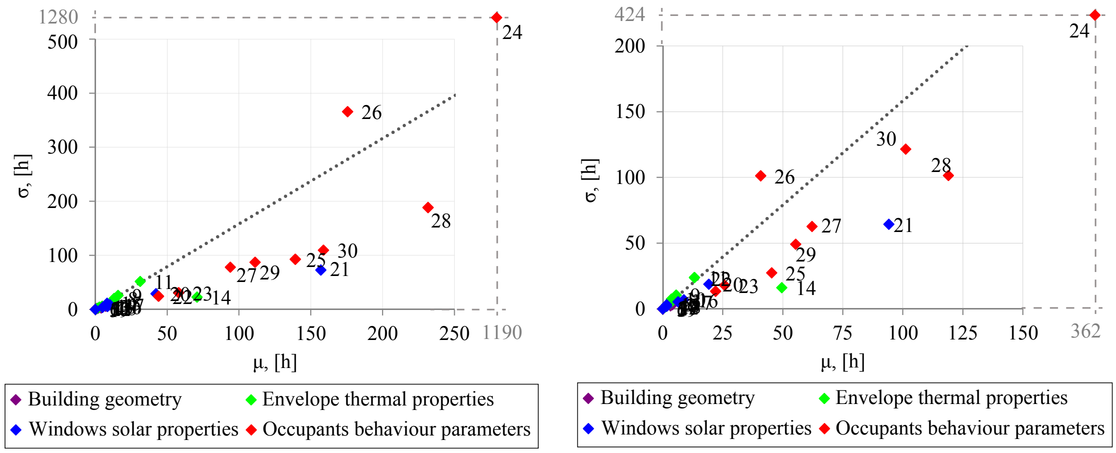


Figure 5.2: *Results of sensitivity analysis for EN ISO 13790 simplified model expressed as number of hours with operative temperature above 26°C (a) and 27°C (b).*

	Rank	No.	Factor	Hours above 26°C μ, [h]	Hours above 26°C σ, [h]	Hours above 27°C μ, [h]	Hours above 27°C σ, [h]
◆	1	24	Ventilation set-point temperature	1330	1640	321	431
◆	2	26	Basic ventilation rate	210	494	29	75
◆	3	28	Evening ventilation (17-24)	170	171	57	67
◆	4	30	Solar shading set-point	150	146	72	130
◆	5	21	Shading factor	139	95	62	68
◆	6	25	Proportional band	128	92	37	36
◆	7	29	Night ventilation (1-8)	99	99	34	43
◆	8	27	Daytime ventilation (9-16)	74	62	41	79
◆	9	14	Thermal capacity	49	16	22	16
◆	10	23	Internal heat gains from appliances	46	36	13	12

Table 5.8: *Ten most important parameters of SA for EN ISO 13790 simplified model according to the mean value of hours with operative temperature above 26°C.*

Not surprisingly, the most important input parameters for EN ISO 13790 simplified model are related to occupants behaviour. Shading factor and building thermal capacity are specified by the modeller and are uncertain since the modeller is responsible for their estimation, based on guidances provided and his personal skills and experience. The result for Bo Adamson simplified model is illustrated in figure 5.3 and in table 5.9.



(a) (b)

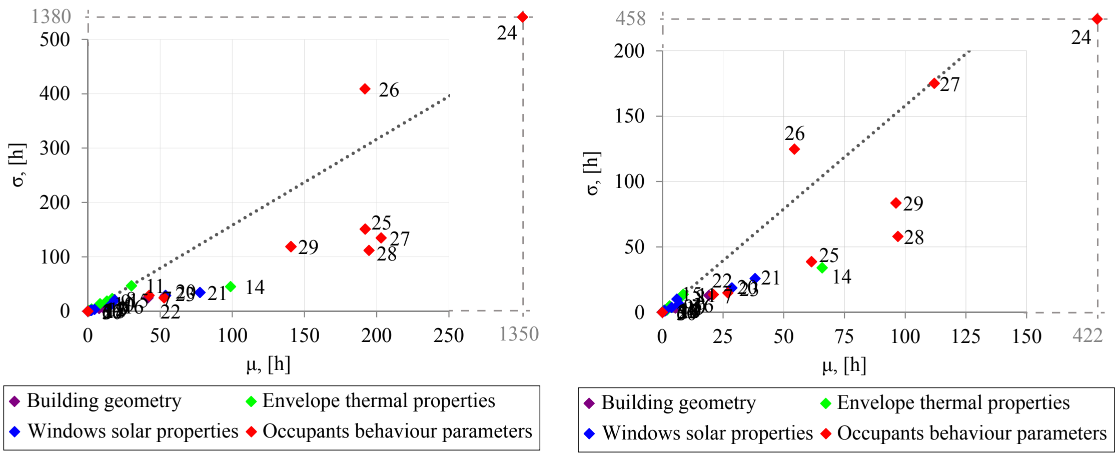
Figure 5.3: *Results of sensitivity analysis for Bo Adamson simplified model expressed as number of hours with operative temperature above 26°C (a) and 27°C (b).*

	Rank	No.	Factor	Hours above 26°C		Hours above 27°C	
				μ, [h]	σ, [h]	μ, [h]	σ, [h]
◆	1	24	Ventilation set-point temperature	1190	1280	362	425
◆	2	28	Evening ventilation (17-24)	232	188	119	101
◆	3	30	Solar shading set-point	159	110	101	122
◆	4	21	Shading factor	157	73	94	64
◆	5	26	Basic ventilation rate	176	366	41	101
◆	6	25	Proportional band	139	93	45	27
◆	7	29	Night ventilation (1-8)	111	87	55	49
◆	8	27	Daytime ventilation (9-16)	94	78	62	63
◆	9	14	Building thermal capacity	71	23	50	16
◆	10	23	Internal heat gains from appliances	58	31	26	18

Table 5.9: *Ten most important parameters of SA for Bo Adamson simplified model according to the mean value of hours with operative temperature above 26°C.*

The most important input parameters for Bo Adamson simplified model are the same as for EN ISO 13790 simplified model, while only actual ranking is slightly different. For example, solar shading factor and set-point are more important for the Bo Adamson simplified model, whereas basic ventilation rate is of less importance.

The result for SBi simplified model is illustrated in figure 5.4 and in table 5.10.



(a) (b)

Figure 5.4: *Results of sensitivity analysis for SBi simplified model expressed as number of hours with operative temperature above 26°C (a) and 27°C (b).*

	Rank	No.	Factor	Hours above 26°C		Hours above 27°C	
				μ, [h]	σ, [h]	μ, [h]	σ, [h]
◆	1	24	Ventilation set-point temperature	1350	1380	422	458
◆	2	27	Daytime ventilation (9-16)	203	135	112	175
◆	3	28	Evening ventilation (17-24)	195	112	97	58
◆	4	25	Proportional band	192	151	61	39
◆	5	26	Basic ventilation rate	192	409	54	125
◆	6	29	Night ventilation (1-8)	141	119	96	84
◆	7	14	Building thermal capacity	99	45	66	34
◆	8	21	Shading factor	78	34	38	26
◆	9	20	Solar transmittance	54	29	29	19
◆	10	23	Internal heat gains from appliances	53	25	27	15

Table 5.10: *Ten most important parameters of SA for SBi simplified model according to the mean value of hours with operative temperature above 26°C.*

There are different trends in result for SBi simplified model among the other simplified models, for instance daytime ventilation is of much higher importance, whereas shading factor is of lower importance. Nevertheless, 9 out of 10 input parameters are the same for SBi simplified model comparing to other models.

The comparison of the most important parameters among the three considered simplified models is shown in table 5.11 along with combined ranking. What is noticeable is that a coherence between the simplified models as they all obtain the same 10 most important parameters, though with different ranking. A table with models output regarding all 31 parameters is located in appendix J.5.

	Number	Parameter	Rank			
			Average	EN ISO 13790	Bo Adamson	SBi
◆	24	Ventilation set-point temperature	1	1	1	1
◆	28	Evening ventilation (17-24)	2	3	2	3
◆	30	Solar shading set-point	3	4	3	-*
◆	26	Basic ventilation rate	4	2	5	5
◆	25	Proportional band	5	6	6	4
◆	21	Shading factor	6	5	4	8
◆	27	Daytime ventilation (9-16)	7	8	8	2
◆	29	Night ventilation (1-8)	8	7	7	6
◆	14	Building thermal capacity	9	9	9	7
◆	23	Internal heat gains from appliances	10	10	10	10

Table 5.11: *Ten most important parameters of three simplified models according to SA calculated by weighted average. *This parameter is not included in the particular simplified model.*

5.2.3 Discussion

Set-point for ventilation is by a large margin the most important parameter in simplified models. It is therefore necessary to keep it inside the model without giving an opportunity for the user to vary it as the consequences in the output can be significant. The same conclusion but with a smaller value is relevant for the solar shading set-point as it is the third important factor in the list. In general, parameters related to occupants behaviour are the most important, among which ventilation related parameters excel the most. The reason why daytime ventilation is of notably higher importance for SBi but not for other simplified models is that it possesses constant internal heat gains daily profile and solar heat gains are distributed according to global solar incidence on horizontal surface, which in turn has often a peak around the noon. For other simplified models the internal heat gains have the peak during the evening, which explains why evening ventilation is of higher importance than daytime ventilation.

Neither building geometry nor envelope thermal properties related parameters, except thermal capacity, are of significant importance to the model output as their influence on model output is rather limited and their uncertainty is within relatively low range. Window properties parameters are neither significantly uncertain, however shading factor is very sensitive to the the model output, especially regarding EN ISO 13790 and Bo Adamson simplified models. Although internal heat gains by occupants parameter is not included in the list of ten the most important parameters, it holds 11th place and should still be considered with high significance, bearing in mind that daily ventilation was artificially split into daytime and evening ventilations. All in all the four groups of most important parameters are:

1. Energy removed by ventilation;

2. Energy supplied by solar;
3. Energy stored in building thermal mass;
4. Energy supplied by appliances and occupants.

5.3 Investigation of important parameters

Investigation of important parameters comprises study of group of parameters, which according to SA are the most contributors to model uncertainty. Furthermore some parameters, for example thermal capacity calculation, are further compared and examined in order to use the most optimal one for all existing simplified models in comparison.

5.3.1 Ventilation

Unlike the thermal capacity, ventilation rates are much more uncertain as they depend on many parameters including occupants behaviour. It thus becomes a complex task to calculate the ventilation rates and the values recommended in SBi-anvisning 213 [2008, p.60], i.e. 0.9 $^{l}/_{s\,m^2}$, represent only a particular dwelling in particular surroundings. Depending on the effective openings area in dwelling it is possible to proportionally increase ventilation rates by the ratio between effective openings area and 1.5%/4% of the gross dwelling area. For the single-sided ventilation 4% are used, whereas for cross ventilation 1.5% are used. In the following cases detailed tools for calculation of natural ventilation, i.e. BSim and COMIS, are used in order to estimate the uncertainty of the guidance provided by SBi 213 comparing to the detailed calculation methods applied for real dwellings.

In following investigation a comparison of ventilation rates via natural ventilation is shown between different cases:

1. **Case 1**. Simulation performed in BSim with recommended ventilation rates from SBi 213;
2. **Case 2**. Simulation performed in BSim with single zone mode, natural ventilation is calculated based on climatic and building conditions.
3. **Case 3**. Simulation performed in COMISexcel with multizone mode, by utilising temperatures previously obtained in Case 2.

BSim model of Eurodanhus was used in simulations, received from SBi. It contains 10 rooms, where the critical one is a living room, see figure 5.5.

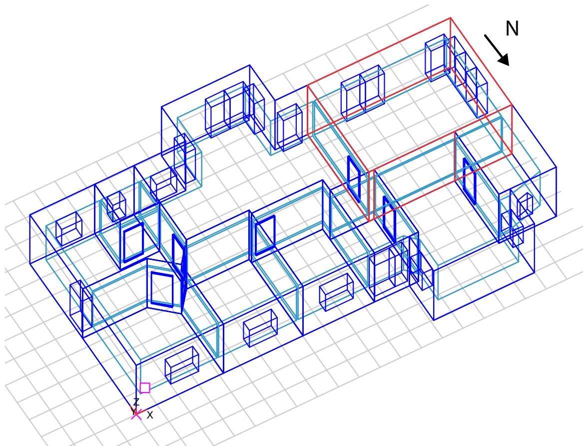


***Figure 5.5:** Geometry of BSim model of Eurodanhus. Red colors indicate a living rooom.*

Result of simulations is illustrated in figure 5.6 where air change rates (ACR) and temperatures are calculated for the living room during one week in July. Air exchange in Case 1 is almost all the time showing maximum performance, i.e. 1.58 h^{-1}. In case 2 ventilation rates are much higher, often reaching 10 air changes per hour, which was set to be a maximum limit in BSim for natural ventilation calculation. Therefore indoor temperature in case 2 is noticeably lower than in case 1. However, by utilising indoor temperatures obtained in case 2 even higher ventilation rates were achieved by means of COMIS tool, cf. figure 5.6. It should be noted that in all cases the same effective opening area was used corresponding to 1.5% of living floor area.

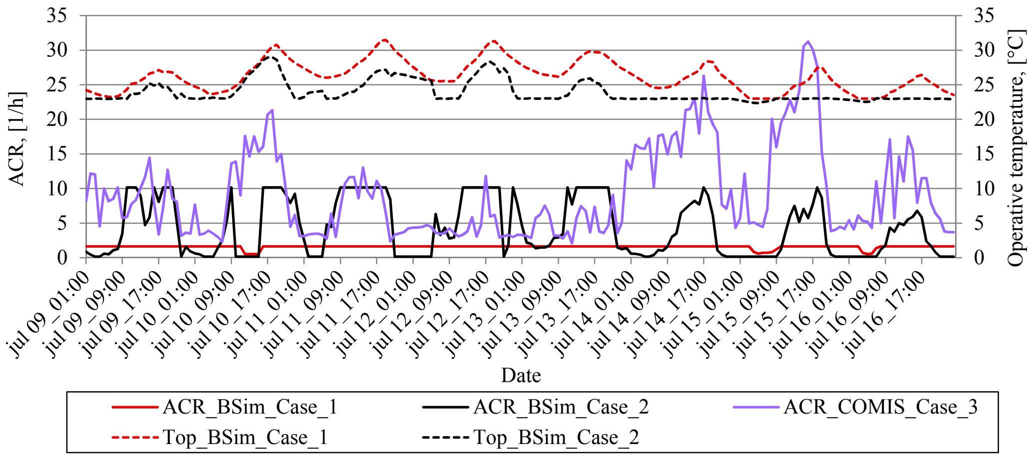


***Figure 5.6:** Comparison of simulations performed in BSim and COMIS for living room during one week in July.*

5.3.2 Solar heat gains

Energy supply from solar was in the sensitivity analysis revealed to be of second highest importance in the prediction of overheating in a thermal zone, mainly because it contributes with large amount of energy during daytime. Some input parameters related to solar shading system, namely the shading factor and the set-point for its application, were determined to be of high importance, cf. table

5.11 at page 49. The importance of the shading factor can be explained by its high variability. Since the shading factor is dependent on the type of shading devices, it is often specified in accordance with predefined tables, [SBi-anvisning 196 2000, p. 307]. However, this implies uncertainty as the determination of characteristics of the shading device, e.g. partially translucent or opaque, can be affected by subjective judgment from the modeller, especially for shading devices with abnormal shapes. Thus, a particular attention should be paid in determining the shading factor from the modeller as this input parameter appears as user input in Be10.

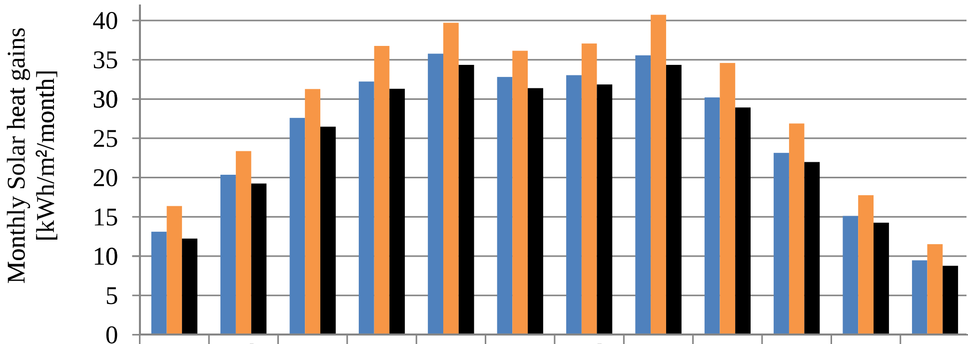
The solar shading set-point is a highly occupants behaviour related input parameter, which is making it rather difficult to estimate. Since experience shows that people are bothered more by bright sunlight than by high internal temperatures, internal solar shading devices should be controlled independently of the room temperature and activated according to a solar incidence more than 150 W/m^2 on the internal surface of the glazing element, [Wittchen et al. 2011, p. 21]. Although the one particular number was chosen as a subjective limit for model input, it is evident that it can vary within a certain range depending on user preferences and other conditions.

During the review of simplified models boundary conditions, the SBi solar algorithm, used in Be10 and hence also SBi simplified model, was revealed to differ from others because it preliminary determines monthly solar heat gains, which subsequently are converted into hourly values. This generates hourly distribution of solar energy different from the other solar algorithms. Based on these objectives calculation of monthly solar heat gains and the hourly distribution of solar energy are preliminary investigated separately, followed by an investigation of the combined effect of solar heat gain calculation and distribution along with several solar case studies.

Solar energy calculation

The SBi solar algorithm differs from others with regards to determination of solar heat gains as it utilises another approach due to the necessity of doing monthly calculations. Basically, the major difference comprises monthly aggregation of partial shadow and shading factors. Furthermore, the angular dependence of solar incidence is accounted differently as this factor varies during the day.

The monthly magnitudes of solar heat gains for different solar algorithms are illustrated in figure 5.7 for south-facing windows. For these monthly solar heat gains, the window properties for the reference building listed in table 5.3 are used. As the Bo Adamson simplified model utilises the solar algorithm of EN ISO 13790 [2008], which is theoretically described in appendix O, its results are similar to EN ISO 13790 and will not appear in figure 5.7. Additionally, the solar algorithms are compared with BSim, as it is considered to be a satisfying estimate of the reality. The BSim model of the reference building is attached as DVD-appendix A.2 - $BSim\_model_{c}ase_{0}$.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
EN ISO 13790	13	20	28	32	36	33	33	36	30	23	15	9	308
SBi (Be10)	16	23	31	37	40	36	37	41	35	27	18	12	352
BSim	12	19	26	31	34	31	32	34	29	22	14	9	295

Figure 5.7: *Monthly solar heat gains from different solar calculation algorithms for reference building (case 0) with orientation of windows towards south.*

Since it is an assumption in the SBi simplified model, that the critical room is determined according to magnitude of solar heat gains, [Mortensen 2012, p. 7], these results achieve further importance. In general, the monthly solar heat gains determined by different solar algorithms differ systematically form each other. The EN ISO 13790 and especially SBi solar algorithm have a tendency to be higher for each month compared with BSim.

The difference is located in method regarding treatment of varying solar energy transmittance. The same approach comprising usage of angular profile is utilised in both EN ISO 13790 solar algorithm and BSim, but regardless of window structure as it only consider one angular dependence. The angle dependence for hourly and monthly calculation is thoroughly described in appendix O.

Hourly distribution of solar energy

The SBi solar algorithm further differs from others by preliminary calculating monthly solar heat gains in an aggregated and averaged way, intended for energy calculations, and convert them into hourly values by using the global solar radiation on a horizontal surface, cf. subsection 4.3. This brings a possible error to the final result as this distribution applies the same pattern for all buildings, independently of their windows orientation. In order to emphasise the consequence of this simplified approach, it is investigated according to its impact on number of hours with excessive operative temperatures.

To clarify the difference in hourly solar energy distributions, deviation of solar incidence in SBi solar algorithm compared to BSim using Perez' solar algorithm is emphasised in figure 5.8 as averaged daily profiles of solar incidence for one particular week for a window orientated towards each cardinal direction. Week 23 (4th - 10th of June) containing the largest amount of solar incidences in the summer period is chosen as a representative week. The solar algorithm applicable for EN ISO 13790 simplified model is not included in figure 5.8 as it utilises hourly solar incidences implemented from BSim, hence its distribution will be identical to BSim without any deviation. The reason for comparing hourly distributions of solar incidences and not solar heat gains is the desire to preliminary emphasise differences in model output solely due to solar energy distributions and not the calculation. The daily sum of solar incidences calculated for week 23 are listed for each cardinal direction beneath the figures in table 5.12 along with their absolute and relative deviations. The hourly absolute deviation of solar incidence in SBi solar algorithm compared to BSim using Perez' solar algorithm is illustrated throughout the representative week in appendix O.4 for a window orientated towards each cardinal direction, for which the largest peaks of 500 $^{W}/_{m^2}$ are experienced for east during the morning and west during the evening.

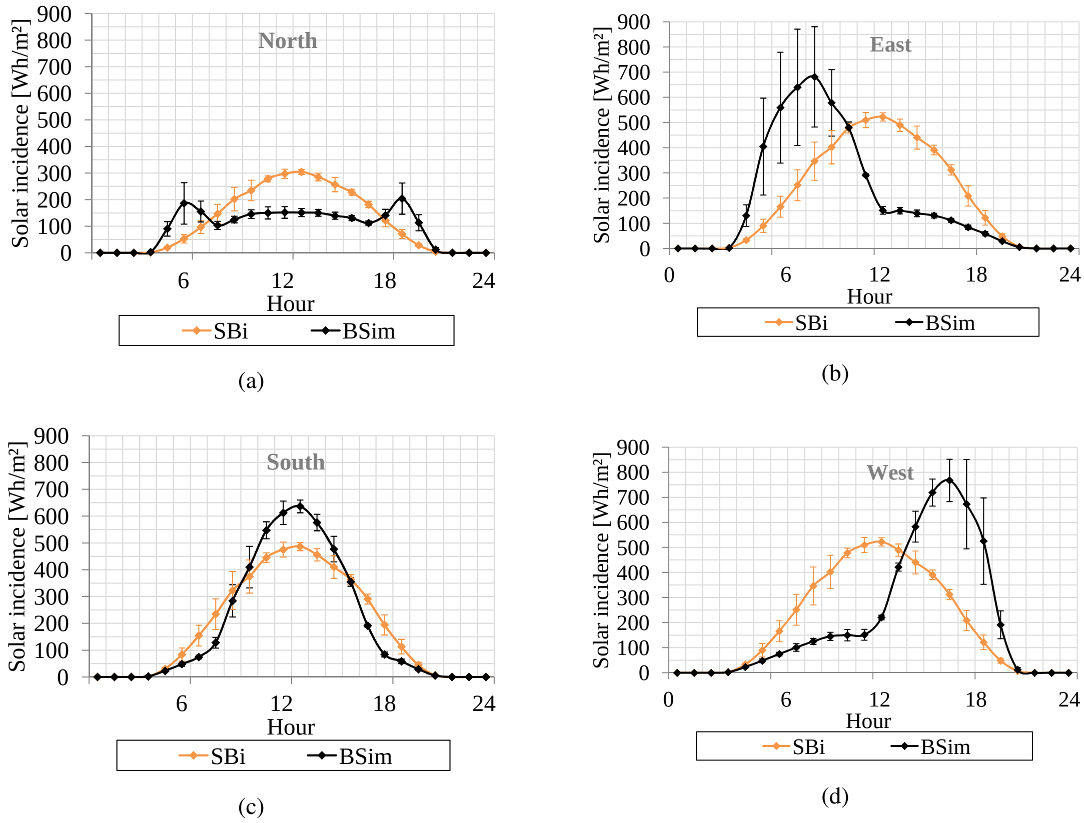


Figure 5.8: *Averaged daily profiles for solar incidence during the representative week 23 calculated for window orientated towards north (a), east (b), south (c) and west (d).*

	north	east	south	west
	$[^{Wh}/_{m^2}]$	$[^{Wh}/_{m^2}]$	$[^{Wh}/_{m^2}]$	$[^{Wh}/_{m^2}]$
SBi	2809	4822	4495	4822
BSim	2263	4630	4545	4937
Deviation	546(24%)	192(4%)	-50(-1%)	-115(2%)

Table 5.12: *Daily sum of solar incidences along with absolute and relative deviation calculated for week 23 for each cardinal direction.*

Figure 5.8 reveals a noticeable difference among distributions of solar incidence. In particular for windows orientated towards east in the morning and towards west in the evening respectively, where a difference of approximately 400 $^{W}/_{m^2}$ is experienced. In order to determine the influence of using different approaches for solar energy distributions, namely SBi and BSim, these are implemented in the SBi simplified model, cf. the workflow illustrated in figure 5.9. Notice that only the distributions of solar heat gains are affecting the difference in model output.

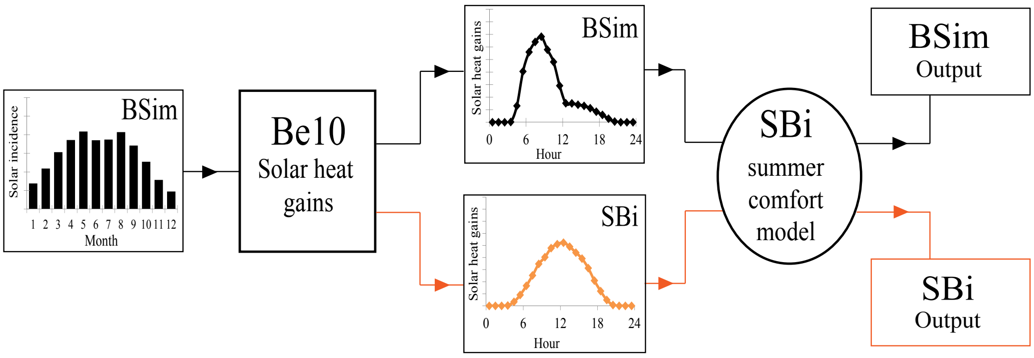


Figure 5.9: *Description of approach used for investigating regarding the influence of predicting summer thermal comfort by means of different hourly distributions of solar heat gains.*

The results of above mentioned investigation are illustrated in figure 5.10(a) for hours with operative temperatures exceeding 26°C and in figure 5.10(c) for hours with operative temperatures exceeding 27°C respectively when simulating the reference building (case 0) containing windows facing different cardinal directions. The absolute deviations are, along with the final results, presented in figure 5.10(b) for hours with operative temperatures exceeding 26°C and in figure 5.10(d) for hours with operative temperatures exceeding 27°C respectively.

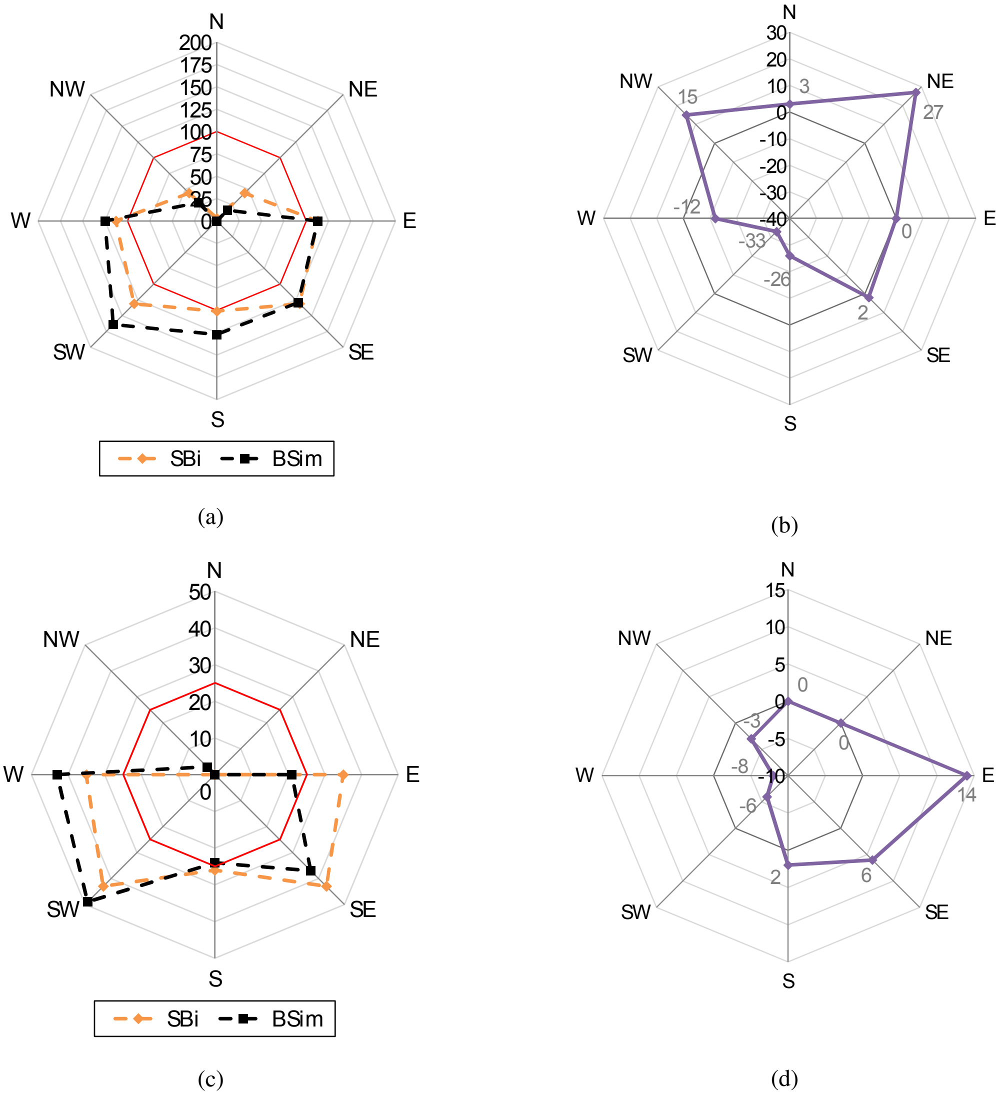


Figure 5.10: *Prediction of overheating in the reference building (case 0) for SBi simplified model utilising different hourly distributions of solar incidence for each cardinal direction. The prediction of overheating is expressed in hours with operative temperatures exceeding 26°C (a) along with its absolute deviations (b) and 27°C (c) along with its absolute deviations (d). Red lines mark the requirements.*

Deviations of SBi solar algorithm appears due to its aggregation and redistribution. The magnitude of absolute deviation between hourly solar distributions is noteworthy, as the SBi solar energy distribution experiences an underestimation of hours with operative temperatures exceeding both 26°C and 27°C when windows are orientated towards south, south-west and west. This can partly be explained by usage of symmetric solar incidences in SBi solar algorithm, as it assumes similarity between solar incidence from east and west. Nevertheless, as SBi simplified model is intended for checking compliance of Danish BR2015 regarding thermal indoor environment, possible distinct agreement between models output regarding whether or not these are fulfilled is more important. Thus, for the refernce building (case 0) model fulfillments of building requirements regarding the risk of overheating are listed in table 6.3 in which no difference is experienced between the two considered solar energy distributions.

	N	NE	E	SE	S	SW	W	NW
SBi	✓	✓	÷	÷	÷	÷	÷	✓
BSim	✓	✓	÷	÷	÷	÷	÷	✓

Table 5.13: *Models fulfillments of requirements from the Danish BR 2015 regarding the risk of overheating for the reference building (case 0) comprising windows orientated towards each cardinal direction.*

Combined effect

As it is the combined effect of the calculation and subsequently hourly distribution of solar heat gains which is of importance to the final output, this will furthermore be investigated in terms of the error SBi and EN ISO 13790 solar algorithm brings compared to BSim. For this investigation, the SBi simplified model applying different solar algorithms is used as illustrated in figure 5.11.

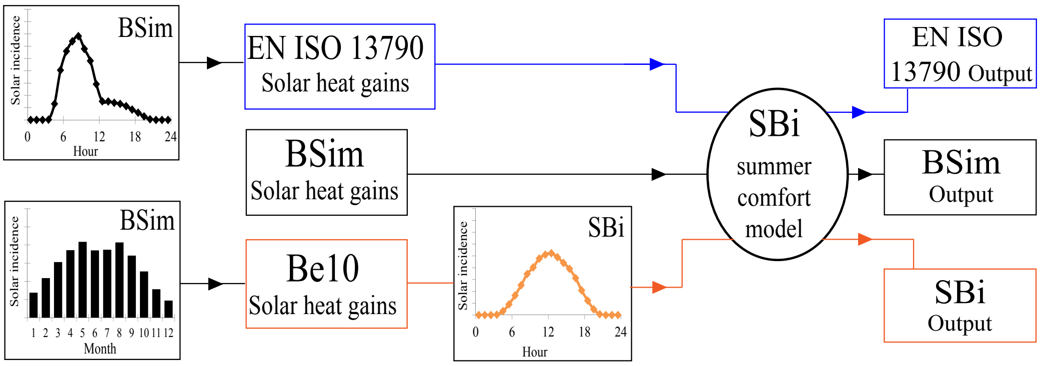


Figure 5.11: *Description of approach used for investigating regarding the influence of predicting summer thermal comofrt by usage of different solar algorithms, namely BSim using Perez' solar algorithm, EN ISO 13790 and SBi solar algorithms.*

The results are illustrated in figure 5.12(a) for hours with operative temperatures exceeding 26°C and in figure 5.12(c) for hours with operative temperatures exceeding 27°C respectively when simulating the reference building (case 0) containing windows facing different cardinal directions. The absolute deviations are, along with the final results, presented in figure 5.12(b) for hours with operative temperatures exceeding 26°C and in figure 5.12(d) for hours with operative temperatures exceeding 27°C respectively.

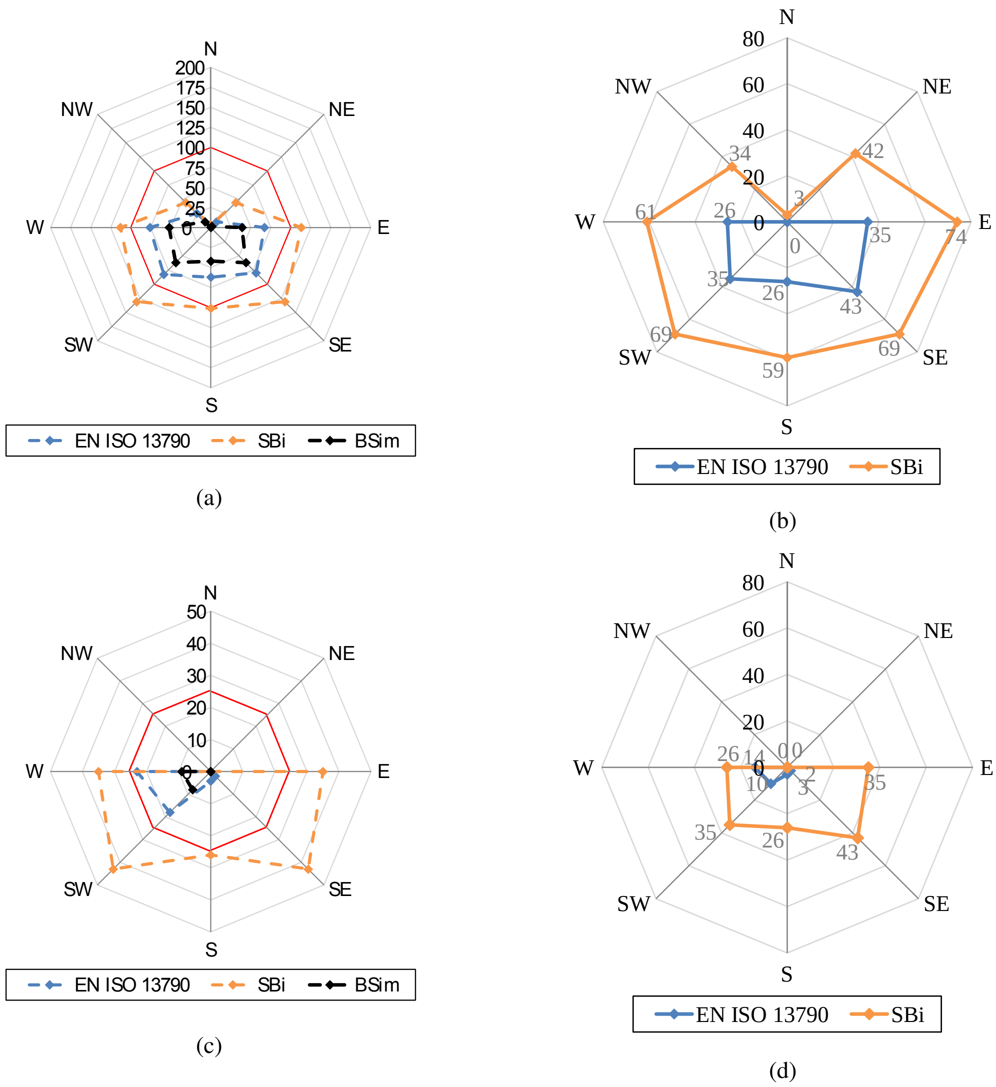


Figure 5.12: *Prediction of overheating in the reference building (case 0) for SBi simplified model utilising different hourly calculations of solar heat gains for each cardinal direction. The prediction of overheating is expressed in hours above 26°C (a) along with its absolute deviations (b) and 27°C (c) along with its absolute deviations (d). Red lines mark the requirements.*

	N	NE	E	SE	S	SW	W	NW
EN ISO 13790	✓	✓	✓	✓	✓	✓	✓	✓
SBi	✓	✓	÷	÷	÷	÷	÷	✓
BSim	✓	✓	✓	✓	✓	✓	✓	✓

Table 5.14: *Models fulfillments of building requirements regarding the risk of overheating for the reference building (case 0) comprising windows orientated towards each cardinal direction.*

The error obtained for the reference building is crucial, as only the results obtained by BSim using Perez' solar algorithm and EN ISO 13790 solar algorithm fulfills the requirements regarding risk of overheating for each cardinal direction. The simplified hourly solar calculation algorithm utilised in EN ISO 13790 is chosen to be the most favourable one as it does only increase the complexity of the model calculation procedure and not the amount of input data while keeping precision at a reasonable level.

Single parameter case study for solar energy

Previous investigation will be supplemented with further investigations by using solar case studies, in order to enhance the results for different solar algorithms and to emphasise the strengths and weaknesses used in different types of dwellings. The cases are chosen based on the results of the sensitivity analysis and are described in table 5.15.

Case	**Description**	**Thermal capacity** C_m, $[\mathrm{Wh}/{}^\circ\mathrm{C\,m^2}]$	**Shading factor** f_c, [-]
0	Reference building	120	0.65
1a	Extra light construction	**38**	0.65
1b	Light construction	**69**	0.65
1c	Extra heavy construction	**161**	0.65
2a	Efficient solar shading	120	**0.40**
2b	No solar shading devices	120	**1.00**

Table 5.15: *Description of conditions in single input parameter case study. Numbers marked with bold font are different in particular case from reference building (case 0).*

The described cases are executed for SBi simplified model by utilising SBi and EN ISO 13790 simplified solar algorithm and BSim respectively, cf. figure 5.11. The results regarding excessive operative temperatures are illustrated in figure 5.13 for east-, south- and west facing windows. These three cardinal direction were determined to be critical according to figure 5.12. Results for window for critical room orientated towards north is excluded because this scenario rarely occurs in reality along with it limited deviation.

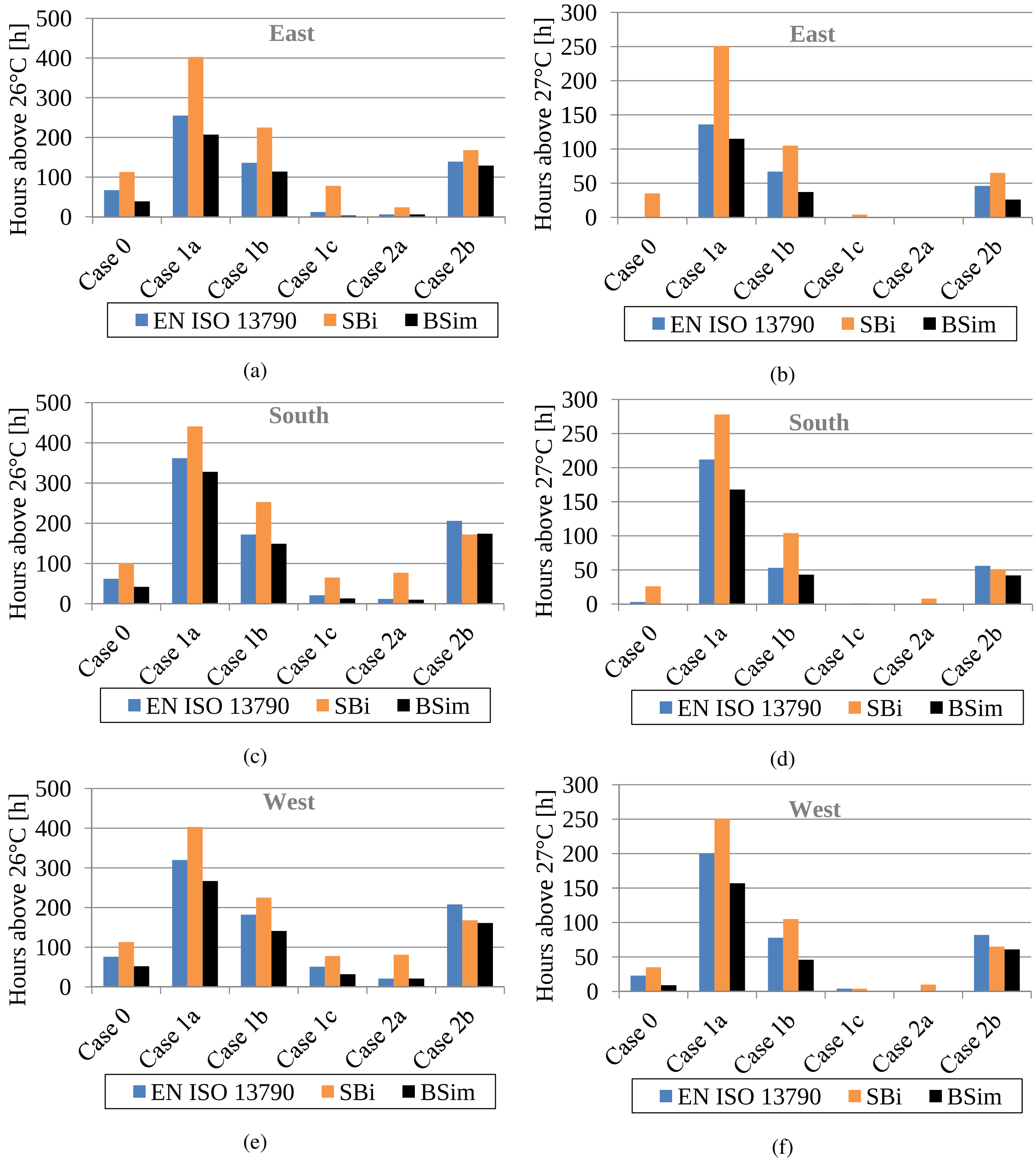
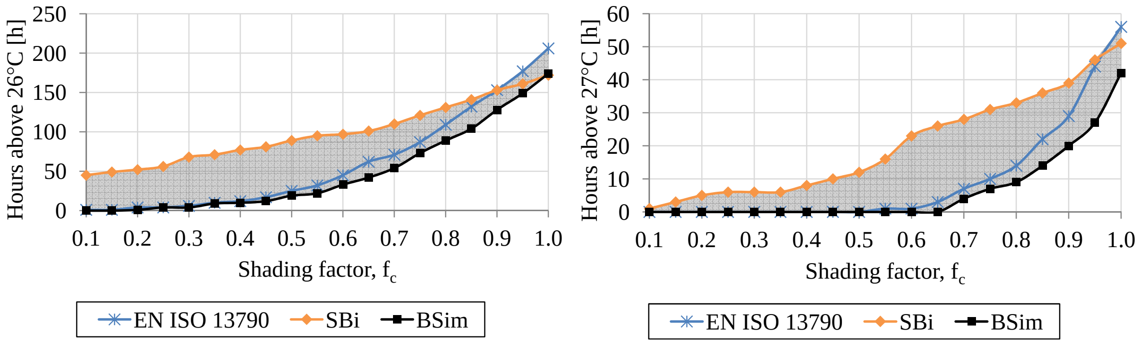


Figure 5.13: *Prediction of overheating in the reference building (case 0) by using different solar algorithms in several case studies. The prediction of overheating is expressed in hours with operative temperatures exceeding 26°C and 27°C for windows orientated towards east (a,b), towards south (c,d) and towards west (e,f).*

The difference between solar algorithms reveals the same trend for various thermal capacities. By focusing on case 2 regarding solar shading factor, a significant difference in results is experienced as the SBi simplified solar algorithm deviates +67 and -2 hours above 26°C from BSim for a south-facing window, when utilising a shading factor of 0.4 and 1.0 respectively. The trend of this deviation is substantial, as the largest absolute deviation appears for the lowest amount of hours with excessive operative temperatures.

In order to perform a thorough analysis of the effect in excessive operative temperatures by varying shading factor, results of SBi simplified model with SBi and EN ISO 13790 solar algorithms and BSim respectively, utilising various shading factors are illustrated in figure 5.14. This analysis only consider south-facing windows of the reference building as shading factor experienced the largest variations for this orientation.



(a) (b)

Figure 5.14: *Prediction of overheating in SBi simplified model for the reference building (case 0) with windows orientated towards south by using SBi and EN ISO 13790 solar algorithms along with BSim. The prediction of overheating is expressed in hours in hours with operative temperatures exceeding 26°C (a) and 27°C (b).*

The deviation between SBi solar algorithm and BSim, expressed with grey transparent colour in figure 5.14, emphasises an unequal importance of shading factor, as the result of BSim is rather sensitive compared to results of SBi solar algorithm. This fact is supported by the sensitivity analysis conducted in section 5.2, cf. table 5.11. The reason for the distinct importance of solar shading is a combination of different calculation of solar heat gains and their hourly distribution. As the SBi solar algorithm applies monthly shading factors, a different annual solar heat gains is obtained for varying shading factor, cf. figure 5.15.

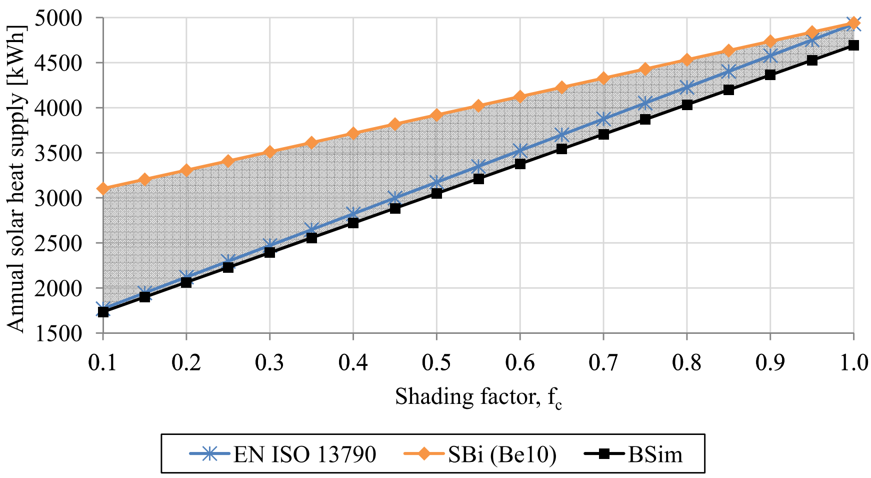
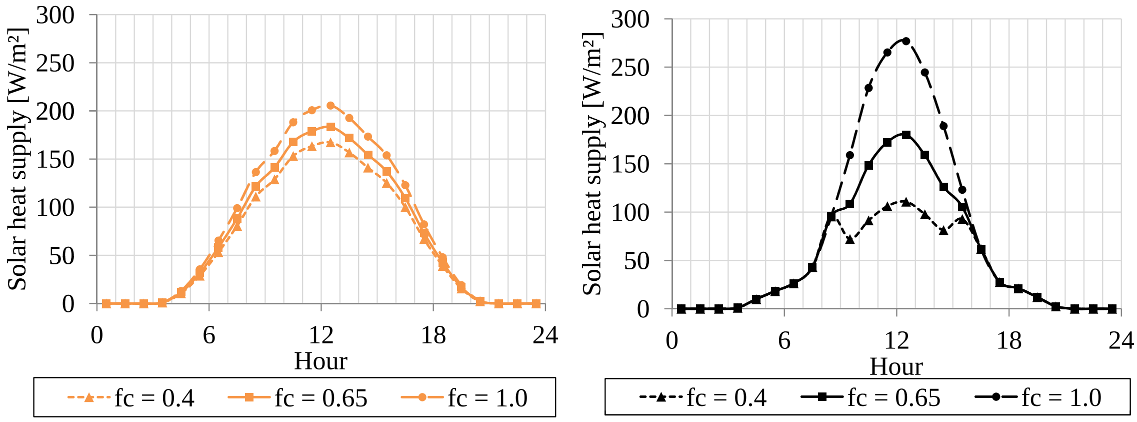


Figure 5.15: *Annual solar heat gains for the reference building (case 0) with windows orientated towards south by using SBi and EN ISO 13790 solar algorithm along with BSim using Perez' solar algorithm according to shading factor variations.*

As the annual solar heat gains vary significantly for various shading factors, this deviation affects the hourly values. SBi solar algorithm distributes aggregated solar heat gains, cf. figure 5.16(a), and a difference will occur as BSim solely decreases the solar heat gains when these excess the solar shading set-point, cf. figure 5.16(b). This is illustrated in figure 5.16 for varying solar shading factors.



(a) (b)

Figure 5.16: *Averaged daily profiles of solar heat gains during week 23 for the reference building (case 0) with windows orientated towards south by using SBi (a) and BSim (b) solar algorithm according to different applied shading factor.*

The investigation emphasises an additional disadvantage in using hourly distribution of monthly aggregated solar heat gains, as peaks which are sensitive to the shading factor are decreased and rather incorrect calculation of the hourly solar heat gains will be obtained.

As a general conclusion, the determination of hourly solar heat gains utilised in SBi simplified model implies a substantial error to the final output, as it possibly can affect whether or not the building requirements regarding the risk of overheating are fulfilled. The largest errors are experienced when efficient solar shading is applied, because of the monthly aggregated implementation of its hourly affect on operative temperature is implemented.

5.3.3 Internal heat gains

There are two approaches of accounting internal heat gains in the models, i.e. specified in SBi 213, [SBi-anvisning 213 2008], and recommended in standard EN ISO 13790 [2008]. SBi 213 specifies internal heat gains by using average building values for people and appliances, i.e. 1.5 $^{W}/_{m^2}$ and 3.5 $^{W}/_{m^2}$ respectively, with constant daily profiles. In contrary, the approach recommended in EN ISO 13790 standard distinguishes two types of rooms with different purposes, i.e. living room/kitchen with great daily heat load and usage mainly during daytime-evening and other types of room with rather modest daily heat load and night time usage, cf. table 4.4. Furthermore weekly average values in both approaches vary significantly. All above mentioned differences have a large impact on models output, see figure 5.17. Note, that in this case living room/kitchen is considered as a critical room and simulations were done for reference building, cf. section 5.1.

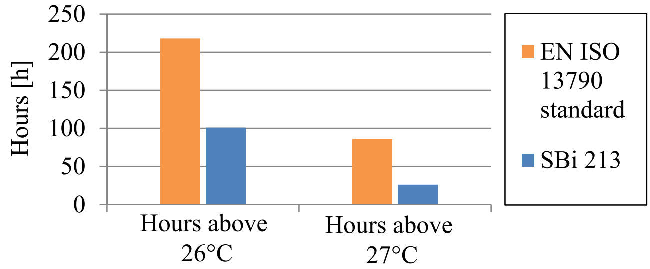


Figure 5.17: *Number of hours with operative temperature above 26°C and 27°C calculated by means of SBi simplified model. Internal heat gains daily profiles from EN ISO 13790 and SBi 213 are utilised for living room/kitchen.*

It is therefore necessary to investigate what influence is of high importance, i.e. daily profile or/and average weekly value, and choose the most realistic internal heat gains approach for usage in every model for further comparison of models in chapter 6.

Influence of daily profile

In order to find out how important is daily profile for models output an investigation was done by using the same average magnitude of internal heat gains, i.e. 5 $^{W}/_{m^2}$, with different profiles. One constant profile is suggested by SBi 213 and two profiles are suggested by EN ISO 13790 standard - for living room/kitchen and other rooms. Results from two simplified models are reflected in figure 5.18.

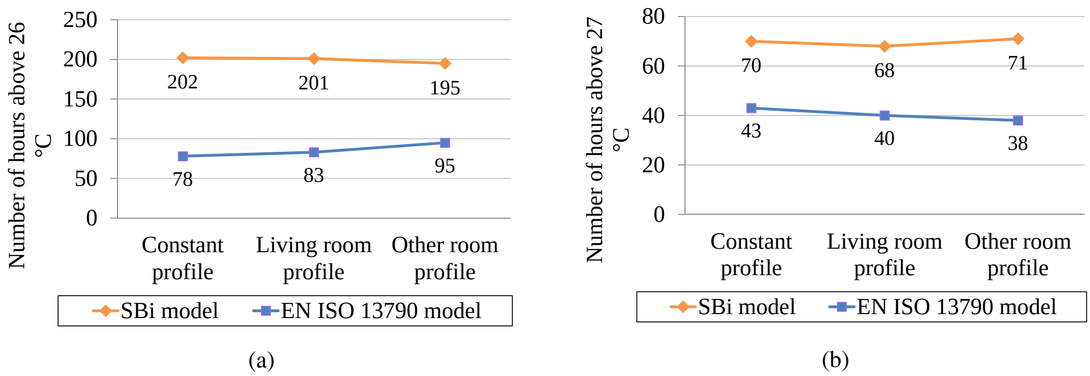


Figure 5.18: *Output of models with the same magnitude of internal heat gains but different daily profiles regarding number of hours above: 26°C (a) 27°C (b).*

Results in figure 5.18 indicate about a negligible influence of the daily profile on models output. Therefore the major contributor to diverse results obtained in figure 5.17 is the average magnitude of internal heat gains, which is investigated in next paragraph.

Influence of internal heat gains magnitude

In order to study the influence of internal heat gains magnitude on models output as well as to find the optimal magnitude the following investigation is performed, see full description of investigation in section N.4. By using statistical data covering all Danish detached houses an average number of residents was revealed - 2.62. Based on this number and other statistical references regarding occupancy patterns in danish detached houses a weekly profile was established. It was thus necessary to split occupancy profile valid for entire dwelling into two types of rooms, i.e. living room/kitchen and other rooms. An assumption was then applied stating that 70% of all non-sleeping time occupants spend in living room/kitchen, whereas the rest in other rooms. An estimate of heat production of adult occupant was made depending on spaces occupied, based on common activities in dwelling described in ASHRAE [2009], resulted in 123.8 W for living room/kitchen and 76.9 W for other rooms. By use of average net floor areas 182 m^2, 78 m^2 and 103 m^2 corresponding to entire dwelling, living room/kitchen and other rooms respectively the average magnitude of internal heat gains was calculated, see figure 5.19.

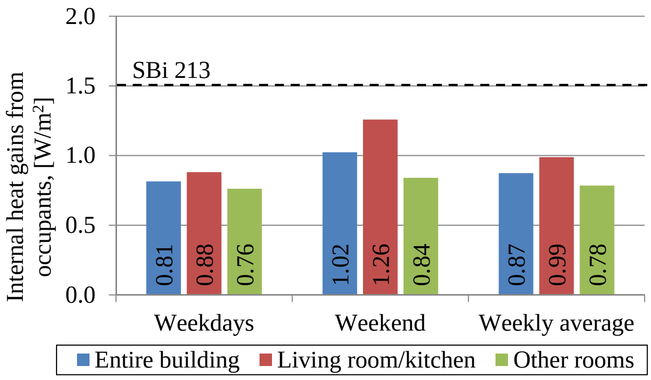
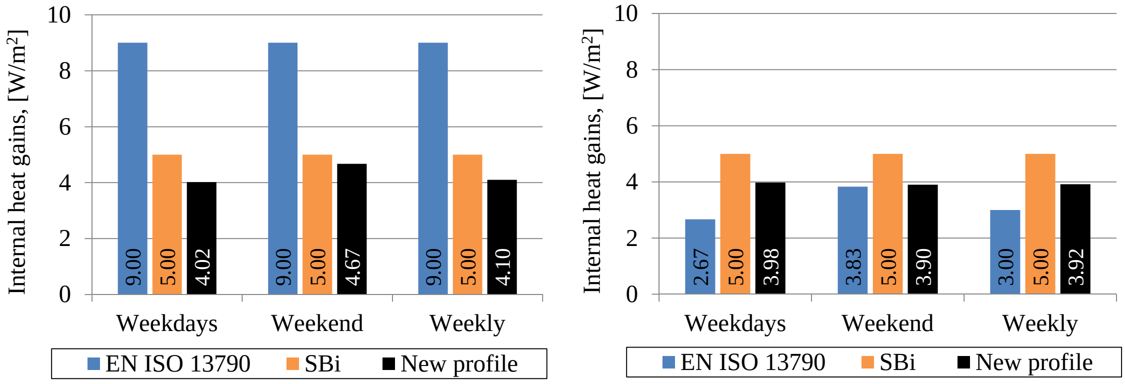


Figure 5.19: *Average internal heat gains from occupants depending on the spaces occupied.*

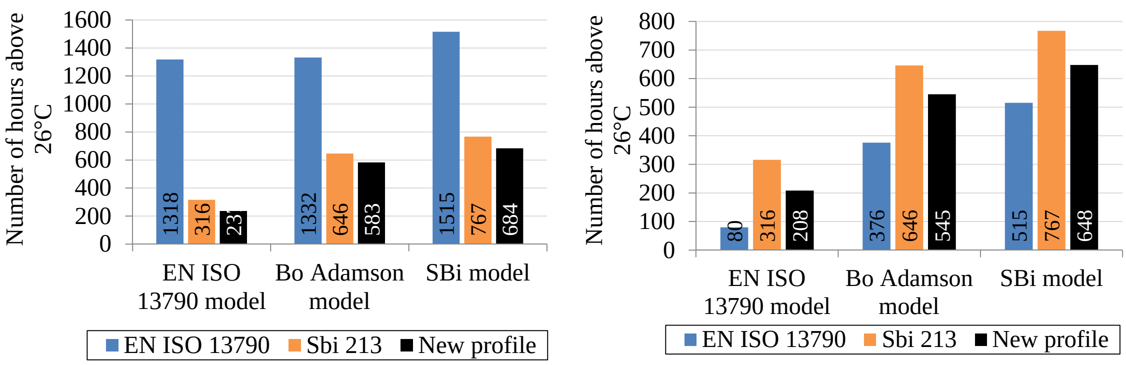
Obtained internal heat gains from figure 5.19 are very close to ones used in SBi 213. Internal heat gains from appliances were found by using equation (N.3), which estimates annual electricity consumption in dwellings based on residents number and net dwelling area. The internal heat gains from appliances were calculated to 3.06 $^{W}/_{m^2}$ for both weekdays and weekend, corresponding to 2.62 residents and net dwelling area of 182 m^2. This value is again close to one used in SBi 213, i.e. 3.5 $^{W}/_{m^2}$, though as in case of internal heat gains from occupants is also slightly lower. The total calculated internal heat gains are reflected in figure 5.20. Obtained results for new profile are rather close to SBi 213 values, whereas internal heat gains from EN ISO 13790 standard have around 100% higher magnitude compared to new profile in case of living room/kitchen and approximately 50% lower magnitude in case of other rooms.



(a) (b)

Figure 5.20: *Comparison of average values of internal heat gains for: living room/kitchen (a), for other rooms (b).*

To make a final conclusion whether the EN ISO 13790 or SBi 213 internal heat gains calculation approach is more optimal, the result of their performance is compared with performance of the new profile regarding the number of hours above 26°C of operative temperature as this is the output of the reviewed simplified simplified models. For both SBi 213 and new profile a constant daily profile is utilised, whereas for EN ISO 13790 approach two different profiles are utilised, i.e. for living room/kitchen and other rooms. Figure 5.21 shows results of three simplified simplified models with respect to three internal heat gains profiles, i.e. EN ISO 13790, SBi 213 and the new profile respectively.



(a) (b)

Figure 5.21: *Comparison of internal heat gains profiles regarding the number of hours above 26°C of operative temperature for: living room/kitchen (a), other rooms (b).*

There is a strong correlation between figures N.9 and 5.21, which indicates that overheating in critical room is proportionally dependent on the magnitude of average internal heat gains, whereas daily profile has negligible influence on overheating. Based on this the internal heat gains specified in SBi-anvisning 213 [2008] are evaluated to the most optimal ones and will be implemented in all simplified simplified models for further models comparison in chapter 6.

5.3.4 Thermal capacity

It was expected that a thermal capacity is within the most important parameters influencing thermal comfort. However, according to results of SA, cf. section 5.2, it is noteworthy only in EN ISO 13790 simplified model, whereas in others models it has rather modest importance. The fact that in EN ISO 13790 simplified model the thermal capacity is of higher importance than in other models can be explained by higher use of thermal mass temperature node as additional heat gains and heat loss by transmission are affecting this node, see figure F.3 in appendix.

All three previously reviewed simplified models possess different thermal capacity calculation algorithms, i.e. in SBi simplified model an estimated thermal capacity should be typed in, whereas other models use embedded calculation algorithms. Both EN ISO 13790 and Bo Adamson simplified models utilise simplified methods, respectively simplified method from EN ISO 13786 [2007, Annex A] described in section **??** and method from Danvak ApS [1987] described in section G.1 in appendix.

In order to proceed with models comparison in chapter 6 all models should have the same calculated thermal capacity of the reference building, described in section 5.1, to avoid effect of varying thermal capacity in different models. Therefore a comparison and analysis of different simplified calculation approaches is made by utilising a detailed calculation approach, described in standard EN ISO 13786 [2007].

Four cases intended for investigation of different building construction elements are established as described in table L.3 in appendix. They are made in accordance with description of different types of building constructions in table L.2 and can be categorised in four types, i.e. very light, light, heavy, very heavy. Results of thermal capacity calculation for these four types of building constructions are reflected in figure 5.22.

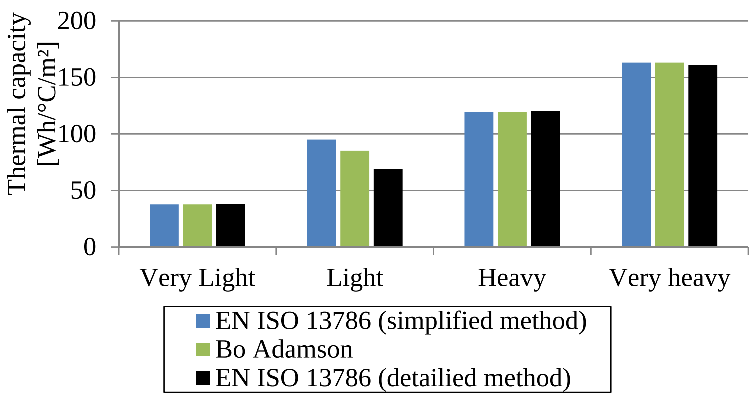


Figure 5.22: *Results of thermal capacity calculation for different types of building constructions. Construction components are described in appendix L.3*

During this comparison some weaknesses of simplified methods were revealed, which resulted in deviation of calculated thermal mass from EN ISO 13786 detailed method for light, heavy and very heavy construction types, especially in case of EN ISO 13786 simplified method. Unlike the EN ISO 13786 detailed method, which utilises heat transfer matrix of a building component from surface to surface, simplified methods require material thermal properties of only an accumulation layer, which is determined by the position between internal surface and insulation layer. Approximation of thermal capacity in simplified methods is based on determination of the penetration depth and subsequently thickness of accumulation layer. Simplified method specified in EN ISO 13786 standard approximates accumulation layer thickness based on ζ, see equation (5.4) and section **??**. Bo Adamson simplified method splits all materials in light and heavy with respective maximum accumulation layer thicknesses of 50 mm and 100 mm, which, in fact, is only one of the five criteria of accumulation layer thickness determination, see section G.1..

$$\zeta = \frac{d}{\delta} \tag{5.4}$$

ζ	Ratio of material thickness to penetration depth, $[-]$
d	Thickness of an internal layer, [m]
δ	Periodic penetration depth of a heat wave in a material, [m]

Further in the report three building construction components are used, where one material layer is varied from 5 mm to 300 mm, cf. table 5.16, in order to analyse where simplified methods do wrong approximations.

External wall		**External wall**		**External wall**	
Material	Thickness, [m]	Material	Thickness, [m]	Material	Thickness, [m]
Light-weight concrete	0 - 0.3	Concrete	0 - 0.3	Brick	0 - 0.3
Stone wool 39	0.2	Stone wool 39	0.2	Stone wool 39	0.25
Wood	0.03	Wood	0.03	Brick	0.108

Table 5.16: *Building construction components with one varying material layer.*

Results of comparison of simplified methods with detailed method are illustrated in figures 5.23 - 5.25. In case of light-weight concrete, cf. figure 5.23, both simplified methods do good approximations of thermal capacity until 50 mm thickness, whereas for thicker material simplified method specified by EN ISO 13790 standard is overestimating and Bo Adamson method is underestimating thermal capacity. Deviations of both simplified methods are significant. Bo Adamson method implies 50 mm maximum thickness of accumulation layer for light materials group, which light-weight concrete was decided to be referred. At the same time in EN ISO 13786 simplified method 100 mm thickness is used as a maximum thickness due to effective thickness assumption, see case B section **??**. Furthermore, EN ISO 13790 simplified method uses another assumption for accumulation layer, when thickness of light-weight concrete becomes more than 180 mm (2*ζ=180 mm, case C section **??**), i.e. assumption which utilises solely penetration depth, which results in lower accumulation thickness and subsequently thermal capacity. The decrease of thermal capacity after material thickness 0.11 m calculated by EN ISO 13786 detailed method is caused by the flow of previously stored energy out of the material and interaction with inflowing heat, [Ma and Wang 2012].

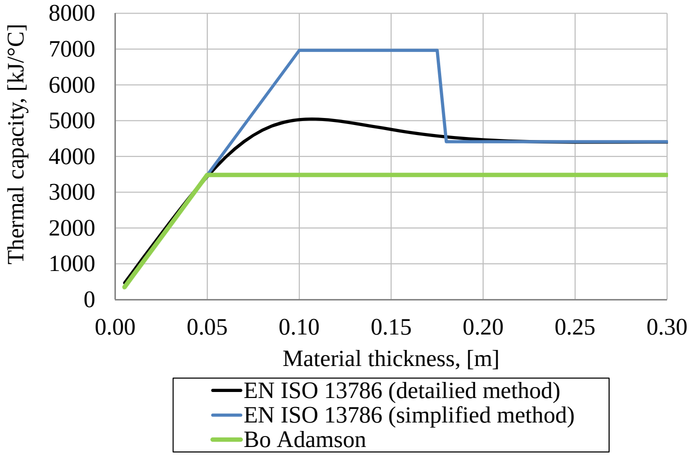


Figure 5.23: *Comparison of thermal capacity calculation methods depending on thickness of light-weight concrete.*

Both simplified methods approximate well building construction component with varying concrete layer, cf. figure 5.24. There is an underestimation, when concrete thickness becomes thicker than 100 mm, which can occur in floor slabs.

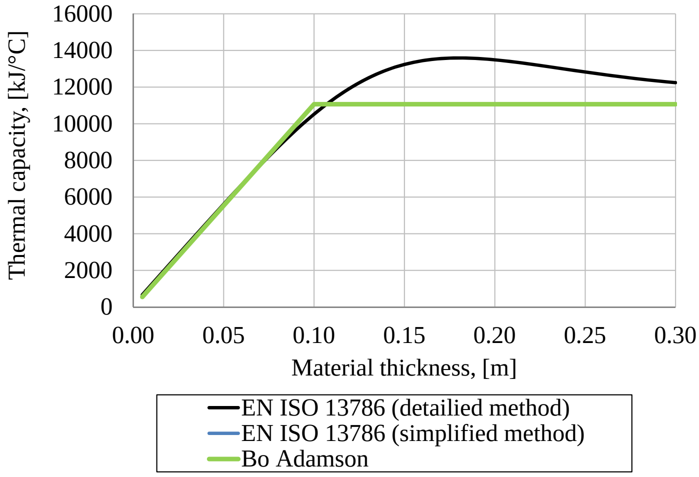


Figure 5.24: *Comparison of thermal capacity calculation methods depending on thickness of concrete.*

There is also another good approximation of thermal capacity of both simplified methods regarding building construction component with varying bricks layer. In this case, however, the thickness of bricks has a particular magnitude and it is limited by brick format in different countries. In Denmark standard thickness of brick layer is 108 mm, [tænk i tegl], therefore approximated thermal capacity should be examined for this thickness.

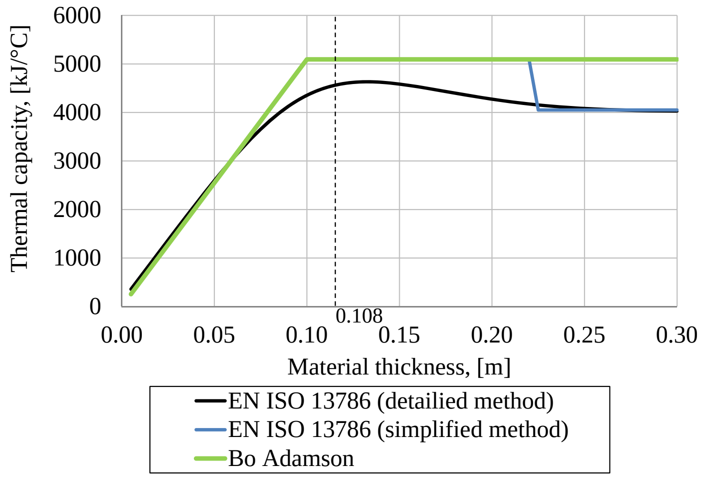


Figure 5.25: *Comparison of thermal capacity calculation methods depending on thickness of brick.*

The most significant deviation of simplified methods from detailed method occurs when light-weight concrete appears, up to 50%, while for bricks and concrete with 50 - 100 mm thickness approximated thermal capacity shows acceptable agreement with detailed method. For concrete deviation enhances for heavy components with big concrete thickness, like floor slabs. However, taking into account results in figure 5.22 it was decided to use detailed method for calculation of thermal capacity for all simplified models in chapter 6 to avoid incorrect thermal capacity values.

5.3.5 Specific heat loss by transmission

All three simplified simulation simplified models utilise the calculation algorithm described in appendix M for determination of the specific heat loss by transmission. However, SBi simplified model preliminary utilise this calculation algorithm for the opaque construction of the entire building intended for energy calculation purposes and subsequently divides it for the critical room according to the relative floor area. Thus, some uncertainties are connected to the transmission heat loss in this simplified simulation simplified model. This can be explained by the desire to reduce the amount of input data in the model, cf. subsection 4.3. The drawback of this approach is an error in result due to diverse location of critical room in the building, cf. figure 5.26, in which the areas remains the same. In contrast, due to the important determination of solar heat gains affecting the critical room, the specific heat loss by transmission through windows is correctly implemented, simply by selecting the windows attached to the critical room in the window tab in Be10.

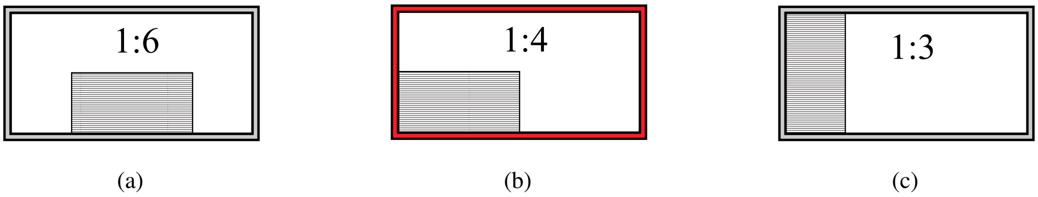


Figure 5.26: *Different plan views of single-family houses with a critical room having one external wall (a), two external walls (b) and three external walls (c). Red colour indicates the plan utilised by SBi model for transmission heat loss calculation.*

If the correct thermal transmission area of the critical room should be implemented in the forthcoming version of Be10, it needs the same approach as for applying windows. Although, this requires that thermal transmission areas for different external surfaces are divided manually by the user which will affect the unambiguity and reproducibility of the simplified simplified model. Furthermore, according to the sensitivity analysis, the factors affecting the specific heat loss by transmission are not of significant importance in building thermal simulations intended for determination of excessive temperatures. This can be explained by the often not very variable and sensitive factors for a design building among the building geometric and envelope thermal properties factors as certain tolerances must be fulfilled in the workmanship. For this reason, the specific heat loss by transmission will not be further investigated in this thesis.

Chapter 6

Evaluation of models calculation procedures

In order to examine the influence of simplifications and differences incorporated in calculation procedures of simplified models an evaluation is undertaken in current chapter. This is performed by means of singe and combined input parameter case study, where the reference building described in section 5.1 is utilised as a base case. In addition, a theoretical Building Energy Simulation TEST (BESTEST) is executed, where four free-float test cases are used in order to reveal an influence of simplifications applied in the simplified models.

6.1 Evaluation of simplified models by means of case studies

6.1.1 Limited input versus detailed input

It was previously investigated how the complexity of the input influences several components of simplified calculation procedures, i.e. specific heat transfer between room air and internal surfaces and thermal mass and internal capacity, cf. subsection 4.2.4. These differences are valid only for EN ISO 13790 and Bo Adamson simplified models, since SBi simplified model originally possesses limited input in order to be attractive for the users in terms of speed and convenience. Although simplified models with limited input are under the attention in the current project due to its scope, detailed input of the models is also reviewed, since its increased accuracy can outweigh models simplicity in case of limited input. Results of calculated specific heat transfers via limited and detailed input for the reference building are illustrated in figure 6.1.

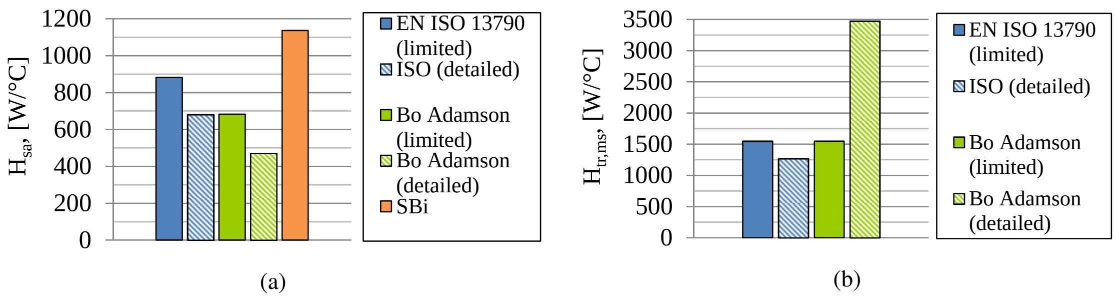


Figure 6.1: *Calculated specific heat transfer between room air and internal surfaces (a) and between internal surfaces and thermal mass (b) by means of simplified models with limited and detailed input. Case - reference building, see description in section 5.1.*

Specific heat transfer between room air and internal surfaces in SBi simplified model is dominating among others, cf. figure 6.1(a). It is calculated via equation H.1, where heat transfer coefficient was manually developed by SBi taking into account allocated furniture inside the critical room, [Aggerholm 2013]. Noteworthy is that according to figure 6.1(a) use of detailed input results in lower heat transfer. It is due the fact that surface-to-floor dimensionless ratio in reference building equals to 3.6, which is lower than suggested 4.5 in EN ISO 13790 standard. Specific heat transfers between thermal mass and internal surfaces according to figure 6.1(b) are significantly different between EN ISO 13790 and Bo Adamson models with detailed input, as they utilise different equations for treatment of material properties. However EN ISO 13790 model does not experience such a large drop as Bo Adamson model when limited input is utilised, because HTCs used were developed and adapted for this model. For Bo Adamson model difference in using limited and detailed input for specific heat transfers between thermal mass and internal surfaces can lead to significant consequences in output, though no other alternative simplified methods were found.

6.1.2 Single input parameter case study

In this section the precision of simplified models is investigated by means of different cases, modified from the reference building (case 0). Five building input parameters are varying throughout the case study, namely building thermal capacity, solar shading factor, room height, window thermal transmittance and ventilation rate. All these input parameters represent user input, which modeller can vary depending on his own estimation as well as building specifications. Furthermore, summer ventilation rate, solar shading and thermal capacity are among the most important input parameters according to the sensitivity analysis result, cf. table 5.11. Room height variation is not accounted in simplified models with limited input, cf. figure 6.1(a), thus it is important to estimate the magnitude of the error regarding this issue. As regards to window thermal transmittance, the main purpose of including it in current comparison is to check the behavior of SBi simplified model, in which, unlike the other simplified models, transmission heat losses directly influence room air temperature, see subsection 4.2.6. Parameters specifying different conditions of cases are described in table 6.1. Different total building thermal capacities were previously calculated for different building classes in subsection 5.3.4. In case 3a the lowest allowed room height in dwellings is chosen according to Danish Energy Agency [2010, section 3.3.1.(5)]. The same applies for case 4b, where the highest allowed window thermal transmission is chosen, [Danish Energy Agency 2010, section 7.3.2.(1)].

Case	Description	Thermal capacity C_m, $[{}^{Wh}/_{°C\,m^2}]$	Shading factor f_c, [-]	Room height h, [m]	Window thermal transmission U_w, $[{}^{W}/_{m^2\,°C}]$	ventilation rate q_{ve}, $[{}^{l}/_{s\,m^2}]$
0	Reference building	120	0.65	2.7	1.2	2.4
1a	Extra light construction	**38**	0.65	2.7	1.2	2.4
1b	Light construction	**69**	0.65	2.7	1.2	2.4
1c	Extra heavy construction	**161**	0.65	2.7	1.2	2.4
2a	Efficient solar shading	120	**0.40**	2.7	1.2	2.4
2b	No solar shading devices	120	**1.00**	2.7	1.2	2.4
3a	Low room height	120	0.65	**2.3**	1.2	2.4
3b	High room height	120	0.65	**3.1**	1.2	2.4
4a	Low window thermal transmission	120	0.65	2.7	**0.6**	2.4
4b	High window thermal transmission	120	0.65	2.7	**1.8**	2.4
5a	Low ventilation rate	120	0.65	2.7	1.2	**2.0**
5b	High ventilation rate	120	0.65	2.7	1.2	**2.8**

Table 6.1: *Description of conditions in single input parameter case study. Numbers marked with bold font are different in particular case from case 0 (reference building, see description in section 5.1).*

Results of simplified models are compared with BSim, which in the present thesis is assumed to give a reasonable approximation of reality. It was previously investigated that EN ISO 13790 simplified model predicts significantly lower operative temperatures by employing Crank-Nicolson numerical method comparing to Euler (forward) method, cf. chapter P, therefore both of them present in current comparison in order to check which shows better fit with reality. There are different simplifications applied in simplified models, for example simplified treatment of shortwave and longwave radiation inside the thermal zone, cf. subsection 4.2.5, lumped capacitances, which are possible to implement in BSim by setting up more complex, physically realistic model. Furthermore, the transient conduction in BSim building materials is utilised in another and more complex way, i.e. by using Finite Volume Method (FVM) and dividing building materials into various control volumes, [SBi 2004b]. In addition it is possible to vary number of time steps and thus increase the precision of the output. For presented cases 32 time steps per hour is sufficient, according to analysis of the time steps influence executed in appendix I.1.

The results of single case study are shown in figure 6.2. EN ISO 13790 model with Crank-Nicolson numerical method calculates operative temperatures systematically lower than BSim and therefore is not commented in this section.

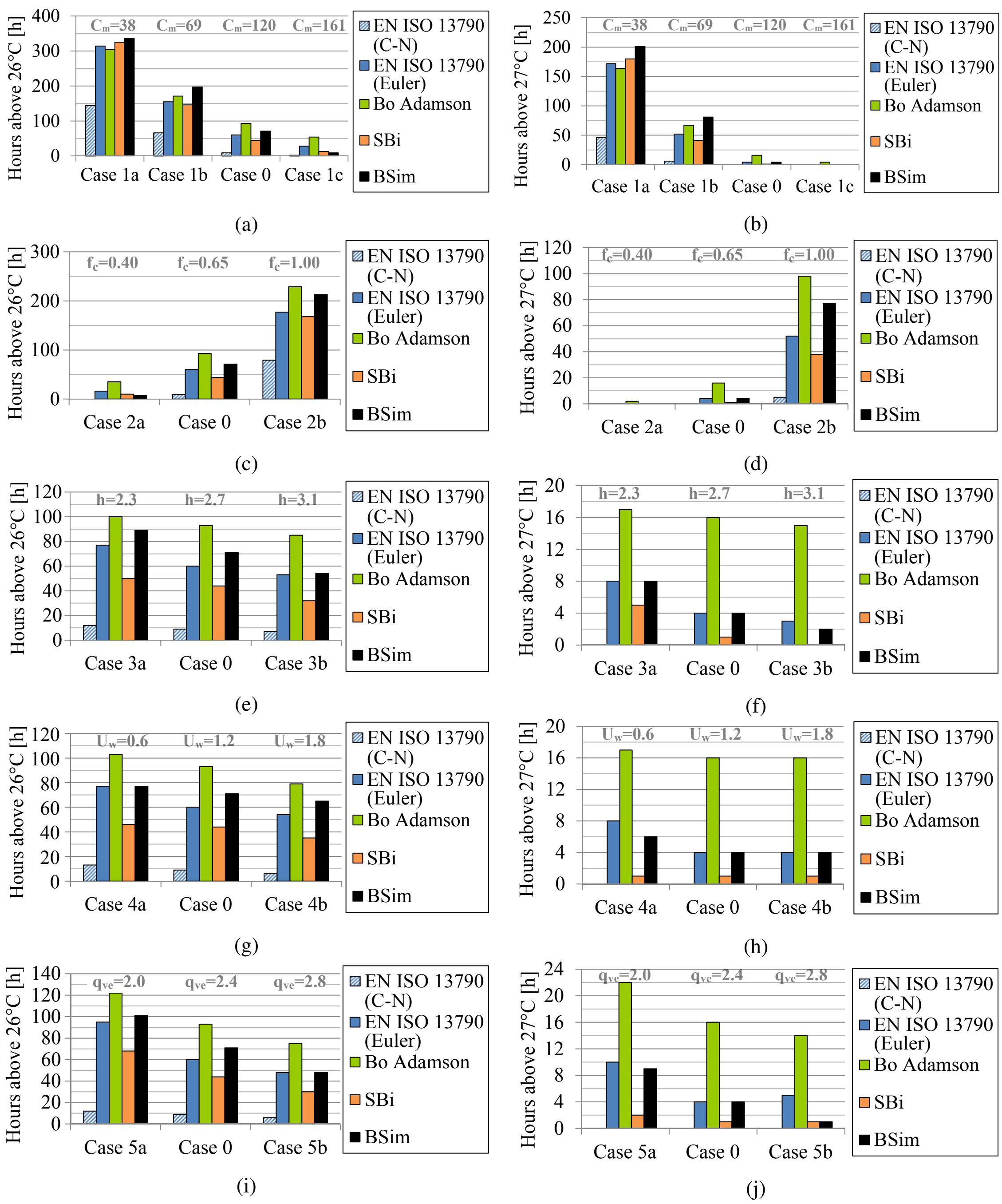


Figure 6.2: *Comparison of simplified models and BSim for case 1-5. Output is expressed in hours with operative temperature above 26°C (a,c,e,g,i) and 27°C (b,d,f,,h,j). Case - reference building.*

In general it was observed that Bo Adamson simplified model overestimates the result, which is likely due to lowered specific heat transfer between internal surfaces and thermal mass comparing to the model, but with detailed input, cf. subsection 6.1.1, whereas SBi simplified model makes underestimation. However these trends apply mainly for heavy building construction class, cf. figures 6.2(a) and 6.2(b), and since it is the building class for the reference building these trends are spread among the other cases as well. For different building thermal capacities simplified models show diverse behaviour. SBi simplified model performs better for extreme building thermal capacity, i.e. very light and very heavy building constructions. Unlike Bo Adamson simplified model, which in case 1 is subjected to substantial variations, EN ISO 13790 Euler simplified model shows moderate deviations from BSim.

Analysis of case 2 reveals the precision of simplified models with regards to varying solar shading factor. Results in figures 6.2(c) and 6.2(d) indicate following trends: as more efficient is solar shading as better agreement of SBi simplified model and BSim, whereas opposite applies for Bo Adamson simplified model. Again, as in case 1, EN ISO 13790 model shows moderate deviations from BSim.

Results regarding case 3, cf. figures 6.2(e) and 6.2(f), indicate that room height influences the output of models, though in a diverse way, since they utilise simplified coefficients of calculating precise surface-to-floor ratio.

Case 4 demonstrates low sensitivity of SBi simplified model to changes of the window thermal transmittance as well as very high underestimation, cf. figures 6.2(g) and 6.2(h). Such a low sensitivity can be explained by utilising heat flow path by transmission between external environment and room air, which differs from how transmission heat flow is treated in other simplified models.

Case 5 emphasizes again high importance of ventilation rates and in this case all models, except EN ISO 13790 Euler simplified model in case 5b demonstrate proportional results regarding ventilation rate variation.

Different thermal capacity allocation within thermal zone

Another difference in model output can occur for buildings with the same building thermal capacity, but its different allocation within the thermal zone, e.g. dominating floor or walls thermal capacity. It is not taken into account in simplified models as they operate using lumped thermal capacity, whereas BSim possesses such a distinction, where the modeller is required to set up the materials of each building construction element with respective areal thermal capacity. Furthermore, there is a detailed modelling of solar incidence beam with respect to internal surfaces by means of XSun tool incorporated in BSim.

In order to check how different BSim model performance is with respect to above mentioned issue case 6 is established. Both models have the same building thermal capacity, calculated via EN ISO 13786 detailed method, however different construction elements (only internal layers considered):

- Case 6a - ceiling, external and internal walls with light-weight concrete and floor with combination of tiles and concrete;
- Case 6b - ceiling with wood, external and internal walls with brick and floor with combination of tiles and concrete.

Detailed description of building construction elements can be seen in table L.5 in appendix. According to the above mentioned description model in case 6a has equal distribution of areal thermal capacity among walls and ceiling, whereas the model in case 6b has dominating areal thermal capacity of external and internal walls. In both cases floor construction is kept the same to emphasize the difference between walls and ceiling. Note, that both models possess building thermal capacity equal to 120 $^{Wh}/_{°C\,m^2}$ of heated floor area corresponding to heavy building class.

Result regarding case 6 is shown in figure 6.3 where the difference between two cases is approximately 15% and 30% for hours with operative temperature above 26°C and 27°C respectively. The distinct result indicates another drawback of simplifications implemented in models calculation procedures.

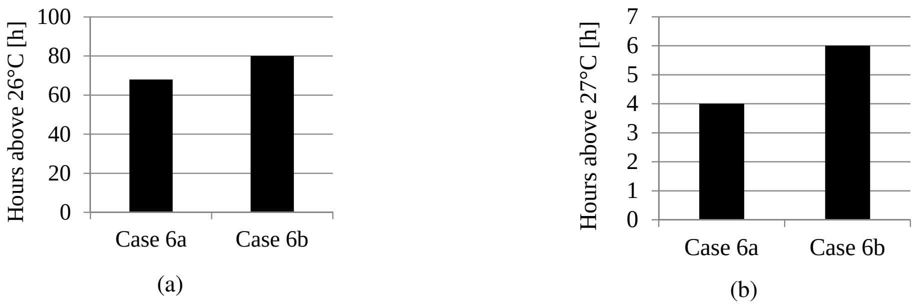


Figure 6.3: *Comparison of BSim model performance for case 6. Output is expressed in: hours above 26°C (a), hours above 27°C (b). Both models have the same total thermal capacity, but different areal thermal capacity of particular building elements.*

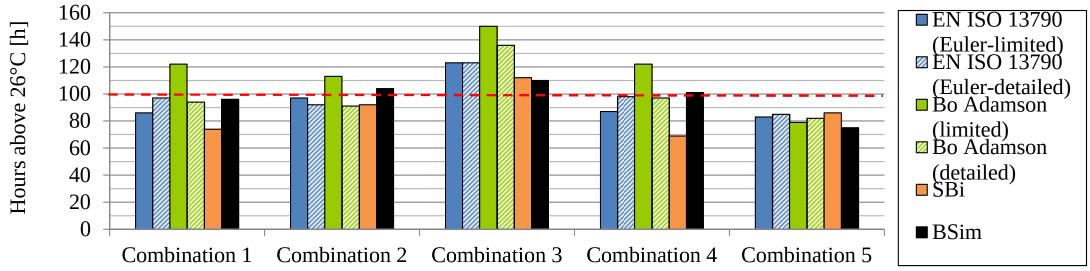
6.1.3 Combined input parameter case study

In order to further investigate the precision of the simplified models five combined cases are established with varying three most important parameters according to single input parameter study, i.e. building thermal capacity, solar shading factor and natural ventilation rate, cf. table 6.2. Combined cases represent future low-energy buildings with thermal environment close to one required in Danish BR2015. Note, that EN ISO 13790 model with Crank-Nicolson is not included in this comparison, as it systematically underestimates operative temperature. In order to emphasize the importance of complexity of models input data presented in subsection 6.1.1, it was decided to include Bo Adamson and EN ISO 13790 simplified models with detailed input.

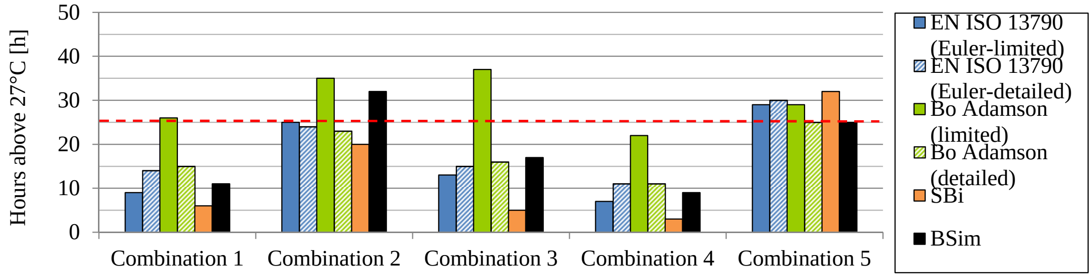
Case	**Thermal capacity** C_m, $[^{Wh}/_{°C\,m^2}]$	**Shading factor** f_c, [-]	**Ventilation rate** q_{ve}, $[^{l}/_{s\,m^2}]$
Combination 1	120	**0.75**	2.4
Combination 2	**69**	**0.50**	2.4
Combination 3	**161**	**0.80**	**1.80**
Combination 4	120	0.65	**2.00**
Combination 5	**38**	**0.20**	2.4

Table 6.2: *Description of varying parameters in different combined input parameter cases. Numbers marked with bold font are different in particular case from case 0 (reference building).*

Results of comparison via combined cases are illustrated in figure 6.4. In general, all simplified models had diverse performance comparing to BSim, with both over- and underestimations, although with some distinct trends. Comparing simplified models with limited input and BSim the same conclusion from single study applies here, i.e. in majority of cases Bo Adamson simplified model overestimates, SBi simplified model underestimates, whereas the result of EN ISO 13790 Euler simplified model is in between above mentioned models. It seems that for SBi simplified model very light and very heavy buildings are more favourable, combination 5 and 3 respectively, as for the light and heavy building it does significant underestimation, cf. combination 1, 2 and 4. A reason for underestimation of SBi simplified model result is partly specific heat transfer between internal surfaces and room air, which is higher that for other simplified models because of assuming presence of furniture inside the thermal zone, cf. figure 6.1(a).



(a)



(b)

Figure 6.4: *Comparison of simplified models and BSim for combined input parameter case study. Output is expressed in hours with operative temperature above 26°C (a) and 27°C (b). Red dashed lines indicate requirement regarding overheating in dwellings.*

The complexity of input has different impact of different simplified models. The reason for this is that simplified heat transfer coefficient between internal surfaces and thermal mass implemented in both EN ISO 13790 and Bo Adamson models was developed within EN ISO 13790 standard and it does a fine approximation for the corresponding model and too coarse approximation for Bo Adamson model, cf. figure 6.1(b). The consequences of simplifying input in Bo Adamson model are larger for building with high thermal mass, combination 3, and lower for building with low thermal mass, combination 5.

In this comparison simplified models intended for compliance with Danish BR2015 regarding the risk of overheating in dwellings are used. Therefore an important evaluation of simplified models precision is whether they fulfill or do not fulfill the requirement, see table 6.3. Although EN ISO 13790 Euler models with both simplified and detailed input showed better agreement with BSim results in figure 6.4, according to table 6.3 it is both Bo Adamson models which have more fulfillments of Danish BR2015.

	Combined 1	Combined 2	Combined 3	Combined 4	Combined 5
EN ISO 13790 (Euler-limited)	✓	✓	÷	✓	÷
EN ISO 13790 (Euler-detailed)	✓	✓	÷	✓	÷
Bo Adamson (limited)	÷	÷	÷	÷	÷
Bo Adamson (detailed)	✓	✓	÷	✓	✓
SBi	✓	✓	÷	✓	÷
BSim	✓	÷	÷	÷	✓

Table 6.3: *Models fulfillments of building requirements regarding risk of overheating in dwellings for each combined case.*

Based on results of single and combined case study several conclusions can be drawn. SBi simplified model in most of the cases underestimates the thermal environment in buildings comparing to BSim. Such a performance contradicts with the intention of SBi to be on the "safe side" when simplifications in the model were established, [Mortensen 2012, p. 8]. Results of both EN ISO 13790 Euler and Bo Adamson simplified models have in most of cases good agreement with BSim when detailed input is available, cf. figure 6.4, however for limited input, which is more preferable for compliance checking model, only EN ISO 13790 model demonstrates acceptable fit with BSim.

6.2 Evaluation of simplified models by means of BESTEST

6.2.1 Description of BESTEST

BESTEST (Bilding Energy Simulation TEST) is a benchmark for building energy simulation programs conducted by International Energy Agency (IEA). BESTEST includes comparative testing for entire building simulation programs and diagnostic methods, in order to diagnose sources of prediction disagreements, [Judkoff and Neymark 1995]. Different selected "reference" programs comprise the state-of-the-art of detailed building simulation capability in USA and Europe and used for comparison testing. They include BLAST, DOE2, ESP, SERIRES, S3PAS, TASE and TRNSYS, cf. subsection Q.1.1 in appendix. BESTEST includes set of cases intended for validation of particular features, such as thermal capacity, solar heat gains, window shading devices, venting and various thermostat controls, [NOËL 2004, p.6]. These cases are represented by a simple geometry building, cf. figure 5.1, varying different parameters from case to case. An advantage of using BESTEST for programs validation is that in each case one parameter or interaction of two parameters are isolated, so each case can distinctly show the weaknesses of the program. There are 14 qualification cases and four additional free-floating cases, where neither heating nor cooling systems are utilised. Since the simplified models reviewed in current work do not possess any heating or cooling systems and their respective controls, cf. section 4.3, it was decided to execute solely free-float cases which are described below. A detailed description of free-float cases can be found in appendix Q.2.

1. 600FF - lightweight building, which examines south solar transmission;
2. 650FF - lightweight building with additional air exchange, which examines venting;
3. 900FF - heavyweight building, which examines solar and thermal mass interaction;
4. 950FF - heavyweight building with additional air exchange, which examines venting and thermal mass interaction;

For all cases heat gains comprise fixed internal heat gains of 200 W and varying solar heat gains, whereas heat losses are different for 600FF/900FF and 650FF/950FF. The former includes heat losses by transmission and infiltration, while the latter includes heat losses by transmission, infiltration and ventilation. Weather used in BESTEST is described in appendix Q.1.2. It was necessary to implement calculated by BSim hourly solar incidence radiation into the simplified models as they do not possess the algorithm of calculating direct and diffuse solar incidence radiation on surfaces. BSim calculates solar incidence radiation with acceptable precision comparing to the reference programs, cf. appendix Q.1. In BESTEST only net areas are accounted for the heat transmission and room air temperature is used for comparison of results in free-float cases. In order to account only internal areas of building constructions for transmission losses calculation in BSim an option *Thermal Bridge* was unselected.

It is important to emphasize several assumptions associated with BESTEST. They refer to solar energy distribution within the room. BESTEST requires to use the programs with highest level of details and in case a program does not calculate internal solar energy distribution there are solar distribution fractions which can be inserted manually by the user, [Judkoff and Neymark 1995, table 1-9]. It is not possible to implement them in current simplified models as they originally incorporate solar distribution fractions in RC schemes, see section 4.2. However these fractions comprise solar distribution among either air or internal surfaces or/and thermal mass, whereas in BESTEST fractions specify distributions among different internal surfaces, which is not the case in simplified models which utilise lumped capacitance model and do not distinguish between different internal surfaces. Solar distribution algorithm used in BESTEST assumes that no solar radiation is directly absorbed by the zone air, [**?**, p.1-9], which contradicts with SBi simplified model as solar radiation is utilised solely by internal air in this model. Another assumption is that all incidence radiation is initially hitting the floor and then diffusely reflected onto other surrounded surfaces. This assumption emphasizes thermal capacity of floor as of highest importance. Description of simplified models and BSim used in BESTEST can be found in appendix Q.2.

6.2.2 Results

Results of the BESTEST in general indicate that simplified models do not possess sufficient accuracy comparing to the advanced reference programs. In contrary, in spite of some falls behind the range of BESTEST accuracy, BSim has showed a sufficient accuracy as illustrated in figure 6.5. The fairly accurate result of SBi simplified model in figure 6.5(a) is explained by the RC scheme the model is based on, where all heat gains and heat losses affect solely room air, which, in fact, is used in BESTEST evaluation. Furthermore, figure 6.5(c) shows that the differences in mean annual temperature among simplified models are negligible. It is important to mention, that there are no pass/not pass requirements in BESTEST. Instead, if the model performance is within the range of results from advanced "reference" programs, the model performance can be admitted as sufficient.

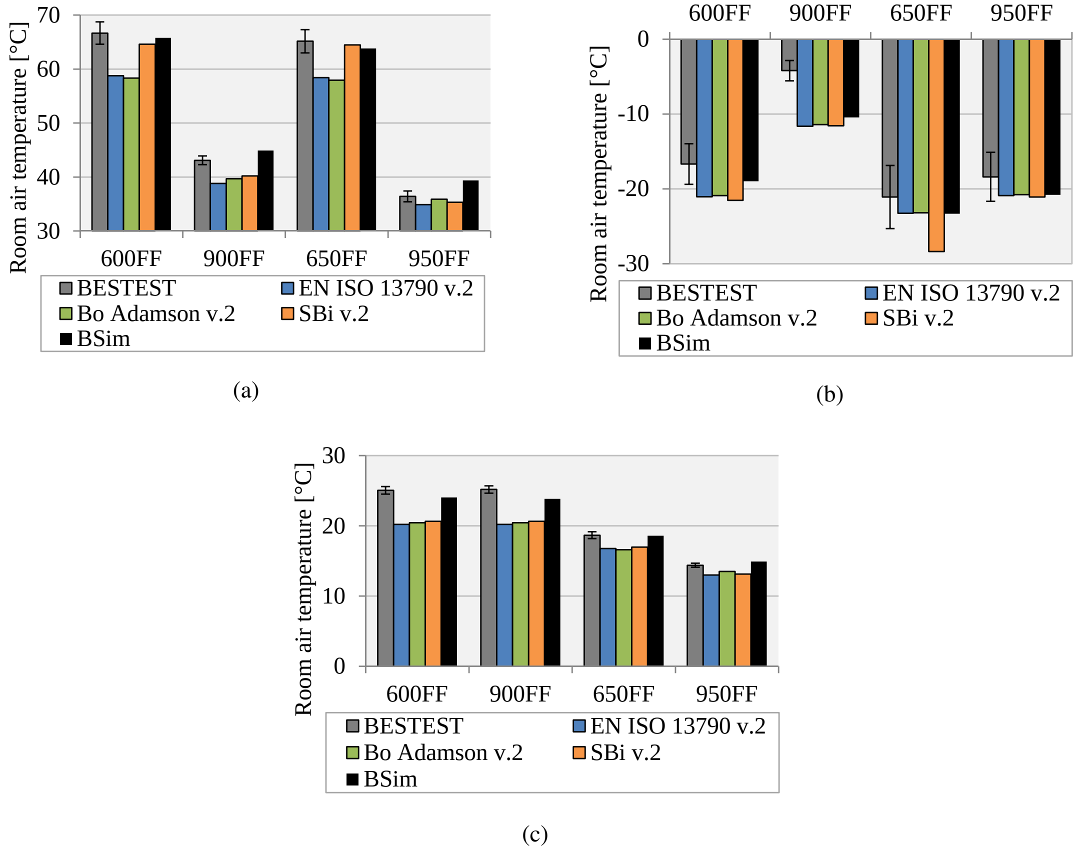


Figure 6.5: *Maximum (a), minimum (b) and average (c) hourly annual temperatures in BESTEST and simplified models together with BSim. Plus/minus standard deviation is used to indicate the range of BESTEST results.*

The biggest deviations of hourly room air temperatures between BESTEST and simplified models occur for test cases without venting, i.e. 600FF and 900FF, figures 6.6(a) and 6.6(b) respectively. However, for cases with venting, i.e. 650FF and 950FF a sufficient fit to BESTEST results is obtained, except the SBi simplified model, which falls behind the BESTEST range, cf. figure 6.6(c). Unlike the simplified models, there is strange result for hourly temperatures in BSim, especially in heavyweight test cases (900FF and 950FF), although the average annual temperatures are calculated with sufficient precision comparing to BESTEST, cf. 6.5(c).

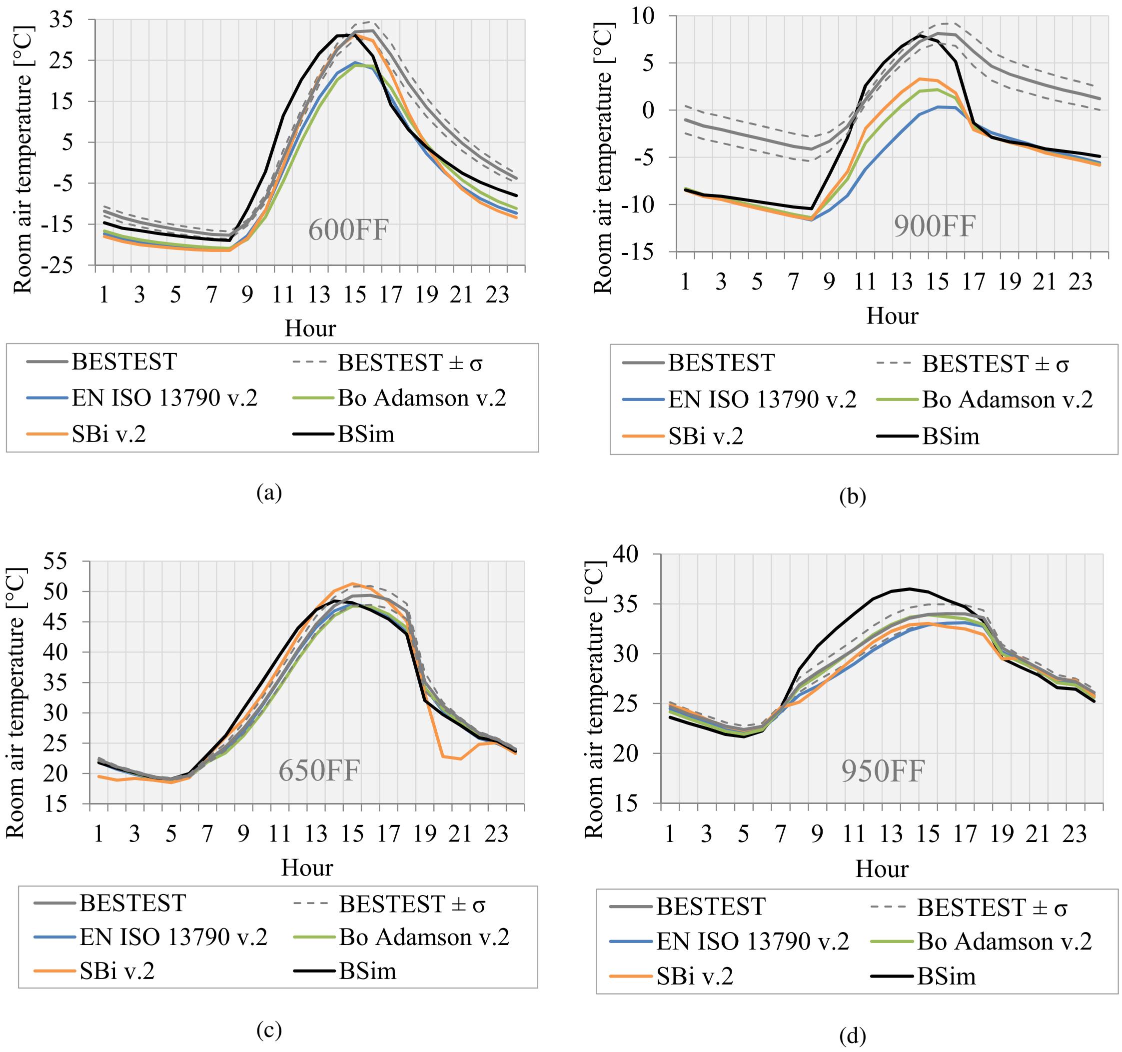


Figure 6.6: *Hourly free-floating room air temperatures valid for simplified models and BSim. Results are graphical shown for case 600FF during January 4th (a), for case 900FF during January 4th (b), for case 650FF during July 27th (c) and for case 950FF during July 27th (c). Plus/minus standard deviation is used to indicate the range of BESTEST results.*

Annual hourly 1°C temperature bin frequencies for test cases 900FF indicate a large deviation of temperatures between simplified models and BESTEST and rather lowest deviations among simplified models, see figure 6.7. Result from BSim is following the trend from BESTEST, although with higher fluctuations. Since test case 900FF examines solar and thermal mass interactions, simplifications within these two aspects are the main issues of significant underestimation from simplified models comparing to BESTEST. Calculated annual solar heat gains in simplified models and in BSim are 1024 $^{kWh}/_{m^2}$ and 933 $^{kWh}/_{m^2}$ respectively, which are within the range of BESTEST results, i.e. 914 - 1051 $^{kWh}/_{m^2}$. Therefore the treatment of shortwave radiation inside the room in conjunction with thermal capacity are the main issues of underestimated result from simplified models. Indeed, these processes are treated with large simplifications, cf. section 4.2.5 and appendix E.

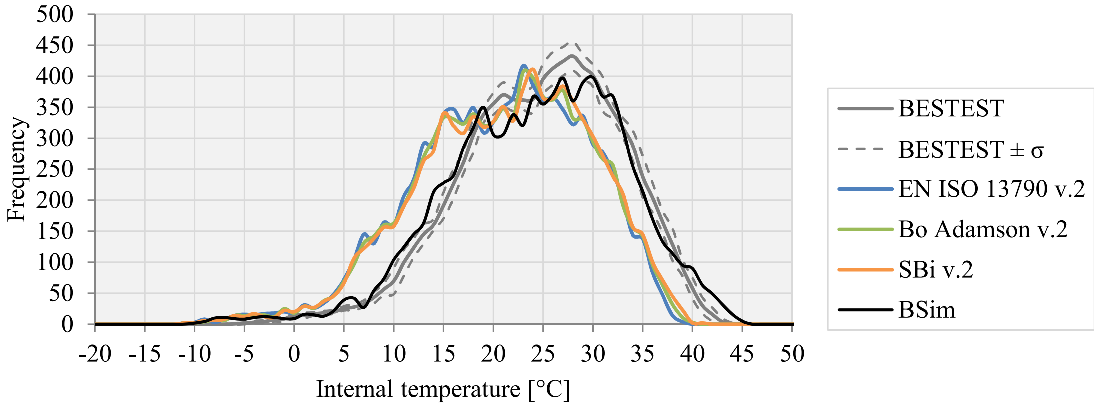


Figure 6.7: *Annual hourly 1°C temperature bin frequencies from -20°C to 50°C for case 900FF. Plus/minus standard deviation is used to indicate the range of BESTEST results.*

6.3 Summary

Current chapter examines the calculation procedures implemented in simplified models, where the behaviour of simplified models was found to be diverse and significantly varying both among single and combined input parameters case studies. A proper treatment of interior shortwave solar radiation was "tuned" differently among simplified models. For example, the most sophisticated flowpaths of shortwave solar radiation is realised in EN ISO 13790 model, which showed the most moderate deviations from BSim among other simplified models. During establishment of SBi simplified model the EN ISO 13790 simplified model was further simplified in order to be on the safe side, although the performance of SBi simplified model showed an opposite effect. Although Bo Adamson simplified model demonstrated a sufficient precision comparing to BSim when detailed input was utilised for calculation of specific heat transfer between internal surfaces and thermal mass, the focus in this project is on models utilising limited input.

Effect of simplifications incorporated in models calculation procedures was explicitly shown in BESTEST, which utilises rather theoretical conditions for test cases in order to emphasize of different effects, such as treatment of interior shortwave solar radiation or venting, etc. In all free-floating cases simplified models experienced a significant underestimation comparing to BESTEST result, especially for test cases without venting. This, again, indicates the significance of simplifications and assumptions utilised in models calculation procedures, such as lumped thermal capacitance, interior shortwave solar radiation and transient conduction in construction elements.

Chapter **7**

Evaluation of aspects of compliance checking model

In this chapter different simplified models with different complexity are evaluated from the perspective of application within the context of building regulations. The purpose of evaluation is to find the most attractive model regarding the aspects of compliance checking model, satisfying all interested parties, i.e. model users, local authorities, model developers and society. The current evaluation comprises three models, where one of them is the original SBi simplified model and two others are established based on investigations and evaluation in chapters 5 and 6 respectively.

7.1 Description of method

The method of evaluation is based on number of quality aspects of a model intended for compliance with building regulations requirements retrieved from EN ISO 13790 standard. The method and evaluation of simplified models are subjective as they are based on opinions of authors of the current thesis. Each participating model is evaluated according to each quality aspect with number of points ranging from 1 (bad) to 5 (good) and finally a summary outlines the most balanced model. Notice, that each quality aspect is of equal importance.

Aspects related to quality of the model intended for compliance with BR were first introduced for the reader in section 2.1.2 and they are illustrated in figure 7.1. Aforementioned aspects represent all interested parties, i.e the model users, local authorities, model developers and society, whose wishes should be taken into account. The level of accuracy of the compliance checking models is evaluated by means of BSim software, which is assumed to give a sufficient estimate of reality. Variation of the precision is represented by means of robustness, which indicates an ability to withstand various conditions in wide application. Unambiguity and reproducibility defines model ability of giving the same or similar output when different users set up the model for the same building and is strongly correlated with input data. Speed and convenience are essential for the user; simple model and limited input require minimum time and thus reduced costs to acquire and learn as well as to set up the model. Internal transparency characterises the model ability to be tracked for each time step by model developers. This is achieved when the calculation procedure is based on physical rules and clearly described by set of equations with limited number of parameters containing values without "unknown background". [EN ISO 13790 2008, p.129-130].

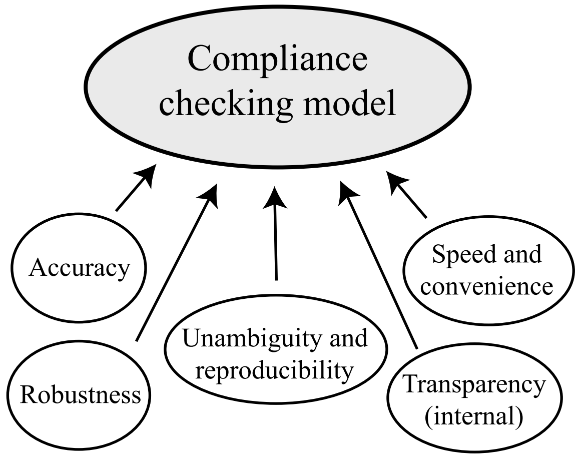


Figure 7.1: *Aspects of the model intended for compliance with building regulations. Re-drawn from EN ISO 13790 [2008, p. 128].*

7.2 Description of models

For current evaluation three simplified models are selected, where the first one represents original simplified model from SBi (v.1) and other models have increased complexity of model and/or input, cf. table 7.1.

	SBi v.1 "limited input" "simple model"	**EN ISO 13790 v.3** "limited input" "complex model"	**EN ISO 13790 v.4** "detailed input" "complex model"
RC scheme*	SBi	EN ISO 13790	EN ISO 13790
Numerical method*	Euler forward	Euler forward	Euler forward
Solar heat gains**	SBi + Be10	EN ISO 13790	EN ISO 13790
Internal heat gains**	SBi 213	SBi 213	SBi 213
Transmission heat losses**	SBi 213	SBi 213	EN ISO 13790
Ventilation heat losses**	SBi 213	SBi 213	SBi 213
Building thermal capacity**	SBi 213	SBi 213	EN ISO 13786 (detailed)
Specific heat flow between internal surfaces and air***	Integrated (simplified)	EN ISO 13790 (simplified)	EN ISO 13790 (detailed)
Specific heat flow between internal surfaces and thermal mass***	-	EN ISO 13790 (simplified)	EN ISO 13790 (detailed)

Table 7.1: *Specifications of simplified models used in evaluation.*Described in section 4.2, **described in section 5.3, ***described in section 6.1.1.*

Second simplified model, i.e. EN ISO 13790 v.3, represents a model with the same input as SBi v.1 model, though a more complex calculation procedure. It was achieved by implementing hourly solar heat gains calculation algorithm from EN ISO 13790 standard. It proved to be significantly more precise than SBi solar heat gains calculation algorithm, cf. subsection 5.3.2, however not demanding any additional input information, which is an advantage of the compliance checking model. In addition, RC scheme of EN ISO 13790 model was chosen as its performance has the best agreement with BSim results among the investigated simplified models. Furthermore, it does not systematically underestimates the result as SBi model, which is also desirable for compliance model in order to promote better thermal environment in dwellings and not vise versa.

Third simplified model, i.e. EN ISO 13790 v.4, further increases the complexity of EN ISO 13790 v.3 model by using additional input data. The purpose of this model is to investigate whether the increased accuracy of the model outweighs the enhanced time for set up of all necessary input data. By using additional input data regarding construction elements areas and material properties it became possible to calculate more precisely building thermal capacity as well as surface HTC and HTC between thermal mass and internal surfaces.

The simplified models with varying complexity of user input and calculation procedure are all used for simulation of the thermal indoor environment in the critical room of the five test buildings and prediction of excessive operative temperatures quantity.

The evaluation of accuracy and robustness is performed for four comfort houses, namely Stenagervænget 12, 28, 37 and 39 as well as for Eurodan huse in order to obtain reliable results for future low-energy buildings. A description of the five test houses appears in appendix R. The dwellings were chosen as they possess diverse building thermal capacity and usage of solar shading.

7.3 Accuracy

Accuracy of simplified models specifies the level to which a simulation output conforms to the correct value, [Oxford University Press 2012b], and is thus an adequate indication of the precision of the model output. For checking compliance with Danish BR2015, the accuracy of simplified model is a matter of definition. By solely focusing on the requirement, namely model output expressed as hours with operative temperature exceeding 26°C and 27°C, this is illustrated in figure 7.2 and 7.3 for the five test buildings. The results are comparably illustrated in figure **??** with BSim which gives a satisfying approximation of reality.

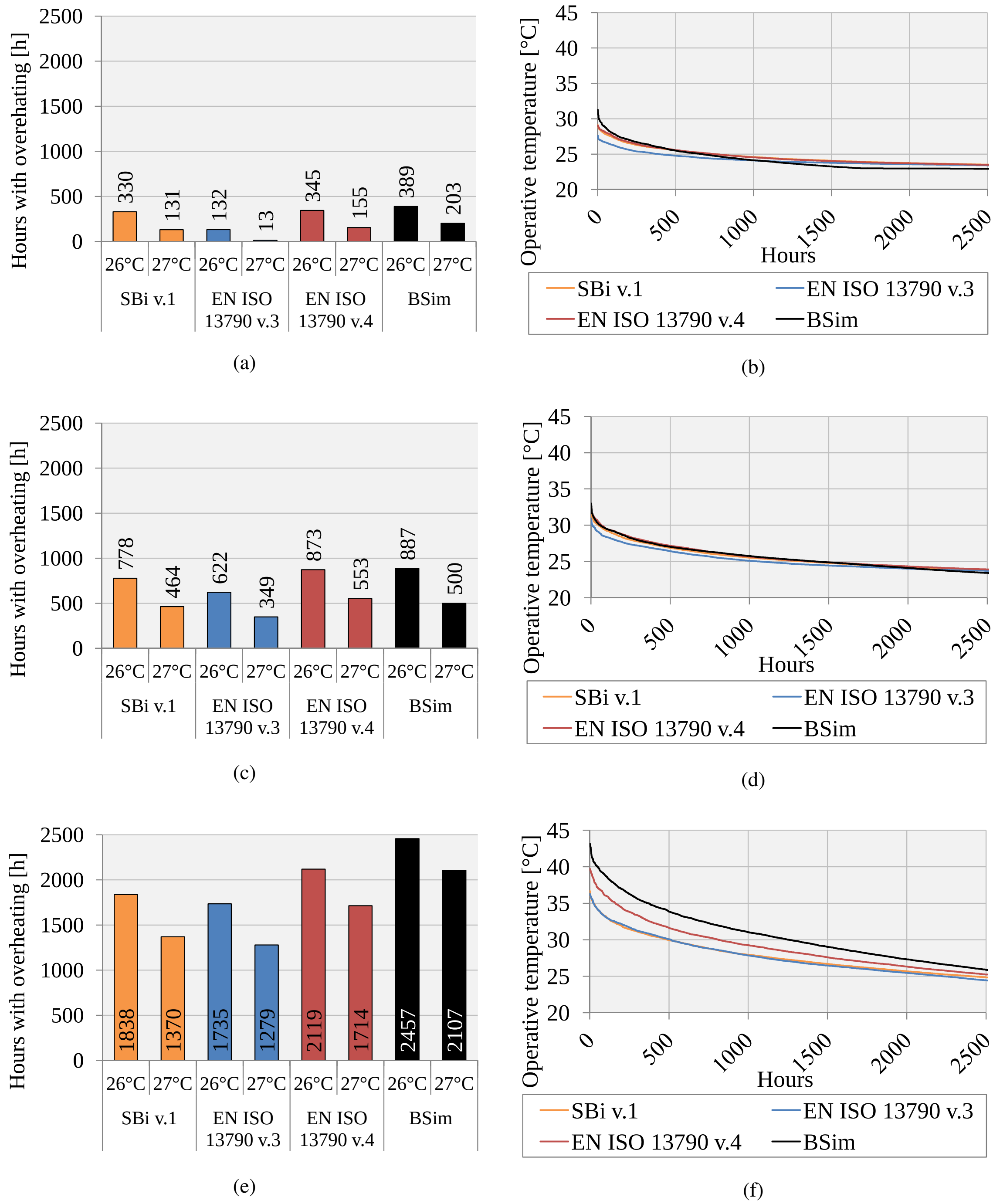
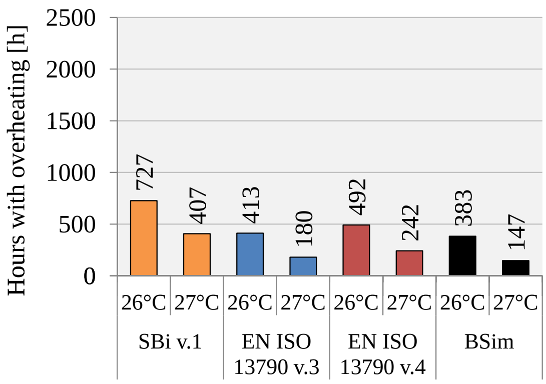
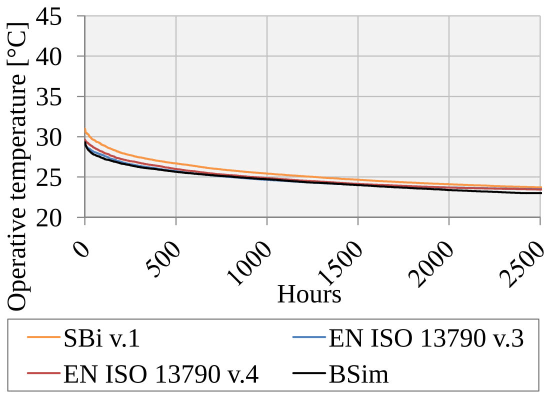


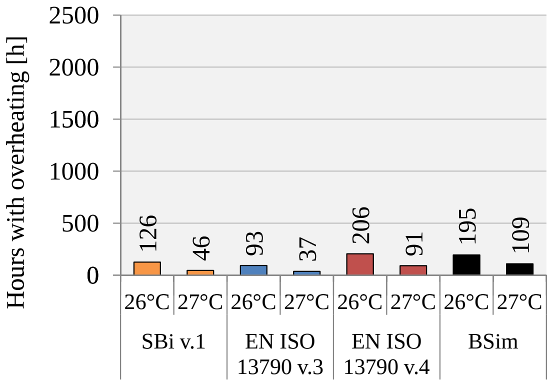
Figure 7.2: *Annual quantification of operative temperature. Results are expressed as number of hours with operative temperatures exceeding 26°C and 27°C along with sorted distribution of operative temperatures, all of which are valid for Stenagervænget 12 (a,b), Stenagervænget 28 (c,d) and Stenagervænget 37 (e,f).*



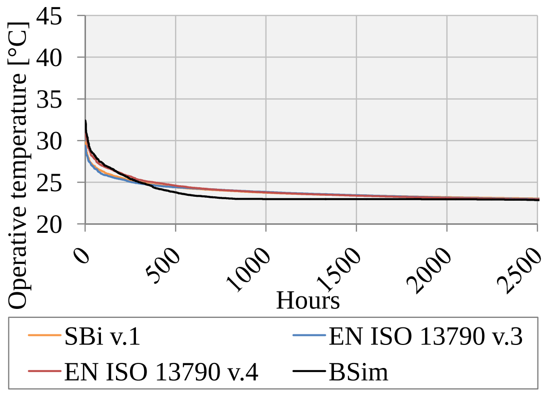
(a)



(b)



(c)



(d)

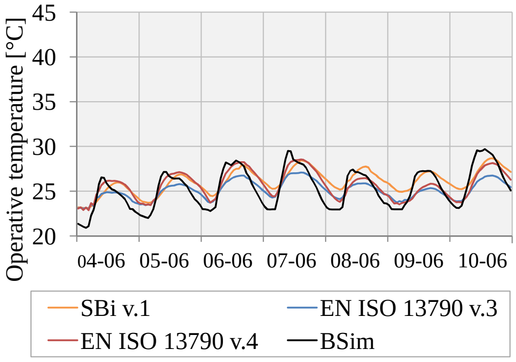
Figure 7.3: *Annual quantification of operative temperature. Results are expressed as number of hours with operative temperatures exceeding 26°C and 27°C along with sorted distribution of operative temperatures, all of which are valid for Stenagervænget 39 (a,b) and Eurodan huse (c,d).*

In order to quantify the deviation of model output in simplified models compared to BSim, minimum (largest underestimation), maximum (largest overestimation) and average relative deviation for each simplified model among test buildings are listed in table 7.2 for excessive operative temperatures.

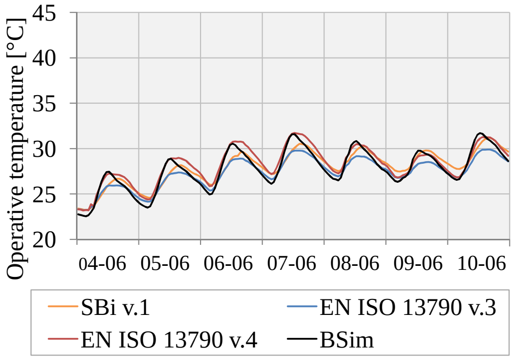
Criteria		**SBi v.1**	**EN ISO 13790 v.3**	**EN ISO 13790 v.4**
Hours with $T_{op} > 26°C$	Minimum	-35%	-66%	-14%
	Maximum	90%	8%	28%
	Average	36%	37%	12%
Hours with $T_{op} > 27°C$	Minimum	-58%	-94%	-24%
	Maximum	177%	22%	65%
	Average	62%	50%	27%

Table 7.2: *Accuracy evaluation of calculation procedures utilised in simplified models by means of minimum, maximum and average deviation from from BSim.*

EN ISO 13790 simplified model v.4 obtains the model output deviating relatively 12% and 27% for hours with operative temperatures exceeding 26°C and 27°C respectively to reality (BSim), and is thus considered as the most reliable simplified model capable of checking compliance with Danish BR2015 regarding risk of overheating. However, SBi simplified model v.1 is likewise, though in a lower degree, not divergent significantly from BSim for especially Stenagervænget 12 and 28. Nevertheless, by focusing on average deviations in table 7.2 SBi simplified model experiences deviation of 36%, which is similar to EN ISO 13790 v.3, and the largest average deviation of 62% for hours with operative temperatures exceeding 26°C and 27°C. The EN ISO 13790 simplified model v.3 experiences a systematical decreased model output compared to BSim and the most substantial underestimation of -66% and -94% for hours with operative temperatures exceeding 26°C and 27°C respectively, whereas the deviations of the others are rather based overestimations.



(a)



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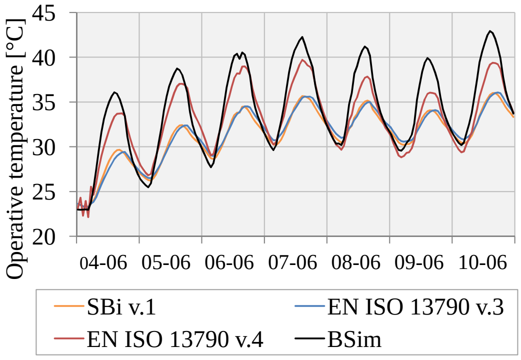

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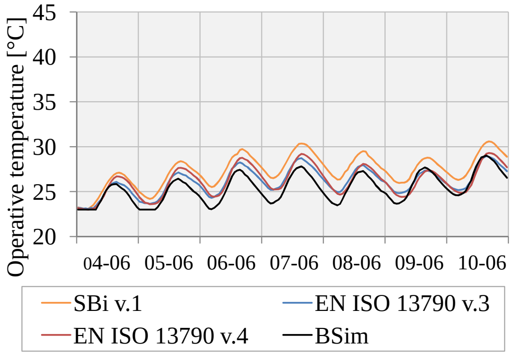

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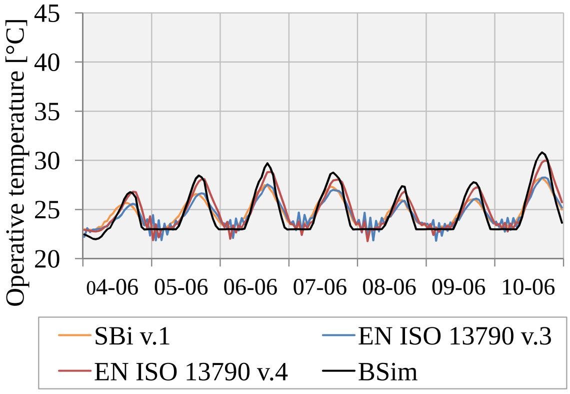


(e)

Figure 7.4: *Operative temperatures obtained in week 23 from simplified models with varying complexity of user input and calculation procedure for Stenagervænget 12 (a), Stenagervænget 28 (b), Stenagervænget 37 (c), Stenagervænget 39 (d) and Eurodan huse (e).*

In order to further analyse the operative temperatures simulated in simplified model and improve the determination of simplified model accuracy regarding model output, the temperature daily distributions are illustrated for each test building in figure 7.9 for week 23, which comprises the largest amount of solar incidence and often occurring excessive temperatures.

A trend for a slightly larger fluctuation for the operative temperatures simulated in BSim, and in lower degree EN ISO 13790 v.4, can be explained by overestimation of thermal capacity of the thermal zone in simplified model comprising limited input, as they consider the thermal capacity of the entire building and thermal zone to be equal. These usage of often higher thermal capacity for simple user input is the main contributor for decreased level of accuracy.

As the solar algorithm utilised in SBi simplified model v.1 implies a higher annual solar heat supply to the thermal zone, this error along with the aforementioned drawback regarding thermal capacity determination often equalizes each other and makes the output consistent with the output obtained by BSim, though not always, as a substantial overestimation of 90% and 117% was experienced for Stenagervænget 39 in figure 7.4(d). Furthermore, as revealed in figure 7.4(d) for Stenagervænget 39, where the critical room comprises windows facing mainly towards south-east but also towards north-east, the distribution of hourly solar heat gains independent of the orientation of windows in Sbi simplified model implies a displacement of the excessive operative temperatures, which further decreases the level of accuracy.

7.4 Robustness

Robustness represents the ability to withstand or overcome adverse conditions, [Oxford University Press 2012a]. With respect to energy simulation models it means the ability to provide satisfying accuracy within the wide application. This aspect is of high importance for the compliance checking model, because it is subjected to objects, i.e. dwellings, with varying level of complexity. It is therefore the calculation procedure including all model input parameters, i.e. which are not available for the user, which is responsible for robust performance within the wide application, cf. figure 7.5.

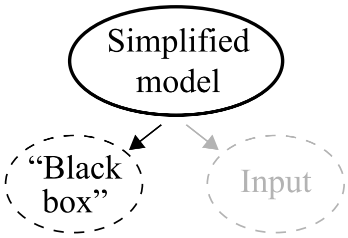


Figure 7.5: *Representation of concept of simplified model. Calculation procedure with all input parameters not available for the user ("black box") is subjected to robustness evaluation.*

There are several differences among the calculations kept inside the "black box" of simplified models, i.e. solar energy calculation algorithm, RC scheme, transmission heat losses calculation algorithm, cf. table 7.1. However only the first two are of importance, whereas the influence of transmission heat losses is negligible. In order to compare how robust are different solar energy calculation algorithms a deviations between simplified models and BSim are calculated for five test houses, see figure 7.6. Note that both EN ISO 13790 v.3 and v.4 possess the same solar energy calculation algorithm.

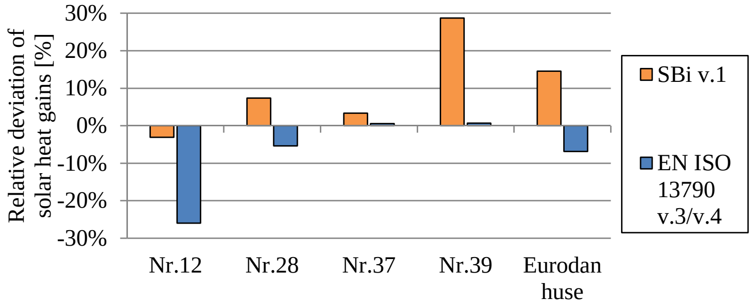
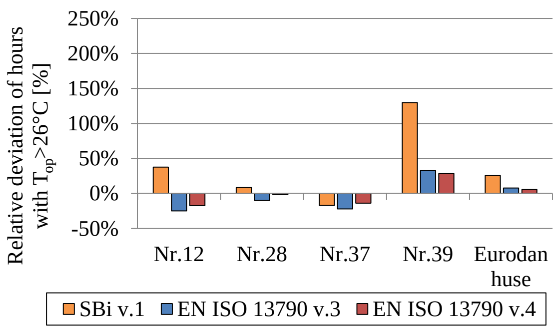


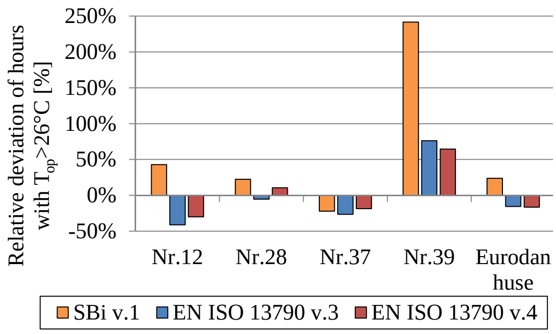
Figure 7.6: *Relative deviations between solar heat gains calculation algorithm of simplified models and BSim by means of four comfort houses and Eurodan huse.*

In general solar energy calculation algorithm from EN ISO 13790 v.3/v.4 is significantly more robust than one from SBi models v.1, due to the hourly calculations and implemented angular dependence of solar energy transmittance. However, for comfort house Nr.12, which incorporates large overhang cf. figure (REF to test house description), a substantial deviation between EN ISO 13790 v.3/v.4 and BSim is obtained. The reason for this deviation could be in uncertainties regarding the overhang constructing approach in BSim, which is built as a separate building.

To compare the level of robustness of total calculation procedures including solar energy calculation, a deviations between the output from simplified models and BSim are calculated for five test houses, see figure 7.7. To isolate (or minimise) the effect of uncertain user input from calculation procedure, all three simplified models possess thermal capacity of the critical room calculated by EN ISO 13790 detailed method, as thermal capacity is the only one different user input among simplified models and BSim.



(a)



(b)

Figure 7.7: *Relative deviations between calculation procedure of simplified models and BSim by means of four comfort houses and Eurodan huse for hours with operative temperature above 26°C (a) and 27°C (b). Thermal capacity of the critical room is calculated for all simplified models by means of EN ISO 13790 detailed method.*

All three models experience both over and underestimations of summer thermal comfort comparing to BSim, whereas the SBi simplified model v.1 produces some significant deviations, especially for the comfort house Nr.39, for which a higher solar energy was calculated. Note, that results in figure 7.3 incorporate differently calculated solar energy due to different solar calculating algorithms implemented.

A final evaluation of robustness is made according to variation of the output precision experienced among five test houses, cf. figure 7.7. The robustness in the current analysis accounts for output precision variation and not for precision itself, meaning that if the result of simplified model comparing to BSim is overestimated for around 30% within all tested houses, than the calculations used in the simplified model are not very accuracate, although very robust. The variation of output precision is expressed by means of standard deviation, see table 7.3.

	Precision variation		
Criteria	**SBi v.1**	**EN ISO 13790 v.3**	**EN ISO 13790 v.4**
Hours with T_{op}>26°C	50%	21%	16%
Hours with T_{op}>27°C	92%	41%	34%

Table 7.3: *Robustness evaluation of calculation procedures utilised in simplified models by means of standard deviation.*

Robustness of three simplified models is at distinct levels, where EN ISO 13790 v.3 and v.4 simplified models are showing an average ability to withstand the varying conditions and different level of complexity in five test houses, whereas the level of robustness in SBi v.3 simplified model is modest. The difference between EN ISO 13790 v.3 and v.4 simplified models occurs due to limited and detailed input utilised for calculation of specific transfer transfer between room air and surfaces, cf. section 6.1.1. With all mentioned above, EN ISO 13790 v.3 and v.4 simplified models are assigned with 3 points and SBi simplified model with 1 point regarding level of robustness.

7.5 Unambiguity and reproducibility

Unambiguity and reproducibility of the model are strongly correlated with input data and reflected in precision of the model performance, see figure 7.8. Unambiguous input or, in other words, certain input is not open for more than one interpretation and is very clear, whereas ambiguous input is very uncertain and thus can be interpreted differently by different persons. Limited input is not necessarily unambiguous, whereas many input parameters do not necessarily result in high uncertainty in the output. It is important to keep input as unambiguous as possible, to facilitate the use of the model as well as to lower down the pressure, which the modellers are subjected to when applying assumptions and doing estimations. The input unambiguity thus influences the precision of the model performance, as the modeller with different level of knowledge executing energy simulation can ruin all precision of the calculation procedure by doing wrong estimations of input parameters.

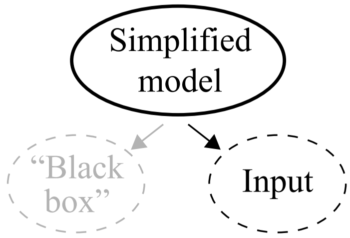


Figure 7.8: *Representation of concept of simplified model. User input parameters, which are available for the user, are subjected to models unambiguity and reproducibility evaluation.*

The difference in user input parameters between three simplified models is that first two models require building thermal capacity as an input, whereas the third model requires information regarding construction elements areas and material properties for calculation of thermal zone thermal capacity as well additional specific heat transfers. Building thermal capacity represents an important parameter, cf. sensitivity analysis results in subsection 5.2.2 and accuracy evaluation above, which can significantly influence the output. In case of first and second models input regarding building thermal capacity is uncertain as it is based on experience and knowledge of particular person and/or modest guidance provided by SBi 213, cf. table L.2. Input of third model, by contrast, is fairly unambiguous as it requires information regarding areas and materials, which are available from building specifications or/and technical drawings.

Table 7.4 shows the estimated and calculated thermal capacity values for five test houses. Note that estimations were done in accordance with guidance from SBi 213.

	Nr.12	**Nr.28**	**Nr.37**	**Nr.39**	**Eurodan huse**
Estimated thermal capacity, C_m, $\left[{}^{Wh}/_{{}^\circ C\, m^2-floor}\right]$	120	120	100	80	80
Calculated thermal capacity, C_m, $\left[{}^{Wh}/_{{}^\circ C\, m^2-floor}\right]$	62	76	50	61	46

Table 7.4: *Estimated and calculated thermal capacity applied in simplified models for five test houses. For comfort houses only the the number of house is stated. Calculation of thermal capacity was done by means of EN ISO 13786 detailed method.*

Figure 7.9 reflects the variation of results from simplified models, when estimated and calculated thermal capacity are used. Since the estimated thermal capacity is significantly higher than calculated, the result of predicted excessive temperatures is substantially lower, i.e. within the range of 70% for SBi simplified model and 90% for EN ISO 13790 v.3 simplified model. Variation between simplified models occur due to different RC schemes incorporated and thus different treatment of thermal capacity.

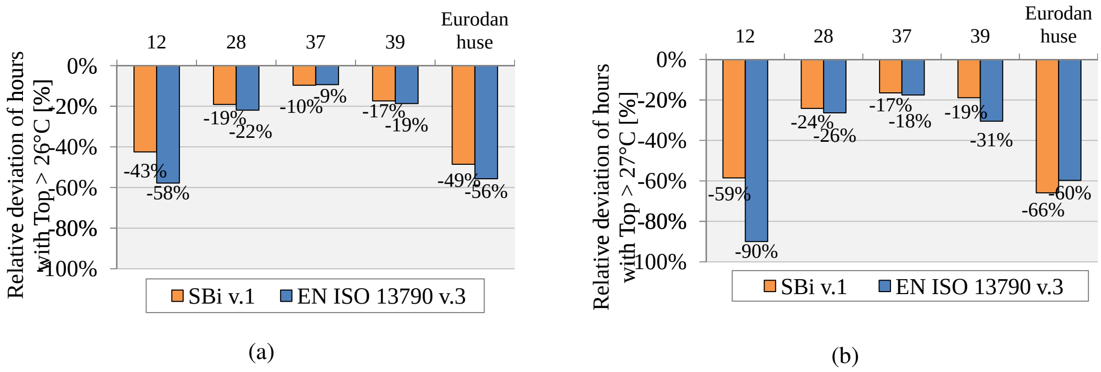


Figure 7.9: *Relative deviations regarding risk of overheating simulated in SBi simplified model v.1 and EN ISO 13790 simplified model v.3 by utilising estimated and calculated thermal capacity. The results are expressed as relative deviation in operative temperatures exceeding 26°C (a) and 27°C (b). For comfort houses only the the number of house is stated.*

Other user input parameters, which require estimation from the modeller are ventilation airchange rates and solar shading factor, which are the same for all simplified models, however quite uncertain in case of ventilation airchange rates and fairly certain in case of solar shading factor.

Taking above mentioned into account it was decided that non of the models possesses very certain input data, since natural ventilation airchange rates are uncertain and mistakes in these values can lead to significant consequences in result, as was experienced in sensitivity analysis cf. section 5.2. However the rest of input data is fairly unambiguous for EN ISO 13790 v.4.0 model, which is assigned with 4 points, while SBi v.1 and EN ISO 13790 v.3 models are assigned with 2 point as required input regarding building thermal capacity is uncertain and leads to substantial deviations in the result in case of wrong estimations applied.

7.6 Transparency (internal)

Simplified energy simulation model appears for the users as the so called "black box", which encompasses all calculations performed by the model with only several input parameters available for the user. The calculation procedure, however, is open for the developers, who desire to have it of limited size and complexity in order to be able to track the results and hence ensure a sufficient robustness of the model. In general simplified hourly models are highly transparent as they allow the person responsible for the calculation procedure to track results by means of spreadsheet version of calculation procedure. However some variations among models still occur:

- SBi v.1 model is based on 3R1C scheme with low complexity, which is utilising two unknown temperature nodes and two corresponding heat balances, cf. appendix H. Flowpaths for heat losses and heat gains are simply treated, which is reflected in low number of equations used for description of the method. However it is difficult to track and sometimes understand the algorithm of solar heat gains calculated on monthly basis and then distributed for each hour. There is no information regarding the way how Be10 calculates monthly coefficients for shadow, shading and angular dependence. Note, that parameters related to solar heat gains belong to ten most important parameters according to sensitivity results in subsection 5.2.2.

- EN ISO 13790 v.3 model is based on 5R1C scheme with three unknown temperature nodes and three corresponding heat balances, cf. appendix F. It is utilising fairly complex flowpaths for heat losses and heat gains, which is reflected in substantially higher number of equations used for description of the method comparing to SBi v.1 model. Implemented in EN ISO 13790 v.3 model hourly solar energy calculation algorithm substantially increases the size of calculation procedure, although makes it more understandable where each value related to solar transmittance comes from.
- Transparency of EN ISO 13790 v.3 model applies to EN ISO 13790 v.4 model as they utilise the same RC scheme and solar energy calculation algorithm. However the transparency of this model is further reduced by implementing detailed building thermal capacity calculation algorithm from EN ISO 13786 standard. This method requires many input parameters, cf. section 7.7, which lead to increase of the size of the calculation procedure. The method additionally involves heat transfer matrices, which are difficult to track.

As the conclusion, none of the simplified models is fully transparent, although SBi v.1. model possess relatively high transparency and therefore is assigned with 4 points. The increased complexity of RC scheme employed in EN ISO 13790 v.3 simplified model is reflected in its evaluation - 3 points. EN ISO 13790 v.4 simplified model is further more complex and therefore less transparent. Therefore this model is assigned with 2 points.

7.7 Speed and convenience

Time to become acquainted and learn the model is similarly low for all simplified models, as all of them are of limited complexity and are based on simple calculation procedure and RC scheme. However, speed of set up the model is substantially varying, since the EN ISO 13790 v.4 simplified model requires additional input, as was discussed in previous section.

- SBi v.1 simplified model is based on EN ISO 13790 simplified energy calculation method with further reduction of complexity, it possesses a very unsophisticated calculation procedure, as was discussed in section 7.6. Furthermore, the user input comprises besides the input required for Be10 energy calculation tool, only five input parameters, i.e. heated floor area, basic ventilation rate and three summer ventilation rates.
- EN ISO 13790 v.3 simplified model incorporates a higher complexity of the calculation procedure and the same number of input parameters as for SBi v.1 simplified model is required.
- The complexity of the calculation procedure based on RC scheme is the same for EN ISO 13790 v.3 and v.4 simplified models. However, in addition to aforementioned five input parameters this model demands 13 input parameters for each construction element, which include area of construction element, material properties, layer thickness for each layer, material properties (density, specific heat capacity, conductivity) for each layer. For entire room, in case of three layers in every construction element a total number of 52 input parameters

is required. Although the number is enormous, it is easy to reduce it nearly by half if the material properties (density, specific heat capacity, conductivity) are specified for each type of material. Nevertheless, the speed of using the model is substantially slower than for other simplified models.

Based on above mentioned SBi v.1 simplified model is assigned with 5 points, EN ISO 13790 v.3 simplified model is assigned with 4 points, while EN ISO 13790 v.4 model is assigned with 1 point.

7.8 Summary

Evaluation summary for simplified models regarding aspects of compliance checking model is illustrated in figure 7.10, which distinctly shows the features of particular simplified model. Final number of points is equal for all models - 14 points from 25 possible.

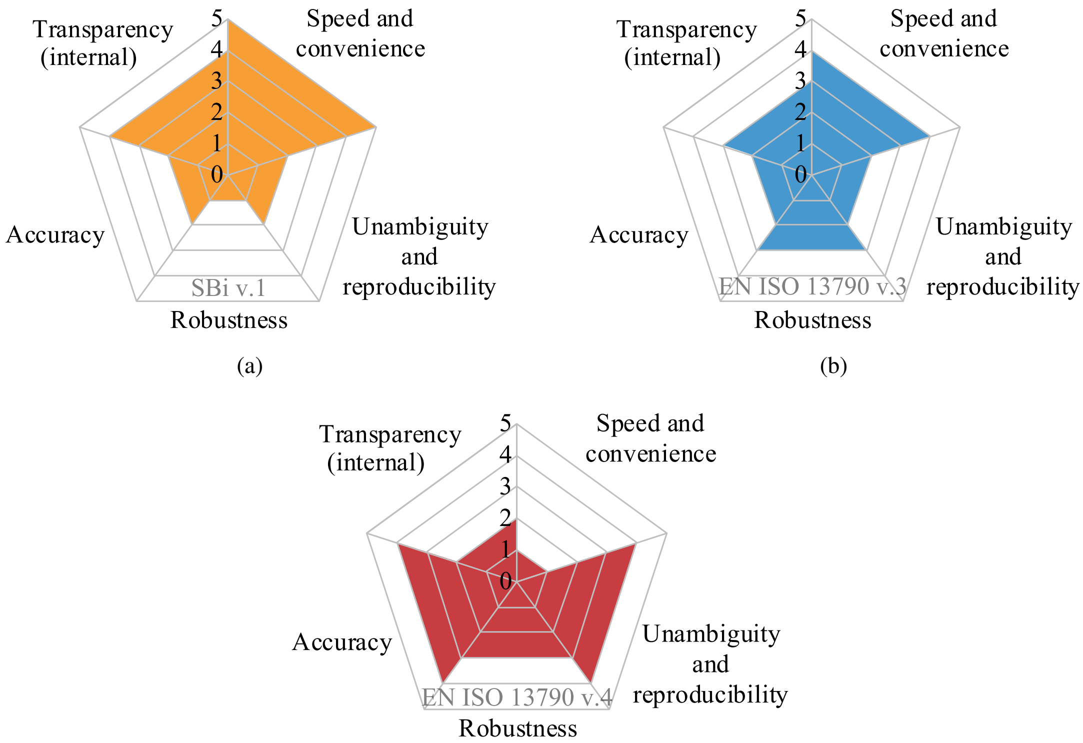


Figure 7.10: *Simplified models evaluation summary regarding the aspects of compliance checking model. SBi v.1 model is in figure (a), EN ISO 13790 v.3 (b) and EN ISO 13790 v.4 (c).*

In spite of the equal total ranking, the model has several distinct trends:

- SBi v.1 simplified model is very much orientated towards speed and convenience, where the suffering aspects are accuracy and robustness;
- EN ISO 13790 v.3 simplified model represents a balance regarding the aspects of compliance checking model, although with slight higher focus on speed and convenience than accuracy;

- EN ISO 13790 v.4 simplified model possesses high accuracy level, together with unambiguous input, which contributes to overall precision as well.

Bearing in mind that all aspects are coherent and change in one leads to changes in other aspects, it is still possible to increase the total ranking, by developing a guidance for building thermal capacity estimation. This will increase the unambiguity of the input and positively reflect in accuracy.

Chapter 8

General discussion

The current thesis considers simplified models intended for checking compliance with Danish Building Regulations regarding thermal comfort in dwellings. The performed investigations have often separated the simplified models into model calculation procedures and boundary conditions/input data. The discussion is mainly based on considerations of the simplified model developed by the Danish Building Research Institute, which is intended for assessing the thermal comfort in order to check compliance with Danish Building Regulations, although another two simplified models were examined at the same time.

Accuracy and robustness of simplified models

Simplified models reviewed in the thesis are based on fully prescribed simple dynamic energy calculation method. Although this calculation method provides hourly input data for control of ventilation and solar shading and thus producing hourly output, the calculated result is not necessarily realistic on hourly basis. This is the consequence of the simplifications used in the method, i.e. lumped capacitances, simplified treatment of transient conduction, shortwave and longwave radiation inside the thermal zone. Due to above mentioned simplifications a manual "tuning" of the way the capacitances are lumped, the way of shortwave radiation treatment, etc, is required. By executing a theoretical Building Energy Simulation TEST (BESTEST) a significant influence of simplifications used in the models calculation procedures was obtained. A notable fact is that the differences in performance among simplified models were found to be rather negligible, whereas the deviations from the performance of advanced programs are substantial, indicating a high influence of simplifications incorporated in models calculation procedures, see figure 8.1.

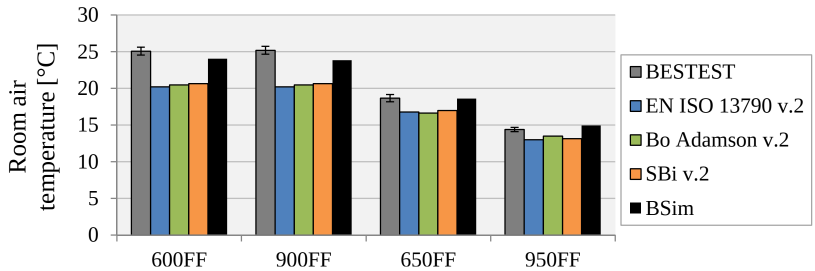


Figure 8.1: *Average hourly annual temperatures in BESTEST and simplified models together with BSim. Plus/minus standard deviation is used to indicate the range of BESTEST results. Details can be found in section6.2.*

Besides very high level of simplicity in calculation procedure of SBi simplified model, there is also an inaccurate solar energy calculation algorithm implemented, which converts solar energy on monthly basis into hourly by using simple approach and corresponding low level of accuracy. All together calculation procedure is subjected to high precision variation, which indicates of rather modest level of robustness and significant underestimations and especially overestimations are possible according to figure 8.2.

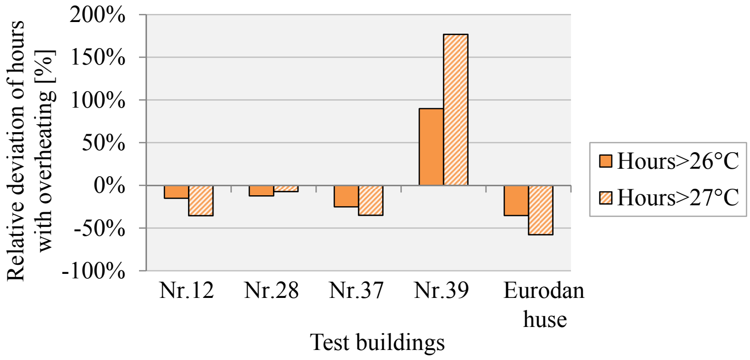


Figure 8.2: *Accuracy of calculation procedure utilised in SBi simplified model comparing to BSim performance for five test buildings. Details can be found in section 7.3.*

Aspects of compliance checking model

Model intended for checking compliance with building regulations should possess certain aspects in order to be attractive for interested parties. Unlike the advanced energy simulation tools, which are utilised in projects of high complexity and in researches, an increase of accuracy and thus complexity of the compliance checking model leads to reduction in other aspects. These are speed and convenience of model usage, which are desired by the modellers, transparency of the calculation procedure, which makes it more difficult to track the calculations and elaborate the calculation algorithms for developers. On the other hand, when too large simplifications are implemented in the model, the robustness will most likely be diminished. It was experienced in the thesis that three simplified models, evaluated with the same overall ranking perform with significantly diverse level of accuracy and robustness, speed and convenience, like simplified models SBi v.1 (original), EN ISO 13790 v.3 and EN ISO 13790 v.4, see the figure 8.3. Last two simplified models were constructed based on knowledge obtained throughout the thesis.

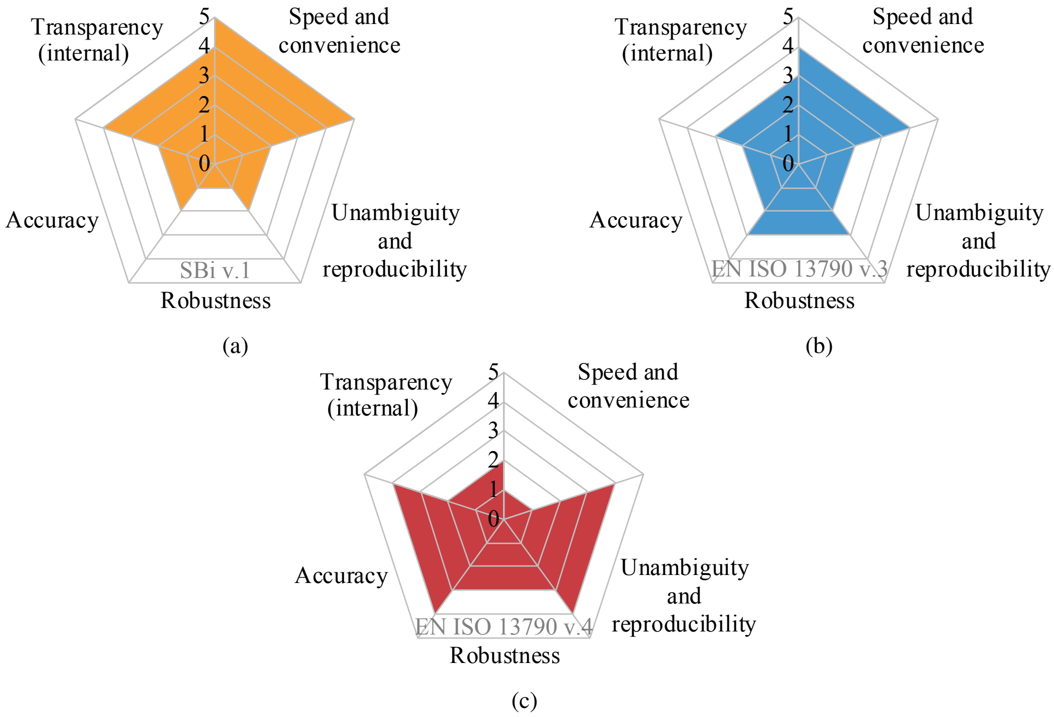


Figure 8.3: *Summary regarding the aspects of the model intended for checking compliance with building regulations for SBi v.1 (a) and EN ISO 13790 v.4 (b) simplified models. Details can be found in section 7.8.*

The method, which was used for evaluation of compliance checking models is subjective as it incorporates personal opinions of authors of the thesis. Furthermore, an assumption was set in the method saying that all aspects (criteria) are of equal importance, which, in fact, is the task for authorities to define what should be of higher importance and desired. A noteworthy is that SBi simplified model possesses a high level of simplicity, which negatively affects robustness and accuracy of the model. With enhanced focus on building regulation requirements regarding energy consumption and thermal comfort in buildings modellers are exposed to a high pressure, and by using SBi simplified model with low level of robustness and accuracy a pressure on modellers can further increase.

An advantage of having a low amount of input data in the simplified model can be diminished by the high uncertainty of the input parameters, as it was experienced in SBi simplified model. Both ventilation airchange rates and building thermal capacity are found to be in the group of the most important input parameters and they require an estimation from the modeller. The SBi simplified model was designed for every person, without requirements for the level of knowledge of the modeller, [Aggerholm 2013]. However, as was investigated in the thesis, the decisions and estimations of the modeller regarding the building thermal capacity can substantially influence the precision of the results as illustrated in figure 8.4. In this case two results are compared by using estimated building thermal capacity via the guidance from SBi 213 and calculated one by means of EN ISO 13786 detailed method.

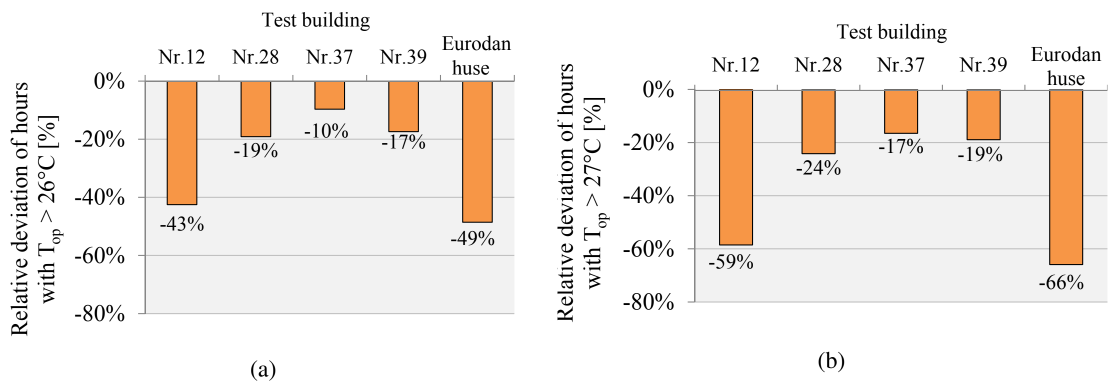


Figure 8.4: *Accuracy variation of results from SBi simplified model due to the difference between estimated and calculated building thermal capacity. Calculation of building thermal capacity was done by means of EN ISO 13786 detailed method. Details can be found in section 7.5.*

It is therefore obvious that either the guidance for determination of building thermal capacity should be elaborated in order to assist the modeller to make a more precise and less ambiguous estimate or the requirements should be set for the level of knowledge of the modeller.

Consideration of uncertainties in building simulation

The requirement specified in the building regulations regarding thermal comfort in dwellings is based on deterministic quantities, namely hours with operative temperatures exceeding 26°C and 27°C, regardless estimation of uncertainties in model output an hence probability of exceeding the requirements. This implies that uncertainty in user input is seldom accounted for in SBi simplified models, established with the purpose of assessing the thermal performance, and simulations are carried out deterministically. The uncertainty analysis of the comfort house Stenagervænget 28 was performed by using 10 the most important input parameters, which were found in executed sensitivity analysis. Some improvements of the thermal comfort were carried out by usage of passive initiatives in order to decrease the overheating in the building to such an extent that it fulfills the building requirements. The results of this uncertainty analysis are illustrated in figure 8.5 as two cumulative distributions associated with key numbers in table 8.1, which specifies the probability of complying with the requirement regarding risk of overheating in dwellings. The conditions used in the uncertainty analysis are listed in appendix S.

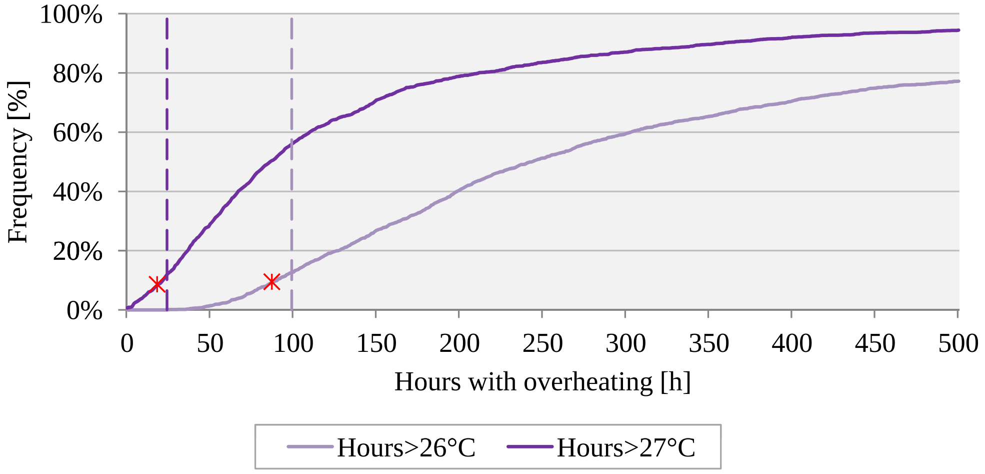


Figure 8.5: *Result of uncertainty analysis regarding hours with overheating valid for Stenagervænget 28 with improved thermal comfort. Red symbols represent the expected (simulated) number of hours with overheating. Dashed lines represent the requirements of Danish Building Regulations. Analysis executed in SBi simplified model. Details can be found in appendix S.*

	Expected number of hours [h]	**Probability to experience expected number of hours** [%]	**Probability of compliance with Danish BR2015 requirements** [%]
Hours>26°C	88	9.5	12.8
Hours>27°C	19	8.7	12.5

Table 8.1: *Key numbers obtained from uncertainty analysis regarding hours with overheating valid for Stenagervænget 28 with improved thermal indoor environment.*

The uncertainty analysis reveals significant importance of varying selected input parameter, as the expected risk of overheating experiences limited probability of being realised at this or even lower level, i.e. 9-10% in case of comfort house Stenagervænget 28. The analysis conducted throughout this thesis reveals a occasionally significant overestimation of hours with excessive operative temperatures. Even though an overestimation compared to "reality" is preferable rather than an underestimation, which will have a negative effect on the society, a too high predicted risk of overheating will affect the building design and unnecessarily increase the cost for the building owner. It is important to remember that the building requirements regarding thermal comfort are introduced in order to ensure a satisfying thermal comfort for residents inside the building. It is hence less important that the actual thermal comfort is fulfilling the requirement. As long as the requirements have contributed to a reasonable usage of passive technologies in the design of the building, it brings the prescribed balance between cost for the society and the building owner.

Chapter 9

Conclusion

The present chapter concludes the results obtained in the current thesis for investigations regarding evaluation of simplified models for checking compliance with Danish Building regulations regarding summer thermal comfort. Application of simplified models is wide, as they can be applied for quick estimations at the preliminary design phase in a building project, for educational purposes as well as for checking compliance with building regulations requirements. However only for the latter application the requirements to the simplified model are strict, i.e. it should satisfy certain aspects, which make the model easy to learn and use, make its input unambiguous, its calculation procedure transparent and therefore robust with a certain level of accuracy. These aspects are important because different interests should be taken into account, i.e. modellers, local authorities, developers, building users and society.

Often only calculation procedure of the simplified model based on resistance-capacitance scheme is under high focus. However, the current thesis reveals the significant importance of boundary conditions and input data utilised in simplified models, which can easily ruin the accuracy of the calculation procedure. Since an upcoming SBi simplified model is of highest importance in the current thesis and it represents the tool with all applied boundary conditions, input data and system controls, the majority of the conclusions are related to this model. The highest error in SBi simplified model is associated with calculation algorithm of solar heat gains, which is a part of model boundary conditions and can be simply substituted by another calculation algorithm. The solar algorithm specified in EN ISO 13790 standard with developed angular dependent profile for solar energy transmittance performs with substantially higher accuracy than SBi solar algorithm comparing to solar heat gains calculated by BSim, though does not significantly increase the complexity of the calculations. In addition, its calculation algorithm is very transparent and easily tracked, unlike the SBi solar algorithm, which utilises "heritage" of Be10 energy calculation tool and corresponding monthly solar heat gains calculation with related monthly shading and shadow factors, which are difficult to understand even for skilled specialists.

Input parameters, revealed to be of high importance in simplified models according to conducted sensitivity analysis are, namely ventilation and solar shading set-points, basic and summer ventilation rates, proportional band for control of ventilation system, thermal capacity of the thermal zone, internal heat gains. The majority of these parameters is very uncertain due to application in dwellings, where, unlike the offices, there is no any systematic behaviour and occupants behaviour is highly diverse. As ventilation and solar set-points accompanying with ventilation proportional band, used in dwellings with natural ventilation, are highly occupants' behaviour related parameters and dependent on the preferences of particular individuals, they should belong to model input and be kept inside the so-called "black box" in order to avoid high ambiguity of the input and wrong use of these input parameters.

Other most important input parameters, such as building thermal capacity, shading factor and ventilation rates are denoted as user input parameters, as the person applying the simplified model is responsible for the reasonable estimate of these parameters. Since SBi simplified model is intended for every user, without requirements to his level of knowledge, [Aggerholm 2013], the influence of the modeller gets further importance in obtaining reliable results. A weak guidance from SBi 213 regarding determination of thermal zone thermal capacity promotes substantially overestimating of the final value, which leads to the lower predicted risk of overheating. Accuracy variation of results from SBi simplified model due to the difference between estimated and calculated building thermal capacity occurs in the range from -10% to -65%, which means that the role of the modeller is considerable regarding the application of SBi simplified model.

Summer ventilation rates were simulated by means of COMIS excel tool for multizone airflow modelling, which reveals a much higher potential for natural ventilation with the same size of openings comparing to guidance from SBi 213. It is a decision of SBi to be on the safe side and suggest rather modest values for the modellers, [Aggerholm 2013], that is why the modeller should be aware of possible underestimated natural ventilation rates.

In spite of significance of the boundary conditions and input data regarding the final output, simplified models calculation procedures can highly influence output result by treating input parameters in different way. Although calculation procedure schemes and applied numerical methods are varying among three reviewed simplified models, it is noteworthy to outline simplifications realised in the methods these models are based on. By using lumped capacitance method a great level of simplicity is achieved, at the same time limiting the application of shortwave and longwave radiation inside the thermal zone together with transient conduction in the simplified models. This fact was distinctly shown by executing BESTEST for simplified models, with use of four free-float cases. Although results of the cases reflect the weaknesses of applied simplified calculation procedures and hence a poor accuracy comparing to the detailed reference programs, the differences in performance among simplified models were found negligible. In single and combined parameters case studies, where more realistic building conditions were applied, simplified models do not show identical performance, they do both over or underestimation of result from BSim, depending on particular features of the simplified model. It is noteworthy, that although calculation procedure used in SBi simplified model incorporates RC scheme from EN ISO 13790 standard, though with large simplifications intended for showing results on the "safe side", [Mortensen 2012-2013], it generally underestimates summer thermal comfort in dwellings. In addition, it shows higher magnitude of variations comparing to EN ISO 13790 simplified model with Euler numerical method, which is the "price" for further simplifications of calculation algorithm from EN ISO 13790 standard.

Comparing to other reviewed simplified models the SBi simplified model possesses the highest level of speed and convenience, lowest complexity of the calculation procedure, although modest accuracy and robustness. The accuracy of the output from SBi simplified model comparing to BSim varies significantly, i.e. from -40% to 90% for the hours with operative temperature above 26°C and from -60% to 180% for the hours with operative temperature above 27°C for the five test houses, cf. section 7.3.

Chapter 10

Future perspectives

Current thesis presents a thorough analysis of simplified models available on the market, which can be employed for checking compliance with Danish BR2015 requirements regarding summer thermal comfort. Large efforts were attached to investigation of boundary conditions and input data, which revealed to be crucial and more important than calculation procedures themselves. Due to the fact that simplified models were mainly opposed to each other and compared to a detailed simulation program BSim, a further investigation of simplified models performance and possible development is related to examination of simplifications, the models are based on. These simplifications include treatment of shortwave and longwave radiation inside the thermal zone, transient conduction in building constructions and lumped capacitance effect. Some of aforementioned simplifications are accounted in simplified models, though by means of manually "tuned" values, which are difficult to examine. These simplifications are the weak points of the simplified models and in future their analysis is essential in order to develop more robust simplified models, which could be possibly validated on hourly basis.

Larger efforts could be attached to BESTEST execution, diagnostic test cases in particularly, which could assist in detecting the weak points where simplified models do highest deviations from detailed simulation programs.

Furthermore, in order to account for occupants' behaviour and check the performance of compliance model regarding the real dwelling behaviour, measurements could be utilised. In this case occupants' behaviour related parameters achieve higher importance and calculation of internal heat gains on room level can be elaborated as in the current thesis this calculation was limited to applied assumptions and lack of statistical data.

As was discovered in the thesis, that user input parameters, which require estimation are very uncertain for SBi simplified model. A modeller with relatively low level of knowledge regarding energy simulation models can significantly influence final result and ruin the precision of calculation procedure. It is therefore necessary to develop a description of SBi 213 guidance and establish a database for standard building construction elements and their calculated by means of EN ISO 13786 detailed method thermal capacities. This activity will make treatment of thermal capacity with substantially less uncertainty. Another aspect regarding calculation of building thermal capacity is related to predefined values from EN ISO 13790 standard, which were omitted in the current project due to questionably low values and reliance on values from SBi 213. Due to the fact that latter is overestimating building thermal capacity, it could be useful to investigate predefined values from European standard and possibly utilise them in future application of simplified models.

Appendix **A**

CD appendix

The following appendix contains a list of included files on the attached CD.

A.1 Survey among companies

Results_of_Survey.xlsx
Data treatment for responses collected by the quantitative survey among Danish companies.

A.2 Simplified models

The present section represents a folder containing all creations and reproductions of simplified models applied for further analysis.

Bo_Adamson_simplfied_model_v.1.xlsx
Reproduction of a simplified Indoor environmental tool conducted in February 2012 by Nanna Svane Madsen and Mads Hulmose Wagner from Aarhus School of Engineering.

EN_ISO_13790_simplfied_model_v.1.xlsx
Creation of a simplified indoor environmental tool based on the simple hourly method prescribed in EN ISO 13790 [2008].

SBi_model.xlsx
Simplified indoor environmental tool provided by SBi intended as an expansion of the present version of Be10.

BSim_model_case_0.xlsx
Creation of a indoor environmental model based on the BSim.

Appendix **B**

Low-energy buildings

The diversity of low-energy house concepts is outlined in current appendix with a brief history of their emergence. Additionally, a list of comfort houses indicates, which of them are employed for particular investigations within the current thesis.

B.1 Low-energy building categories

Throughout the 1970's experimental initiatives towards low-energy buildings to enhance sustainable building development were conducted in different European countries until The Passive House Institute in 1991 introduced the first passive house in Darmstadt, Germany. Since then the concept has experienced an exponentially growing interest and other similar concepts have emerged, leading to a total number of 25000 low-energy buildings all over Europe in 2010 [Lamond 2011]. The definition is very broad but in general low-energy buildings are known to have a lower energy demand than common in national building regulations.

Low-energy house
A *low-energy house* also refers to a specific type of low-energy building in some European countries. These types of buildings and are distinguished by having a lower heating demand by using further insulation and heat recovering ventilation. Additionally, if the building is also designed with an attention to the thermo technical qualities of building materials and components it refers to a "*ultra house*" [Thullner 2010, p. 29]

Passive house
A *passive house* is designed by using well-known passive technologies with the aim of having an annual energy demand for heating below 15 kWh/m^2. This heating reduction is to such an extent that the effect delivered from the ventilation system by heating of the necessary air exchange may cover the design heat loss and consequently the conventional heating systems becomes unnecessary. However, the peak load should not exceed 10 W/m^2. The reduced design heat loss is obtained by having an airtight envelope with a high thermal mass and improved insulation. Furthermore, passive houses often minimizes their heat loss through the envelope by having compact design. In addition, the improved insulation prevents downdraft providing an enhanced thermal indoor comfort [Thullner 2010, p. 29-30].

Zero energy house
A *zero energy house* is rather complex and can be described as an energetically autonomous building having a high thermal storage and use solar energy and photovoltaic systems to generate energy. Thus, the building itself is producing the necessary amount of energy in order to be self-sufficient and independent of fossil fuels. The feasibility of this concept is being heavily discussed regarding economic balance between supplied and demanded energy. Thus, the term ”*nearly zero energy building*” has become a definition for the Energy Performance of Buildings Directive (EPBD) as an aid to future low-energy buildings [Thullner 2010, p. 31].

The implementation of standardized low-energy building concepts has developed differently in each European country and the level of standards and criteria varies because of the different outdoor climate conditions and historical demands for both energy performance and indoor environment of the buildings.

There are various others concepts of highly energy efficient buildings or climate neutral buildings throughout the Europe: zero-energy, 3-litre, plus energy, Minergie etc. The spread and realization of low-energy building projects under different concepts stimulate the production and development of low-energy house compliance products and therefore make the industry ready for new building energy performance challenges. In addition, passive houses and similar building concepts can play an important role in reaching European and national energy reduction targets.

B.2 The Comfort Houses

This section presents the list with low-energy dwellings from *The Comfort Houses* project, [Larsen et al. 2012e] and corresponding investigations, which some of the dwellings are involved in. The Aalborg University was doing measurements in these eight houses during three years from 2008 to 2011. However the data and specifications availability is varying among the houses, which is reason why the number of comfort houses is different for particular investigation.

Investigation	**Chapter/**	**Number of the comfort house**							
	Section	**12**	**28**	**37**	**39**	**43**	**45**	**47**	**49**
Internal heat gains from occupants (SA)	J.4.4	+	+	+	+	+	+	+	+
Internal heat gains from appliances (SA)	J.4.4	+	+	+	+	-	-	-	-
Internal heat gains from occupants	5.3.3	+	+	-	+	+	-	+	+

Table B.1: *List of comfort houses involved in different investigations throughout the thesis. All of them are located on the street Stenagervænget. Plus sign indicates house participation, minus sign indicates house non-participation.*

Appendix **C**

Energy modelling methods

EN ISO 13790 standard promotes application of simplified energy calculation procedures in context of building regulations. In this appendix description of available calculation methods and their differences is provided.

C.1 Types of calculation methods

Although there are two basic energy modelling methods, i.e. quasi-steady-state and dynamic methods, additional third method is provided in EN ISO 13790 standard, namely simplified hourly dynamic method, [EN ISO 13790 2008, p. 15-16]:

- *Quasi-steady-state method*, calculating heat balance over a sufficiently long time period (fo example a month), where dynamic effects are utilised by means of empirically determined gain or/and loss utilization factors;
- *Simplified dynamic hourly method*, which utilises dynamic effects on hourly basis, though in a simplified way;
- *Dynamic method*, calculating heat balance over a short time (typically one hour) taking into account dynamic effects in a detailed way.

Fully prescribed simplified hourly calculation method was added in EN ISO 13790 standard in order to facilitate the calculations using hourly user schedules, such as temperature set-points, ventilation modes, operation schedule, solar shading control depending on indoor and outdoor conditions, see all three methods in figure C.1. Additionally, this method has some features of monthly method, which are beneficial for the user, who apply the method and the person responsible for the calculation procedure and involved in its further development:

- As the calculation procedure is clearly specified and of limited size and complecity, it can be easily traced;
- Unambiguous calculation procedure;
- Limited input data are required;

Disadvantages of this model are that it does not provide detailed description of thermal processes occurring in the building zone, especially when dealing with dynamic effects. Although the method produces hourly results, hourly values are not reliable due to simplifications incorporated. This kind of energy simulation method should be validated on monthly basis, [Dijk and Spiekman 2004, p. 103]. Description of applied simplifications can be found in appendix E with description of lumped capacitance method, which is incorporated in hourly simplified dynamic method and in subsection 4.2.5. Full description of the simple hourly dynamic method is located in appendix F.

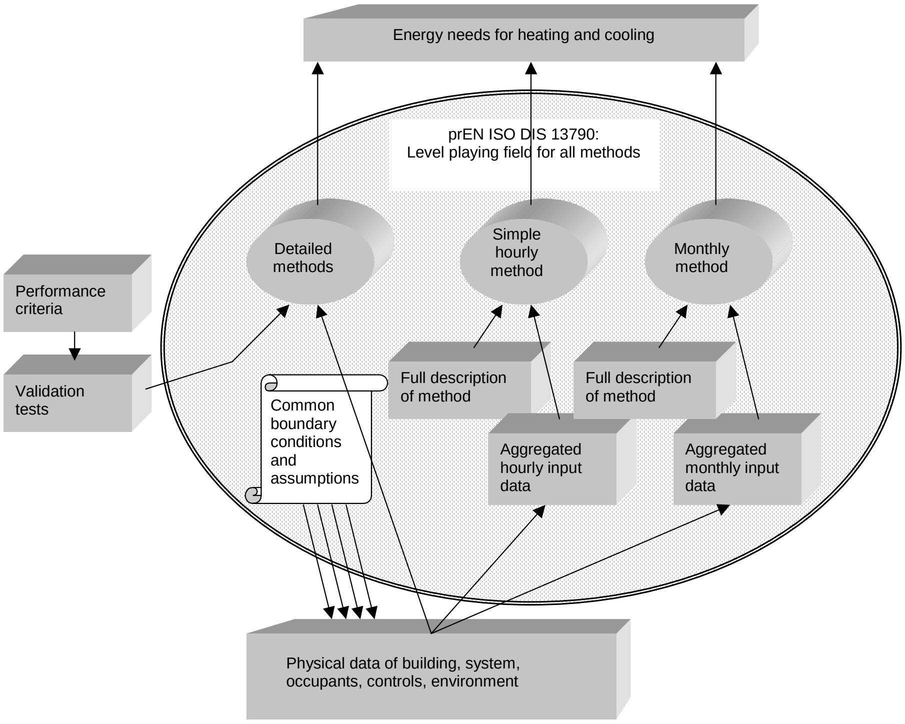


Figure C.1: *Common rules and assumptions for three calculation methods, [H. van Dijk and de Wilde 2005, p. 256].*

Appendix **D**

Survey among companies

This appendix contains a list of the participating companies in the survey followed by the questionnaire and the data results. The purpose is to explain the applied approach to achieve information regarding indoor environmental calculations from the Danish companies and their wish for a simplified compliance model.

D.1 Participating companies

The questionnaire was sent to mainly consulting engineering companies, of which four of seven large companies responded (57% participation), five of six medium companies responded (83% participation) and five of seven small companies responded (71% participation). Furthermore, six contracting companies and four manufacturing companies were involved in the survey as well, of which responses were provided from five contracting companies(83% participation) and three manufacturing companies(75% participation), respectively. Common to all companies was that they consider or even predict the indoor environment in buildings, which is making them suitable to participate in the investigation.

Company	Size	Representation
Niras A/S	Large	Consulting engineering company
Grontmij A/S	Large	Consulting engineering company
Alectia A/S	Large	Consulting engineering company
Orbicon	Large	Consulting engineering company
Moe & Brødsgaard A/S Rådgivende Ingeniører	Medium	Consulting engineering company
ISC Rådgivende Ingeniører A/S	Medium	Consulting engineering company
EKJ Rådgivende Ingeniører A/S	Medium	Consulting engineering company
Esbensen Rådgivende Ingeniører A/S	Medium	Consulting engineering company
Brix & Kamp A/S	Medium	Consulting engineering company
Erasmus & Partnere A/S	Small	Consulting engineering company
Øllgaard Rådgivende Ingeniører A/S	Small	Consulting engineering company
Cenergia Energy Consultants	Small	Consulting engineering company
Ekolab	Small	Consulting engineering company
Stokvad & Kerstens A/S	Small	Consulting engineering company

Table D.1: *List of answered engineering consulting companies.*

Company	Size	Representation
MT Højgaard A/S	Large	Contracting company
Bravida	Large	Contracting company
NCC Construction A/S	Large	Contracting company
Bascon A/S	Medium	Contracting company
Eurodan-huse	Medium	Contracting company
Saint-Gobain ISOVER A/S	Large	Manufacturing company
Velux A/S	Large	Manufacturing company
WindowMaster A/S	Medium	Manufacturing company

Table D.2: *List of answered contracting and manufacturing companies.*

The size of the individual companies have been determined according to table 3.1, for which market information was found for each participating company, [Markedsdata 2013].

D.2 Questionnaire

The questionnaire was sent in an online format to the participating companies both in a Danish and English version in order to achieve quantitative response.

Master thesis "Evaluation of simplified models fro checking compliance with building regulations"

This questionnaire is a part of the master thesis performed by two students from Aalborg University - Viktors Homics and Morten Kirkedal. The purpose is to analyse how the indoor environmental calculations are done in companies in Denmark and whether the companies need a simplified tool, which is capable of doing these calculations.

Note, that the questionnaire is treated anonymously.
**Required*

Specify your name and surname*

Specify company you are representing*

1) How often do you perform thermal comfort and indoor air quality calculations?
(Enter on a scale of 1-5 where 1 corresponds to "never" and 5 corresponds to "for every project")

2) What is your purpose of performing indoor environmental calculations?
(You can select more than one of the following possibilities)

- Authority approval
- Design of building and its components
- Analysis of thermal comfort and indoor air quality
- Other

3) By use of which tools do you perform indoor environmental calculations?
(You can select more than one of the following possibilities)

- BSim
- Be10
- Quasi-steady-state calculation
- IES VE
- PHPP
- Other

4) Please express your opinion about chosen tools.
(e.g. your satisfaction regarding practical usage, accuracy, presentation of results)

5) Do you compare your thermal comfort results with future Building Regulation requirements coming into force in 2015?
(Number of hours with indoor temperature above 26°C and 27°C respectively)

- Yes
- No
- Other

6) Do you need a simplified tool for prediction of indoor environment?
(Enter on a scale of 1-5 where 1 corresponds to "Don't need" and 5 corresponds to "Strong need")

7) What kind of output parameters do you prefer from the simplified tool?
(You can select more than one of the following possibilities)

- Number of hours above 26°C and 27°C
- PPD, PMV indexes
- CO_2 level
- Other
- Relative humidity
- Perceived air quality (PD)
- Insufficient heating

8) Do you estimate uncertainties in indoor environmental calculations?
(Enter on a scale of 1-5 where 1 corresponds to "Never" and 5 corresponds to "Always")

9) How?
(Explain your approach in words)

10) Do you need to implement sensitivity and uncertainty analysis in the indoor environmental calculations?
(Enter on a scale of 1-5 where 1 corresponds to "Don't need" and 5 corresponds to "Strong need")

11) To your experience what are the most uncertain parameters regarding indoor environmental calculations?
(Explain your experience in words)

12) Do you consider occupants behaviour in indoor environmental calculations?
(Enter on a scale of 1-5 where 1 corresponds to "Never" and 5 corresponds to "Always")

13) To what extent do you find it important?
(Enter on a scale of 1-5 where 1 corresponds to "Not important" and 5 corresponds to "Very important")

14) Do you prefer speed or accuracy in indoor environmental simulations?
(Enter on a scale of 1-5 where 1 corresponds to "High speed" and 5 corresponds to "High accuracy")

15) Please express your opinion regarding your choice in previous question.
(Explain your opinion in words)

16) Do you perform stand-alone indoor environmental calculations or do you combine them with energy calculations?
(Enter on a scale of 1-5 where 1 corresponds to "Always stand-alone" and 5 corresponds to "Always combined")

D.3 Data of results

The following tables contain data results in connection with the survey. These data are obtained from responses provided by the participating companies in November 2012. The data treatment is attached as an electronically appendix in appendix A.1 - *Results_of_Survey.xlsx*.

Category of company	**Frequency of answers**					**Mean value**	**Standard deviation**
	1	**2**	**3**	**4**	**5**	μ	σ
Large consulting companies	0	1	0	2	1	3.75	1.09
Medium consulting companies	0	0	3	2	0	3.40	0.55
Small consulting companies	1	2	1	1	0	2.40	1.02
Contracting companies	1	0	1	3	0	3.20	1.17
Manufacturing companies	0	2	0	1	0	2.67	0.94
Total	2	5	5	9	1		

Table D.3: *1) How often do you perform thermal comfort and indoor air quality calculations?*

Category of company	Authority approval	Design	Analysis
Large consulting companies	2	3	4
Medium consulting companies	3	4	5
Small consulting companies	3	2	4
Contracting companies	4	3	4
Manufacturing companies	0	2	3
Total	12	14	20

Table D.4: *2) What is your purpose of performing indoor environmental calculations?*

Category of company	BSim	IES VE	PHPP	Be10	Quasi-steady-state calculation	Other
Large consulting companies	4	2	1	2	2	0
Medium consulting companies	4	3	1	2	1	0
Small consulting companies	2	1	1	4	2	0
Contracting companies	3	0	1	2	1	2
Manufacturing companies	1	2	1	2	0	1
Total	14	8	5	12	6	3

Table D.5: *3) By use of which tools do you perform indoor environmental calculations?*

Category of company	Frequency of answers	
	Yes	No
Large consulting companies	4	0
Medium consulting companies	5	1
Small consulting companies	4	1
Contracting companies	4	0
Manufacturing companies	3	0
Total	20	2

Table D.6: *5) Do you compare your thermal comfort results with future Building Regulation requirements coming into force in 2015?*

Category of company	**Frequency of answers**					**Mean value**	**Standard deviation**
	1	**2**	**3**	**4**	**5**	μ	σ
Large consulting companies	1	0	1	0	2	3.50	1.91
Medium consulting companies	0	1	1	2	1	3.60	1.02
Small consulting companies	0	1	0	1	3	4.20	1.17
Contracting companies	2	0	0	2	1	3.00	1.67
Manufacturing companies	1	0	0	1	1	3.33	1.70
Total	4	2	2	6	8		

Table D.7: *6) Do you need a simplified tool for prediction of indoor environment?*

Category of company	**Number of hours above 26°C and 27°C**	**PMV- and PPD-indexes**	**CO_2 level**
Large consulting companies	4	1	1
Medium consulting companies	5	2	2
Small consulting companies	5	1	1
Contracting companies	5	2	1
Manufacturing companies	3	1	1
Total	22	7	6

Table D.8: *7) What kind of output parameters do you prefer from the simplified tool? First part.*

Category of company	**Relative humidity**	**Perceived air quality (PD)**	**Insufficient heating**	**Other**
Large consulting companies	4	1	0	0
Medium consulting companies	2	1	2	0
Small consulting companies	5	3	3	1
Contracting companies	3	2	1	0
Manufacturing companies	3	0	0	0
Total	17	7	6	1

Table D.9: *7) What kind of output parameters do you prefer from the simplified tool? Second part.*

Category of company	Frequency of answers					Mean value	Standard deviation
	1	2	3	4	5	μ	σ
Large consulting companies	1	2	0	0	1	2.50	1.50
Medium consulting companies	1	2	2	0	0	2.20	0.75
Small consulting companies	0	0	2	2	1	3.80	0.75
Contracting companies	1	1	0	3	0	3.00	1.26
Manufacturing companies	2	0	0	1	0	2.00	1.41
Total	5	5	4	6	2		

Table D.10: *8) Do you estimate uncertainties in indoor environmental calculations?*

Category of company	Frequency of answers					Mean value	Standard deviation
	1	2	3	4	5	μ	σ
Large consulting companies	1	2	0	1	0	2.25	1.09
Medium consulting companies	0	3	0	2	0	2.80	0.98
Small consulting companies	1	2	1	1	0	2.40	1.02
Contracting companies	1	1	1	2	0	2.80	1.17
Manufacturing companies	1	0	0	2	0	3.00	1.41
Total	4	8	2	8	0		

Table D.11: *10) Do you need to implement uncertainty and sensitivity analysis in the indoor environmental calculations?*

Category of company	Frequency of answers					Mean value	Standard deviation
	1	2	3	4	5	μ	σ
Large consulting companies	0	2	0	0	2	3.50	1.50
Medium consulting companies	1	0	1	2	1	3.40	1.36
Small consulting companies	1	1	2	0	1	2.80	1.33
Contracting companies	0	1	1	2	1	3.60	1.02
Manufacturing companies	1	0	0	1	1	3.33	1.70
Total	3	4	4	5	6		

Table D.12: *12) Do you consider occupants behaviour in indoor environmental calculations?*

Category of company	Frequency of answers					Mean value	Standard deviation
	1	**2**	**3**	**4**	**5**	μ	σ
Large consulting companies	0	2	0	0	2	3.50	1.50
Medium consulting companies	1	0	1	2	1	3.40	1.36
Small consulting companies	1	1	2	0	1	2.80	1.33
Contracting companies	0	1	1	2	1	3.60	1.02
Manufacturing companies	1	0	0	1	1	3.33	1.70
Total	3	4	4	5	6		

Table D.13: *13) To what extent do you find it important?*

Category of company	Frequency of answers					Mean value	Standard deviation
	1	**2**	**3**	**4**	**5**	μ	σ
Large consulting companies	0	0	0	2	2	4.50	0.50
Medium consulting companies	0	0	2	2	1	3.80	0.75
Small consulting companies	1	0	3	0	1	3.00	1.26
Contracting companies	1	1	1	1	1	3.00	1.41
Manufacturing companies	0	1	1	1	0	3.00	0.82
Total	2	2	7	6	5		

Table D.14: *14) Do you prefer speed or accuracy in indoor environmental simulations?*

Category of company	Frequency of answers					Mean value	Standard deviation
	1	**2**	**3**	**4**	**5**	μ	σ
Large consulting companies	0	3	1	0	0	2.25	0.43
Medium consulting companies	0	0	4	1	0	3.20	0.40
Small consulting companies	2	0	3	0	0	2.20	0.98
Contracting companies	2	0	1	0	2	3.00	1.79
Manufacturing companies	1	0	1	1	0	2.67	1.25
Total	5	3	10	2	2		

Table D.15: *16) Do you perform stand-alone indoor environmental calculations or do you combine them with energy calculations?*

Appendix **E**

Lumped capacitance method

Current chapter introduces a method, which is a backbone for the calculation procedures of simplified models reviewed in the current thesis. This method provides a great level of simplicity, although possesses significant assumptions, which should be considered in application of simplified energy simulation models.

Lumped capacitance method deals with transient conduction problems and is often used for calculation of heat transfer and subsequently temperatures within a thermal zone. As an important feature of the method, all elements are treated as they are concentrated or, in other words, lumped. It was invented to simplify approximation of heat transfer processes in a building by avoiding complex differential heat equations. The process of transient heat transfer in the lumped capacitance method is described by ordinary differential equation (E.1), [Narowski et al. 2010, p. 2].

$$C\frac{dT}{d\tau} = -H\Delta T \tag{E.1}$$

C_{m}	Thermal capacity, $[\mathrm{Wh}/^{\circ}\mathrm{C}]$
T	Temperature, $[^{\circ}\mathrm{C}]$
τ	Time, [h]
H	Specific heat transfer, $[\mathrm{W}/^{\circ}\mathrm{C}]$

The lumped capacitance method makes an assumption that thermal conductivity in solid materials is high and the heat transfer on the surface is low comparing to thermal conductivity inside materials. Another assumption of the method is that the temperature distribution in solids is uniform, hence it neglects the temperature gradient within solid materials. Furthermore, the thermal mass is lumped into one building thermal capacity, instead of distinguishing between thermal capacity of different building elements and furniture. [Narowski et al. 2010, p. 2].

Many thermal building models are based on this method, starting from 2R1C (two resistors, one capacity) lumped capacitance model. Modifications of this model can lead to more sophisticated models such as 5R1C, presented in EN ISO 13790 [2008], which is capable of calculating besides room air temperature, temperature of internal surfaces and thermal mass.

Appendix **F**

EN ISO 13790 Simple hourly method

This appendix serves a detailed description of a simple hourly method for energy calculation retrieved from EN ISO 13790 [2008]. The description of both the method and assumptions presented in the beginning is followed afterwards by calculation procedure and heat balances establishment.

F.1 Principle of calculation procedure

The calculation procedure EN ISO 13790 simple hourly method is based on energy conservation in the unknown temperature nodes of the lumped capacitance model based on a 5R1C scheme. This is illustrated in figure F.1, in which the resistances between the temperature nodes are replaced with the specific heat transfers, whereas the red circles indicate the nodes for which the temperature should be determined.

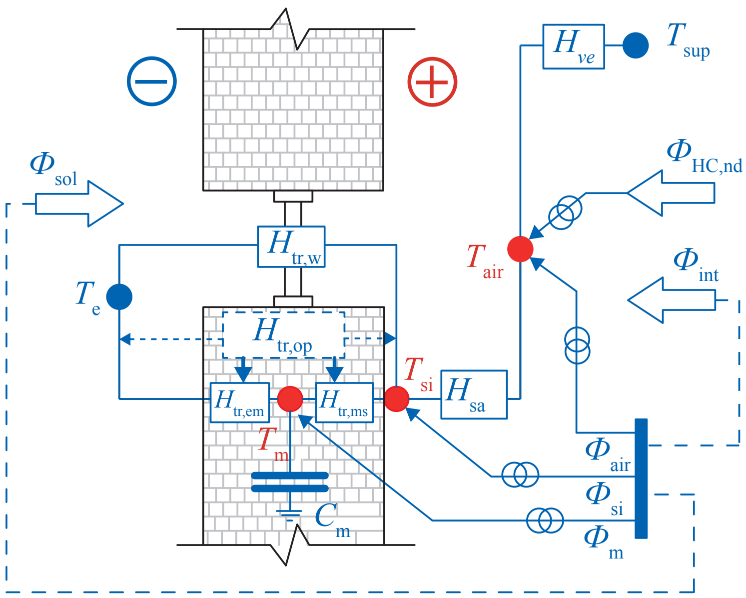


Figure F.1: *Representation of the heat exchange within a building zone by means of lumped capacitance 5R1C scheme. Redrawn from Narowski et al. [2010, p. 3].*

The specific heat loss by transmission is divided into two parts as EN ISO 13790 simplified model distinguishes between opaque building construction elements, $H_{\mathrm{tr,opa}}$, and building elements with a negligible thermal mass, $H_{\mathrm{tr,w}}$, e.g. doors, windows and other glazed elements of the building envelope. Additionally, the specific heat loss of opaque building elements is divided into $H_{\mathrm{tr,em}}$, representing the heat transfer between thermal mass and external environment, and $H_{\mathrm{tr,ms}}$, representing the heat transfer between thermal mass and internal surface. [EN ISO 13790 2008, p. 66]

The specific heat transfer between the internal surfaces and the room air is based on the HTC with a fixed value 3.45 $^{\mathrm{W}}/_{\mathrm{m^2\cdot °C}}$ and area of all surfaces facing the thermal zone. The latter is simplified by using the conditioned floor area and a ratio between internal surfaces area and floor area, see equation (F.1).

$$H_{\mathrm{sa}} = \alpha_{\mathrm{tot}} \cdot A_{\mathrm{tot}} = \alpha_{\mathrm{tot}} \cdot A_{\mathrm{f}} \cdot f_{\mathrm{si,f}} \tag{F.1}$$

H_{sa}	Specific heat transfer between internal surfaces and room air, $\left[^{\mathrm{W}}/_{\mathrm{°C}}\right]$
α_{tot}	Surface HTC, equal to 3.45, $\left[^{\mathrm{W}}/_{\mathrm{m^2\cdot °C}}\right]$
A_{tot}	Area of all surfaces facing the thermal zone, $\left[\mathrm{m^2}\right]$
A_{f}	The conditioned floor area, $\left[\mathrm{m^2}\right]$
$f_{\mathrm{si,f}}$	The dimensionless ratio between internal surfaces area and floor area, which can be assumed to be 4.5, [-]

The division of specific heat loss by transmission through opaque building elements is performed according to the rule of resistors connection in serial electrical circuits. This rule states that the total resistance is equal to sum of all resistances, see equation (F.2).

$$R_{\mathrm{tot}} = R_1 + R_2 + \ldots + R_{\mathrm{n}} \tag{F.2}$$

However, specific heat loss is inverse proportional to resistance, i.e. $H \propto 1/R$, thus the division of the specific heat loss by transmission through opaque building elements is performed via equations (F.3), (F.4) and (F.5). In effective mass area calculation thermal capacity includes thermal capacities of all building elements which are in direct contact with room air, [EN ISO 13790 2008, p.].

$$H_{\mathrm{tr,em}} = \frac{1}{1/H_{\mathrm{tr,opa}} - 1/H_{\mathrm{tr,ms}}} \tag{F.3}$$

$$H_{\mathrm{tr,ms}} = U_{\mathrm{ms}} \cdot A_{\mathrm{m}} \tag{F.4}$$

$$A_{\mathrm{m}} = \frac{C_{\mathrm{m}}^2}{\Sigma A_{\mathrm{j}} \cdot \kappa_{\mathrm{j}}^2} \tag{F.5}$$

$H_{tr,opa}$	Specific heat loss by transmission through opaque building elements, $\left[{}^{W}/_{{}^{\circ}C}\right]$
$H_{tr,em}$	Specific heat loss between thermal mass and external air, $\left[{}^{W}/_{{}^{\circ}C}\right]$
$H_{tr,ms}$	Specific heat transfer between thermal mass and internal surface, $\left[{}^{W}/_{{}^{\circ}C}\right]$
U_{ms}	HTC between thermal mass and internal surfaces with a fixed value of 9.1, $\left[{}^{W}/_{m^2 \cdot {}^{\circ}C}\right]$
A_m	Effective mass area, $\left[m^2\right]$
C_m	Thermal capacity of the thermal zone, $\left[{}^{J}/_{{}^{\circ}C}\right]$
A_j	Area of the building element j, $\left[m^2\right]$
κ_j	Areal thermal capacity of the building element j, $\left[{}^{J}/_{m^2\,{}^{\circ}C}\right]$

Effective mass area can be determined either by calculating via equation (F.5) or rather simple by using relation between effective mass area and floor area provided in the standard, see table F.1.

Building class	A_m, $\left[m^2\right]$
Very light	2.5 x A_f
Light	2.5 x A_f
Medium	2.5 x A_f
Heavy	3.0 x A_f
Very heavy	3.5 x A_f

Table F.1: *Default values for effective mass area, [EN ISO 13790 2008, p.68].*

The thermal capacity of the thermal zone can either be determined according to predefined values dependent of the building class or by applying theoretical calculation by taking into account building construction elements and their capability to accumulate heat. These approaches are thoroughly described in appendix L.

F.2 Distribution of heat flow from thermal loads

A feature of the current simplified model, which intends to increase the accuracy of calculation, is allocation of thermal loads among three temperature nodes regarding the type of heat transfer. This section serves equations, which explain how the heat flow from internal and solar heat sources is distributed among the three unknown temperature nodes and not the calculation of the sources itself. Thermal loads distribution within a thermal zone is shown in figure F.2.

The convective part of internal heat gains is solely influencing the room air temperature, while the solar heat gains and radiative part of internal heat gains are affecting the thermal mass temperature. However, as doors and windows have a negligible thermal mass, only its internal surfaces is affected by the radiative heat flow and a thermal loss, Φ_{loss}, occurs as part of the thermal loads is transmitted through these non-accumulating elements to the external environment.

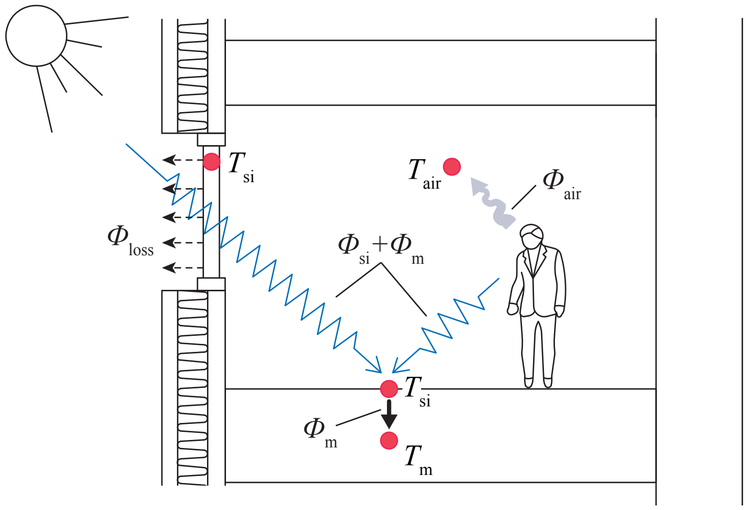


Figure F.2: *Thermal loads distribution within a thermal zone realised in EN ISO 13790 simple hourly method.*

Half of the internal heat gains represents convective part, which influence room air temperature directly, as shown in equation (F.6), while the rest half represents radiative part, which is absorbed by exposed surfaces. This radiant/convective split contradicts with empirically found results, saying that for people with moderate activity radiant/convective split varies from 0.5/0.5 to 0.3/0.7 depending on the clothes, air velocity and indoor temperatures, [Hyldgård et al. 2001, table 1.3], and for equipment convective fraction is often also dominating, [ASHRAE 2009, p. 29.13].

$$\Phi_{air} = 0.5\,\Phi_{int} \tag{F.6}$$

Φ_{int}	Internal heat gain, [W]
Φ_{air}	Heat gain to the node of internal air temperature, [W]

A ratio between effective mass area and all surfaces area represents a weighting factor, which is used to determine which part of radiative internal and solar heat gains is absorbed via thermal mass, as is reflected in equation (F.7). Note, that an assumption of this method is that none of the solar radiation is absorbed by the room air. However in reality, when using internal solar shading, part of the absorbed solar radiation by the shading is subsequently transfered directly to the room air.

$$\Phi_m = \frac{A_m}{A_{tot}}\,(0.5\,\Phi_{int} + \Phi_{sol}) \tag{F.7}$$

Φ_m	Heat gain to the node of thermal mass temperature, [W]
Φ_{sol}	Solar heat gain, [W]

The remaining part of the radiative heat gains influences the internal surfaces temperature, as equations (F.8) and (F.9) indicate. However, due to the assumption that windows and doors do not have any thermal mass, the radiative heat gains, absorbed by windows and doors are considered as a heat losses and thus reduce the heat flow to the thermal mass, see equation (F.10). The reduction is proportional to the ratio of windows area and all internal surfaces area as well as to the ratio of HTC of windows and HTC between internal surfaces of envelope and thermal mass.

$$\Phi_{si} = \left(1 - \frac{A_m}{A_{tot}} - \frac{H_{tr,w}}{U_{ms}\,A_{tot}}\right)(0.5\,\Phi_{int} + \Phi_{sol}) \tag{F.8}$$

$$H_{tr,w} = \sum U_w\,A_w \tag{F.9}$$

$$\Phi_{loss} = \frac{H_{tr,w}}{U_{ms}\,A_{tot}}(0.5\,\Phi_{int} + \Phi_{sol}) \tag{F.10}$$

Φ_{si}	Heat gain to the node of internal surfaces temperature, [W]
$H_{tr,w}$	Specific heat loss by transmission through windows and doors, $[{}^{W}/_{\circ C}]$
U_w	HTC of windows and doors, $[{}^{W}/_{m^2\circ C}]$
A_w	Area of windows and doors, $[m^2]$
Φ_{loss}	Part of thermal loads transmitted to external air, [W]

F.3 Calculation of unknown temperatures

The EN ISO 13790 simplified model conducts the calculation of heat balances established at the nodes of unknown temperatures, illustrated in figure F.3, which has the same meaning as figure F.1, while showing a distinct sequence of temperatures calculation and is more convenient for comparison with other simplified models.

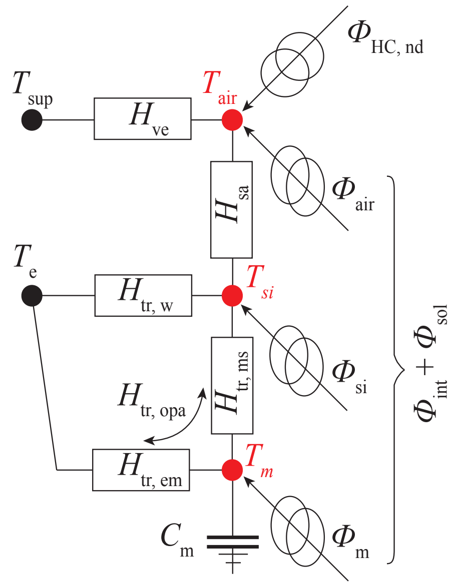
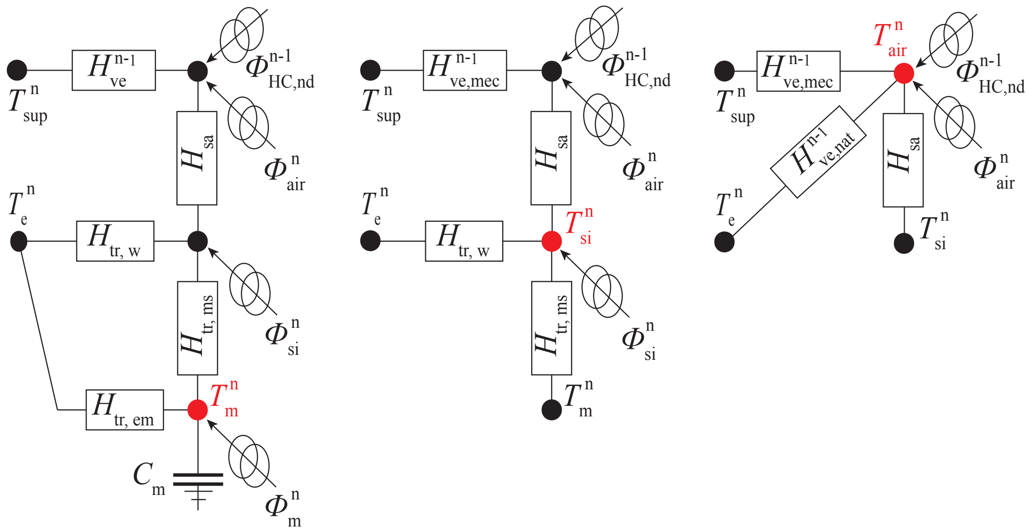


Figure F.3: *5R1C scheme of EN ISO 13790 simple hourly method visualized in thermal-electric analogy. Redrawn from EN ISO 13790 [2008, p. 90]*

This sequential solution of equations implies primarily calculation of thermal mass temperature, while substituting room air and internal surfaces temperatures by their respective heat balance equations. When the thermal mass temperature is determined, it is used for calculation of internal surfaces temperature. Finally, room air temperature is calculated by utilising the previously determined temperature for the present time step. This sequence of unknown temperatures calculation during one time step is illustrated in figure F.4.



(a) (b) (c)

Figure F.4: *Sequence of unknown temperatures calculation for one time step for thermal mass (a), internal surfaces (b) and room air (c).*

For reader's convenience the sequence of heat balances is presented inverse, i.e. room air heat balance is explained first, although it is the last in the calculation sequence. This is done in order to show a straightforward substitution of room air temperature in equation for internal surfaces temperature and analogous substitution of internal surfaces temperature in equation for thermal mass temperature.

F.3.1 Heat balance for room air

Heat balance at the room temperature node is established in equation (F.11), which is based on illustrations in figure F.4(c).

$$\Phi_{\mathrm{H,nd}} + \Phi_{\mathrm{air}} = H_{\mathrm{ve}} \left(T_{\mathrm{air}} - T_{\mathrm{sup}}\right) + H_{\mathrm{sa}} \left(T_{\mathrm{air}} - T_{\mathrm{si}}\right) \tag{F.11}$$

$\Phi_{\mathrm{H,nd}}$	Demand for heating or cooling power, [W]
T_{air}	Node of room air temperature, [°C]
T_{si}	Node of internal surfaces temperature, [°C]
T_{sup}	Node of supply air temperature, [°C]
H_{ve}	Specific heat loss by ventilation, $\left[{}^{\mathrm{W}}/_{\circ\mathrm{C}}\right]$

Subsequently, the room air temperature is derived from equation (F.11) and calculated via equation (F.12). The supply air temperature is rather constant for a mechanical ventilation system whereas for natural ventilation this parameters is equal to the external temperature.

$$T_{air} = \frac{H_{sa}\,T_{si} + H_{ve}\,T_{sup} + \Phi_{air} + \Phi_{HC,nd}}{H_{sa} + H_{ve}} \tag{F.12}$$

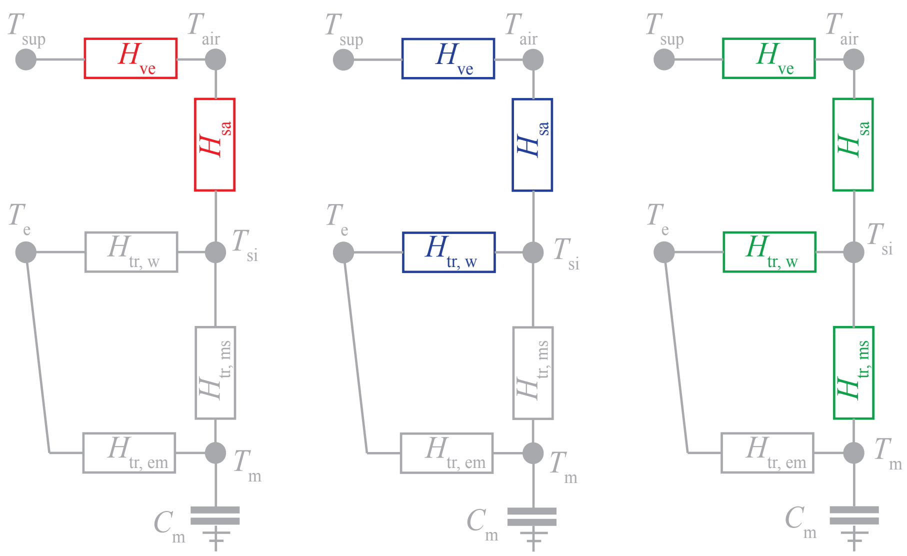
F.3.2 Heat balance for internal surfaces

For the internal surfaces temperature, which is calculated before room air temperature, the heat balance is shown in equation (F.13), which is based on illustrations in figure F.4(b).

$$\Phi_{si} = H_{sa}\,(T_{si} - T_{air}) + H_w\,(T_{si} - T_e) + H_{tr,ms}\,(T_{si} - T_m) \tag{F.13}$$

T_m	Node representing temperature of thermal mass, [°C]
T_e	Node of external air temperature, [°C]

Although room air temperature is not determined at this step, equation (F.13) can have one unknown by inserting equation (F.12) in it. Furthermore, the combined specific heat transfer $H_{tr,1}$, see figure F.5(a), is calculated by using the rules of resistors connection in serial and parallel electrical circuits. Bearing in mind that specific heat loss is inverse proportional to resistance, i.e. $H \propto 1/R$, calculation of $H_{tr,1}$ is shown in equation (F.14). By analogy $H_{tr,2}$ and $H_{tr,3}$, see figure F.5(b) and F.5(c) respectively, which are used later are determined by use of equations (F.15) and (F.16).



(a) (b) (c)

Figure F.5: *Combined specific heat transfers in 5R1C scheme of EN ISO 13790 simplified model. $H_{tr,1}$ (a), $H_{tr,2}$ (b) and $H_{tr,3}$ (c).*

$$H_{\mathrm{tr,1}} = \frac{1}{1/H_{\mathrm{ve}} + 1/H_{\mathrm{sa}}} \tag{F.14}$$

$$H_{\mathrm{tr,2}} = H_{\mathrm{tr,1}} + H_{\mathrm{tr,w}} \tag{F.15}$$

$$H_{\mathrm{tr,3}} = \frac{1}{1/H_{\mathrm{tr,2}} + 1/H_{\mathrm{tr,ms}}} \tag{F.16}$$

Taking aforementioned into account internal surfaces temperature is calculated by equation (F.17).

$$T_{\mathrm{si}} = \frac{H_{\mathrm{tr,ms}}\, T_{\mathrm{m}} + \Phi_{\mathrm{si}} + H_{\mathrm{tr,w}}\, T_{\mathrm{e}} + H_{\mathrm{tr,1}} (T_{\mathrm{sup}} + (\Phi_{\mathrm{air}} + \Phi_{\mathrm{HC,nd}})/H_{\mathrm{ve}})}{H_{\mathrm{tr,ms}} + H_{\mathrm{tr,w}} + H_{\mathrm{tr,1}}} \tag{F.17}$$

F.3.3 Heat balance for thermal mass

Heat balance for thermal mass temperature node includes thermal capacity of the thermal zone, indicating transient conduction and thus is represented by ordinary differential equation (F.18) as well as illustrated in figure F.4(a).

$$C_{\mathrm{m}} \frac{dT_{\mathrm{m}}}{d\tau} = \Phi_{\mathrm{m}} - H_{\mathrm{tr,em}} (T_{\mathrm{m}} - T_{\mathrm{e}}) - H_{\mathrm{tr,ms}} (T_{\mathrm{m}} - T_{\mathrm{si}}) \tag{F.18}$$

$d\tau$	Time step, [s]

In equation (F.18) internal surfaces temperature is unknown, since temperature of thermal mass is calculated first for each time step. Hence, by again using substitutions, this time from equation (F.13) accompanying with combined specific heat transfers determined in equations (F.15) and (F.16), equation (F.18) transforms into equation (F.19).

$$C_{\mathrm{m}} \frac{dT_{\mathrm{m}}}{d\tau} = \Phi_{\mathrm{m}} - H_{\mathrm{tr,em}} (T_{\mathrm{m}} - T_{\mathrm{e}}) - H_{\mathrm{tr,3}} \left[T_{\mathrm{m}} - \frac{\Phi_{\mathrm{si}} + H_{\mathrm{tr,w}}\, T_{\mathrm{e}} + H_{\mathrm{tr,1}} \left(T_{\mathrm{sup}} + (\Phi_{\mathrm{air}} + \Phi_{\mathrm{HC,nd}})/H_{\mathrm{ve}} \right)}{H_{\mathrm{tr,2}}} \right] \tag{F.19}$$

Further transformation implies introduction of the term Φ_{mtot}, equation (F.21), which changes previous equation into equation (F.20).

$$C_{\mathrm{m}} \frac{dT_{\mathrm{m}}}{d\tau} = -T_{\mathrm{m}} (H_{\mathrm{tr,em}} + H_{\mathrm{tr,3}}) + \Phi_{\mathrm{mtot}} \tag{F.20}$$

$$\Phi_{\mathrm{mtot}} = \Phi_{\mathrm{m}} + H_{\mathrm{tr,em}}\, T_{\mathrm{e}} + H_{\mathrm{tr,3}} \left[\frac{\Phi_{\mathrm{si}} + H_{\mathrm{tr,w}}\, T_{\mathrm{e}} + H_{\mathrm{tr,1}} \left(T_{\mathrm{sup}} + (\Phi_{\mathrm{air}} + \Phi_{\mathrm{HC,nd}})/H_{\mathrm{ve}} \right)}{H_{\mathrm{tr,2}}} \right] \tag{F.21}$$

The solution of foregoing ordinary differential equation is based on Crank-Nicolson scheme considering a time step of one hour, where only time change is considered and not space change. The choice of Crank-Nicolson method and not of forward or backward Euler methods can be explained by its more stable performance. As opposed to room air and internal surfaces temperatures, which are the average of one hour, temperature of thermal mass is calculated as an instantaneous value at every step, [EN ISO 13790 2008]. Applying Crank-Nicolson scheme to equation (F.20) with assumption of time step equal to one hour, equation (F.22) is obtained.

$$\frac{C_\mathrm{m}\left(T_\mathrm{m}^\mathrm{n}-T_\mathrm{m}^\mathrm{n\text{-}1}\right)}{d\tau}=\frac{\left[-T_\mathrm{m}^\mathrm{n\text{-}1}\left(H_\mathrm{tr,em}^\mathrm{n\text{-}1}+H_\mathrm{tr,3}^\mathrm{n\text{-}1}\right)+\Phi_\mathrm{mtot}^\mathrm{n\text{-}1}\right]+\left[-T_\mathrm{m}^\mathrm{n}\left(H_\mathrm{tr,em}^\mathrm{n}+H_\mathrm{tr,3}^\mathrm{n}\right)+\Phi_\mathrm{mtot}^\mathrm{n}\right]}{2} \tag{F.22}$$

For a given time step temperature of thermal mass is calculated at the end of the time step from previous value via equation (F.23), which is derived from equation (F.22).

$$T_\mathrm{m}^\mathrm{n}=\frac{T_\mathrm{m}^\mathrm{n\text{-}1}\left[C_\mathrm{m}/d\tau-0.5\left(H_\mathrm{tr,3}+H_\mathrm{tr,em}\right)\right]+\Phi_\mathrm{mtot}}{C_\mathrm{m}/d\tau+0.5\left(H_\mathrm{tr,3}+H_\mathrm{tr,em}\right)} \tag{F.23}$$

Finally, the average temperature of thermal mass is determined by equation (F.24).

$$T_\mathrm{m}=\frac{T_\mathrm{m}^\mathrm{n}+T_\mathrm{m}^\mathrm{n\text{-}1}}{2} \tag{F.24}$$

F.3.4 Operative temperature

The simple hourly method enables the opportunity to apply it for check of the thermal comfort in a thermal zone and increases the accuracy by implementation of convective and radiative parts of thermal loads, as it makes a distinction between room air and internal surface temperatures, [EN ISO 13790 2008, p. 24].

Consequently, when all three unknown temperature nodes are determined an operative temperature can be calculated by utilizing room air and internal surfaces temperatures via equation (F.25). Weighting coefficients, i.e. 0.3 and 0.7 are set up due to the fact that internal surfaces temperature is a combination of air and mean radiant temperatures weighted by the internal surfaces convective (3/8) and radiative (5/8) coefficients. [EN ISO 13790 2008, p. 95]

$$T_\mathrm{op}=0.3\,T_\mathrm{air}+0.7\,T_\mathrm{si} \tag{F.25}$$

T_op	Operative temperature, [°C]

Appendix G

Bo Adamson method

This appendix describes the calculation of the thermal conditions in a room for unsteady conditions by using the theory behind Bo Adamson's method. The method is slightly changed as the equations will be presented in a central difference form.

G.1 Principle of the method

The principle of Bo Adamson method is illustrated in figure G.1. The calculation expressions are designed as central difference equations and consider the unknown thermal factors; room air temperature, temperature of internal surfaces and temperature of heat accumulating layers.

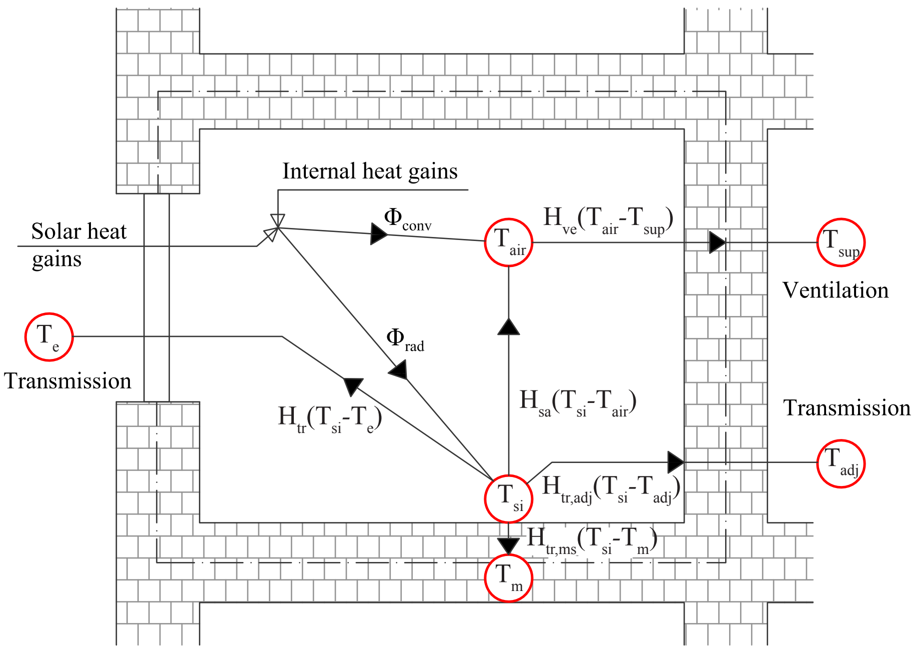


Figure G.1: *Principle of unknown temperature calculation in Bo Adamson method. Redrawn from Danvak ApS [1987, p. 100].*

The Specific heat transfer by transmission through opaque constructions occurs between external air and internal surfaces temperature nodes, without direct influence of the building thermal mass. This decreases the rate of passive cooling of thermal mass at nights during warm periods, and thus increases the risk of overheating, [Heiselberg 2008b, p. 13]. Furthermore, the transmission heat loss through windows, doors and opaque constructions are combined as they have identical applications in the RC scheme. The specific heat transfer between internal surfaces and room air, H_{sa}, is calculated by summing up the convective contribution from each internal surface element.

$$H_{sa} = \sum_{j=1}^{n} \alpha_{tot} A_j \tag{G.1}$$

H_{sa}	Specific heat transfer between internal surfaces and room air, $\left[{}^{W}/_{{}^\circ C}\right]$
α_{tot}	Surface HTC, $\left[{}^{W}/_{m^2 \cdot {}^\circ C}\right]$

It should be emphasized that area of building elements used in specific heat transfer calculation includes only opaque elements. The surface HTC, α_{tot}, which incorporates convective heat exchange depends on direction of the flow, i.e. upward, horizontal and downward. Therefore a distinction is made between ceiling, walls and floor which have the surface HTCs listed in table G.1.

Internal surface	**Surface HTC** α_{tot}, $\left[{}^{W}/_{m^2 \cdot {}^\circ C}\right]$
Ceilings	2.00
Walls	3.00
Floors	2.50

Table G.1: *Surface HTCs for different construction elements, [Danvak ApS 1987, p. 101].*

The specific heat flow between internal surfaces and heat accumulating layer, $H_{tr,ms}$, is depending on the thermal properties of the thermal mass and is calculated according to equation (G.2).

$$H_{tr,ms} = \sum_{j=1}^{n} U_{ms} A_j \tag{G.2}$$

$$U_{ms} = \frac{\lambda}{d/2}$$

$H_{tr,ms}$	Specific heat flow between internal surfaces and heat accumulating layers, $\left[{}^{W}/_{{}^\circ C}\right]$
U_{ms}	Transmission heat transfer coefficient, $\left[{}^{W}/_{m^2 \cdot {}^\circ C}\right]$
A_j	Area of the building element j, $\left[m^2\right]$
λ	Thermal conductivity, $\left[{}^{W}/_{m \cdot {}^\circ C}\right]$
d	Thickness of internal layer, $[m]$

The thermal capacity of the thermal zone can be determined by applying theoretical calculation by taking into account building construction elements and their capability to accumulate heat. These approaches are thoroughly described in appendix L.

The characteristics of heat accumulation of the thermal zone, C_m, can be determined by summarizing the heat capacity of each construction element, except doors and windows which are neglected, by using equation (G.3).

$$C_m = \sum_{j=1}^{n} A_j \cdot d \cdot \rho \cdot c_p \tag{G.3}$$

C_m	Thermal capacity of the thermal zone, $\left[{}^{Wh}/_{°C}\right]$
ρ	Density, $\left[{}^{kg}/_{m^3}\right]$
c_p	Specific heat capacity, $\left[{}^{J}/_{kg\,°C}\right]$

The location of heat accumulating layer according to the internal surface is determined as the minimum of the following criteria, [Danvak ApS 1987, p. 101-102]:

- Internally located in front of light insulation material;
- The thermal transmittance for the heat accumulating layer must be $\geq 2.00\ {}^{W}/_{m^2 \cdot °C}$;
- Distance from internal surface is less than 50 mm for light-weight materials and less than 100 mm for heavy-weight materials;
- Distance from internal surface is half of the wall thickness for internal walls;
- The time constant of the each internal surface can not vary more than a factor three compared to the time constant of the thermal zone or exceed a daily oscillation, cf. equation (L.7).

$$\frac{1}{3}\,\tau_0 \leq \frac{C_{m,j}}{H_{ms,j}} \leq \max \begin{cases} 3 \cdot \tau_0 \\ 24\ \mathrm{h}/(2\,\pi) = 3.8\ \mathrm{h} \end{cases} \tag{G.4}$$

G.2 Distribution of heat flow from thermal loads

The thermal loads occurring from solar and internal heat gains are distributed among two temperature nodes, namely room air and internal surfaces, as it is assumed that heat sources with a relative low temperature, e.g. appliances and people, distribute the emission of heat by convective and radiative part of both 50% as specified in equation (G.5) and (G.6). Radiant heat from solar radiation affects solely the internal surfaces.

$$\Phi_{air} = 0.5\ \Phi_{int} \tag{G.5}$$

$$\Phi_{si} = 0.5\ \Phi_{int} + \Phi_{sol} \tag{G.6}$$

Φ_{air}	Heat gain absorbed by room air, [W]
Φ_{si}	Heat gain absorbed by internal surfaces, [W]
Φ_{int}	Internal heat gains, [W]
Φ_{sol}	Solar heat gains, [W]

The solar heat gains are dependent on the permanent and movable shading, orientation of the collecting areas and their thermal characteristics. A distinction is made between direct and diffuse radiation of which the direct radiation accounts for the main part of the total solar radiation and is solely depending on the azimuth and altitude angle of the sun and the sky conditions, which are determined according to the solar position algorithm explained in appendix O.1. However, the direct solar radiation can be partly controlled by using solar shading. Diffuse radiation is also dependent on the sky conditions but is a rather complex phenomenon which is difficult to calculate. [Danvak ApS 1987, p. 94]

G.3 Calculation of unknown temperatures

Due to simplifications it is only necessary to establish three heat balance equations in order to determine the three aforementioned unknown temperatures. In order to numerically solve these three heat balance equations in differential form, they are changed to central difference equations.

The calculation procedure of heat balances established at the nodes of unknown temperatures in the current simplified model is illustrated in figure G.2, which has the same meaning as figure G.1, while showing a distinct sequence of temperature calculation and is more convenient for comparison with the other simplified models. The equations are derived from heat balances established at the unknown temperature nodes.

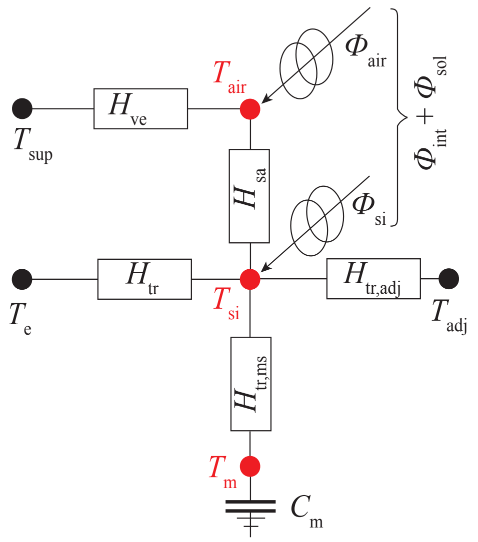


Figure G.2: *Representation of the heat exchange within a building zone by means of lumped capacitance 5R1C scheme. Inspired by EN ISO 13790 [2008, p. 90].*

The sequential solution of heat balance equations implies primarily calculation of the thermal mass temperature first, then internal surface temperature and, finally, room air temperature. This sequence of unknown temperatures calculation during one time step is illustrated in figure G.3.

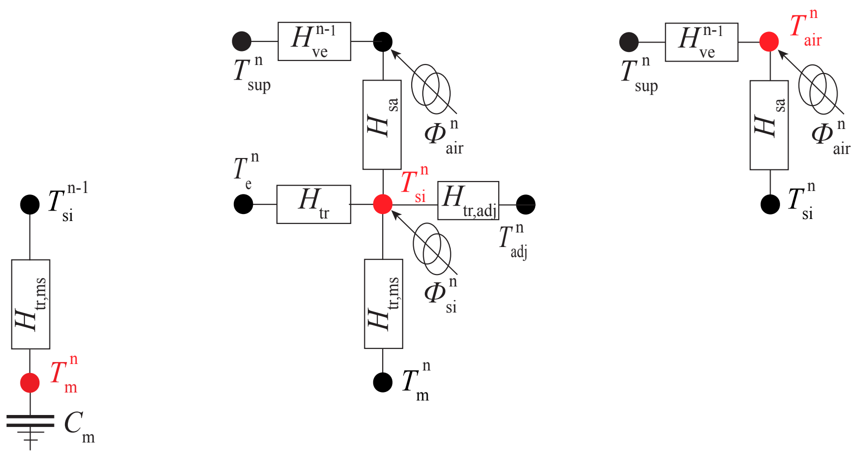


Figure G.3: *Sequence of unknown temperatures calculation for one time step for thermal mass (a), internal surfaces (b) and room air (c).*

The considered simulation time is divided into time steps, $\Delta\tau$, of one hour. Thus the equations valid for the n'th time atep can be expressed as in the following equations. The index n defines the temperatures at the ending of the n'th time step. [Danvak ApS 1987, p. 103-104]

G.3.1 Heat balance for thermal mass

The construction accumulates or emits heat depending on whether the heat is transferred inwards or outwards. This implies as shown in equation (G.7) that the accumulating effect depends on the temperature difference of the heat accumulating layer over time. The thermal capacity of the thermal zone is simplified by having a fictitious infinite thin layer with the same temperature [Danvak ApS 1987, p. 101].

$$H_{\text{tr,ms}}\left(T_{\text{si}} - T_{\text{m}}\right) = C_{\text{m}}\frac{dT_{\text{m}}}{d\tau} \tag{G.7}$$

T_{si}	Temperature of internal surfaces, [°C]
T_m	Temperature of the heat accumulating layer, [°C]
τ	Time, [h]

The solution of the ordinary differential equation, representing the thermal mass heat balance, is based on forward (explicit) Euler scheme by considering a time step of one hour. This implies a rather simplified calculation procedure, as only a temperature from previous step is utilised in the present time step as illustrated in figure G.3(a). In order to enhance the understanding and simplify the approach of establishing the calculation procedure, Bo Adamson method utilises calculation constant. Thus, the equation is presented in specific manner in order to incorporate calculation constants.

$$T_{\text{m}}^{\text{n}} = T_{\text{si}}^{\text{n-1}}\frac{H_{\text{tr,ms}}\,\Delta\tau}{C_{\text{m}}} + T_{\text{m}}^{\text{n-1}}\left(1 - \frac{H_{\text{tr,ms}}\,\Delta\tau}{C_{\text{m}}}\right) \tag{G.8}$$

The solutions of the heat balance equation for thermal mass can be described as in equation (G.9) by having the calculation constants specified below.

$$T_{\mathrm{m}}^{\mathrm{n}} = a_1\, T_{\mathrm{m}}^{\mathrm{n\text{-}1}} + a_2\, T_{\mathrm{si}}^{\mathrm{n\text{-}1}} \tag{G.9}$$

$$a_1 = 1 - \frac{H_{\mathrm{tr,ms}}\,\Delta\tau}{C_{\mathrm{m}}}$$
$$a_2 = 1 - a_1$$

G.3.2 Heat balance for internal surfaces

The heat balance at the internal surfaces temperature node is shown in equation (G.10) and illustrated in figure G.3(b). The method is simplified by having even distribution of radiation over the surfaces independently of the solar incidence, and hence only one temperature of the internal surfaces is used, [Danvak ApS 1987, p. 101]. This implies no radiant heat exchange in between the internal surfaces.

$$\Phi_{\mathrm{si}} = H_{\mathrm{tr,ms}}\left(T_{\mathrm{si}} - T_{\mathrm{m}}\right) + H_{\mathrm{adj}}\left(T_{\mathrm{si}} - T_{\mathrm{adj}}\right) + H_{\mathrm{tr}}\left(T_{\mathrm{si}} - T_{\mathrm{e}}\right) + H_{\mathrm{sa}}\left(T_{\mathrm{si}} - T_{\mathrm{air}}\right) \tag{G.10}$$

H_{tr}	Specific heat flow by transmission, $\left[{}^{\mathrm{W}}\!/_{^\circ\mathrm{C}}\right]$
H_{adj}	Specific heat flow between internal surfaces and adjacent rooms, $\left[{}^{\mathrm{W}}\!/_{^\circ\mathrm{C}}\right]$
T_{air}	Room air temperature, [°C]
T_{e}	External temperature, [°C]
T_{adj}	Temperature in the adjacent rooms, [°C]

For the treatment of foregoing heat balance equation the same procedure is used as in EN ISO 13790 method, which implies extraction of the room air temperature from its heat balance equation (G.15). In addition, the specific heat transfer between internal surface and room air is summed with the specific heat loss by ventilation according to the rules of resistors connection in serial electrical circuits, see equation (G.11). Note, that aspecific heat transfer is inverse proportional to a thermal resistance, i.e. $H \propto 1/R$. Hence the internal surfaces temperature heat balance equation (G.10) transforms into equation (G.12).

$$H_{\mathrm{sa}}\left(T_{\mathrm{si}}^{\mathrm{n}} - T_{\mathrm{air}}^{\mathrm{n}}\right) = \frac{H_{\mathrm{ve}}\, H_{\mathrm{sa}}}{H_{\mathrm{ve}} + H_{\mathrm{sa}}}\left(T_{\mathrm{si}}^{\mathrm{n}} - \frac{\Phi_{\mathrm{air}}^{\mathrm{n}} + H_{\mathrm{ve}}\, T_{\mathrm{sup}}^{\mathrm{n}}}{H_{\mathrm{ve}}}\right) \tag{G.11}$$

$$T_{\mathrm{si}}^{\mathrm{n}}\left(H_{\mathrm{tr,ms}} + H_{\mathrm{adj}} + H_{\mathrm{tr}} + \frac{H_{\mathrm{ve}}\, H_{\mathrm{sa}}}{H_{\mathrm{ve}} + H_{\mathrm{sa}}}\right) = \tag{G.12}$$
$$H_{\mathrm{tr,ms}}\, T_{\mathrm{m}}^{\mathrm{n}} + H_{\mathrm{adj}}\, T_{\mathrm{adj}}^{\mathrm{n}} + H_{\mathrm{tr}}\, T_{\mathrm{e}}^{\mathrm{n}} + T_{\mathrm{sup}}^{\mathrm{n}} \frac{H_{\mathrm{ve}}\, H_{\mathrm{sa}}}{H_{\mathrm{ve}} + H_{\mathrm{sa}}} + \Phi_{\mathrm{air}} \frac{H_{\mathrm{sa}}}{H_{\mathrm{ve}} + H_{\mathrm{sa}}} + \Phi_{\mathrm{si}}^{\mathrm{n}}$$

The equation is presented in specific manner in order to incorporate calculation constants.

$$T_{si}^{n} = \frac{H_{tr,ms}\, T_{m}^{n} + H_{adj}\, T_{adj}^{n} + H_{tr}\, T_{e}^{n} + T_{sup}^{n}\, H_{ve}\, H_{sa} / \left(H_{ve} + H_{sa}\right) + \Phi_{air}\, H_{sa} / \left(H_{ve} + H_{sa}\right) + \Phi_{si}^{n}}{H_{ms} + H_{adj} + H_{tr} + H_{ve}\, H_{sa} / \left(H_{ve} + H_{sa}\right)} \tag{G.13}$$

The solutions of the heat balance equation for internal surfaces can be described as in equation (G.14) by having the calculation constants specified below.

$$T_{si}^{n} = b_1\, T_{m}^{n} + b_2\, T_{adj}^{n} + b_3\, T_{e}^{n} + b_4\, T_{sup}^{n} + b_5\, \Phi_{air}^{n} + b_6\, \Phi_{si}^{n} \tag{G.14}$$

$$b_1 = \frac{H_{tr,ms}}{H_{tr,ms} + H_{adj} + H_{tr} + \left(H_{sa}\, H_{ve}\right) / \left(H_{sa} + H_{ve}\right)} \qquad b_4 = 1 - b_1 - b_2 - b_3$$

$$b_2 = b_1\, \frac{H_{adj}}{H_{tr,ms}} \qquad b_5 = b_4\, \frac{1}{H_{ve}}$$

$$b_3 = b_1\, \frac{H_{tr}}{H_{tr,ms}} \qquad b_6 = b_1\, \frac{1}{H_{tr,ms}}$$

G.3.3 Heat balance for the room air

The heat balance at the room air temperature node is shown in equation G.15 and in figure G.3(c). The thermal capacity of the air is usually neglected and therefore room air heat balance is done as quasi-steady-state heat balance for each time step as shown in equation G.15. The supply air temperature is rather constant for a mechanical ventilation system whereas for natural ventilation this parameters is equal to the external temperature.

$$\Phi_{air} + H_{sa}\left(T_{si} - T_{air}\right) = H_{ve}\left(T_{air} - T_{sup}\right) \tag{G.15}$$

H_{ve}	Ventilation air flow capacity, $\left[{}^{W}/{}_{\circ C}\right]$
T_{sup}	Supply air temperature, $[{}^{\circ}C]$

The equation is presented in specific manner in order to incorporate calculation constants.

$$T_{air}^{n} = T_{si}^{n} \frac{H_{sa}}{H_{sa} + H_{ve}} + T_{sup}^{n} \left(1 - \frac{H_{sa}}{H_{sa} + H_{ve}}\right) + \frac{\Phi_{air}^{n}}{H_{sa} + H_{ve}} \tag{G.16}$$

The solutions of the heat balance equation for internal surfaces can be described as in equation (G.17) by having the calculation constants specified below.

$$T_{air}^{n} = c_1\, T_{si}^{n} + c_2\, T_{sup}^{n} + c_3 \Phi_{air}^{n} \tag{G.17}$$

$$c_1 = \frac{H_{sa}}{H_{sa} + H_{ve}}$$

$$c_2 = 1 - c_1$$

$$c_3 = c_1\, \frac{1}{H_{sa}}$$

G.3.4 Operative temperature

The operative temperature is calculated by utilizing room air and internal surfaces temperatures equally. Hence, the operative temperature in the *n*'th time step is calculated by using equation (G.18).

$$T_{\text{op}}^{\text{n}} = \frac{T_{\text{air}}^{\text{n}} + T_{\text{si}}^{\text{n}}}{2} \tag{G.18}$$

T_{op}	Operative temperature, [°C]

Appendix **H**

SBi simplified model

This appendix serves a detailed description of a SBi simplified model intended for calculation of overheating risk in dwellings. The description of the calculation scheme and assumptions presented in the beginning is followed afterwards by calculation procedure and heat balances establishment.

H.1 Principle and simplifications of the model

The fundamental elements behind the SBi simplified model appear from the simple hourly method in EN ISO 13790 standard, which is described in appendix F, with further simplifications. Unlike the simple hourly method in EN ISO 13790 standard, current simplified model uses three resistances and one capacitance, as illustrated in figure H.1, and hence appears as a lumped capacitance model based on a 3R1C scheme.

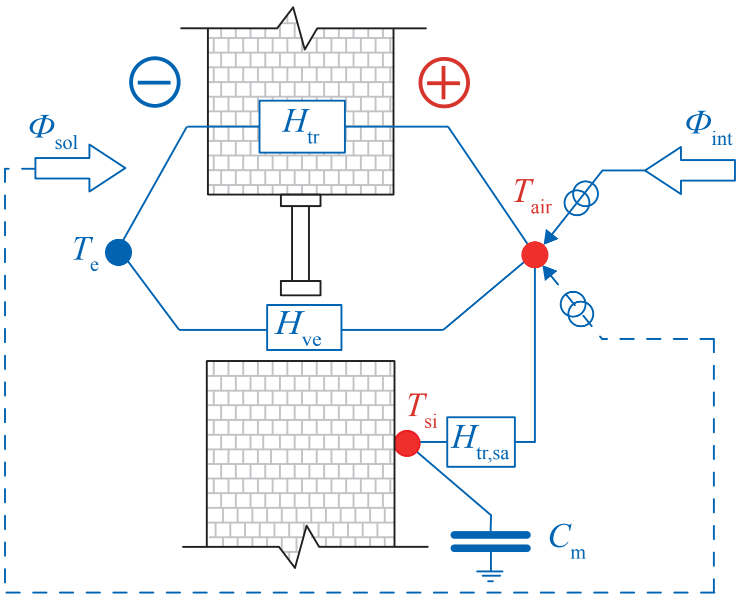


Figure H.1: *Representation of the heat exchange within a building zone by means of SBi 4R1C simplified model. Redrawn from Narowski et al. [2010, p.3].*

Based on thermal-electrical analogy there are three temperature nodes, while only two of them are unknown, more specifically the room air temperature, T_{air}, and internal surfaces temperature, T_{si}. There are four heat losses between temperature nodes and one lumped, in other words concentrated,

capacitance, C_m, at the surface temperature containing all thermal mass of the building including furniture. The heat losses comprise heat losses via ventilation, H_ve, via transmission through doors and windows, $H_\mathrm{tr,w}$, as well as via transmission through opaque building elements, $H_\mathrm{tr,opa}$.
Comparing to the EN ISO 13790 simple hourly method several assumptions were being applied to the current model with further simplification of it:

1. Two unknown temperature nodes are used in current model instead of three in EN ISO 5R1C model, by omitting calculation of the thermal mass temperature. It is therefore assumed that the temperature of the internal building mass is similar to the internal surface, [Mortensen 2012, p. 8].

2. The heat supply from thermal loads, i.e. internal, Φ_int, and solar, Φ_sol, is assumed to be allocated only in the room air. It means that the thermal loads do not have a direct influence on surface temperature. It is explained that although there is an error when sun is directly shining onto walls/floor, in case of internal solar shading the heat is absorbed by solar shading device and then released indoors via convection, by influencing room air temperature, [Mortensen 2012, p. 8].

3. In addition to previous assumption all the heat losses between external and internal environments influence solely the room air temperature without direct effect on the internal surfaces temperature.

4. Although there is a heat loss through opaque constructions from room air to external environment, this heat transfer does not directly influence the temperature of the internal surfaces or building mass. This slows down the cooling process of the building mass, containing thermal capacity during the nights in warm periods, when a passive cooling is an effective way of cooling the building down. As the goal of the model is to determine overheating problems and ensure that the building will not violate the requirement, then this assumption has the purpose to work as a safety factor. [Mortensen 2012, p. 8]

Specific heat transfer between room air and surface temperatures is calculated according to equation (H.1). The surface HTC assumes that thermal zone contains furniture.

$$H_\mathrm{sa} = \alpha_\mathrm{tot} \cdot A_\mathrm{f} \tag{H.1}$$

H_sa	Specific heat transfer between internal surfaces and room air, $\left[{}^{\mathrm{W}}/_{\circ\mathrm{C}}\right]$
α_tot	Surface HTC with a fixed value of 20, $\left[{}^{\mathrm{W}}/_{\circ\mathrm{C\,m^2-floor}}\right]$
A_f	Floor area, $\left[\mathrm{m}^2\right]$

H.2 Calculation of unknown temperatures

The SBi simplified model conducts the calculation of heat balances established at the nodes of unknown temperatures, illustrated in figure H.2, which has the same meaning as figure H.1, while showing a distinct sequence of temperature calculation and is more convenient for comparison with other simplified models.

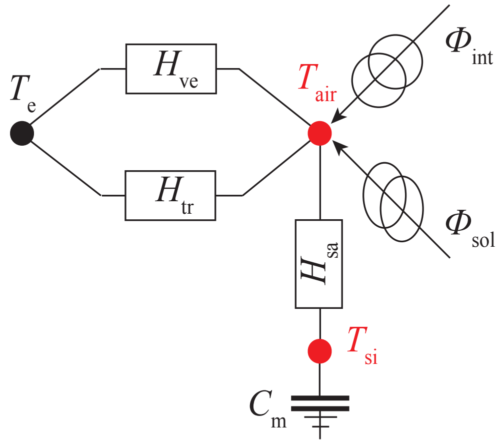


Figure H.2: *SBi 3R1C simplified model visualized in thermal-electric analogy. Redrawn from EN ISO 13790 [2008, p. 90].*

The equations are derived from heat balances established at the unknown temperature nodes. To avoid simultaneous calculation of heat balances and use of matrices, an approach of sequential solution of equations is performed, which implies primarily calculation of the room air temperature first, then internal surfaces temperature. This sequence of unknown temperatures calculation during one time step is illustrated in figure H.3.

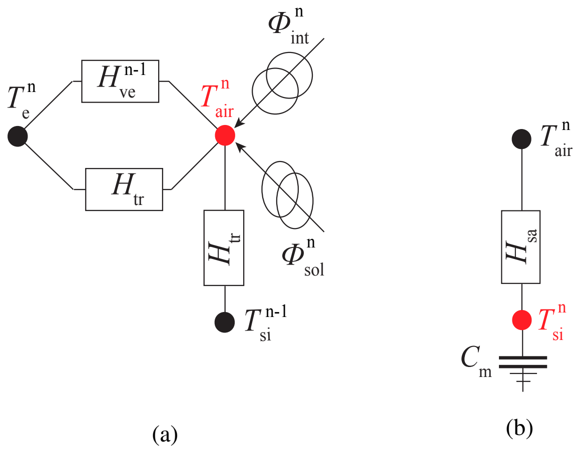


Figure H.3: *Sequence of unknown temperatures calculation for one time step for internal surfaces (a) and room air (b).*

H.2.1 Heat balance for room air

The heat balance at the room air temperature node is shown in equation (H.2) and in figure H.3(a).

$$\Phi^n_{int} + \Phi^n_{sol} = H^n_{ve}\left(T^{n-1}_{air} - T^n_e\right) + H_{tr}\left(T^{n-1}_{air} - T^n_e\right) + H_{sa}\left(T^n_{air} - T^{n-1}_{si}\right) \tag{H.2}$$

Φ_{int}	Internal heat gains, [W]
Φ_{sol}	Solar heat gains, [W]
H_{tr}	Specific heat loss by transmission, $\left[{}^{\text{W}}\!/\!{}_{\circ\text{C}}\right]$
H_{ve}	Specific heat loss by ventilation, $\left[{}^{\text{W}}\!/\!{}_{\circ\text{C}}\right]$
T_{air}	Room air temperature, [°C]
T_e	External temperature, [°C]
T_{si}	internal surfaces temperature, [°C]

In order to have one-by-one solution of heat balances, equation (H.2) involves usage of the known room air temperature of previous time step for calculation of heat losses between internal and external air. Additionally, internal surfaces temperature is also used of the previous hour. Room air temperature of the current time step derived from equation (H.2) is determined in equation (H.3).

$$T_{\text{air}}^{\text{n}} = T_{\text{si}}^{\text{n-1}} + \frac{\Phi_{\text{int}}^{\text{n}} + \Phi_{\text{sol}}^{\text{n}} - H_{\text{ve}}^{\text{n}}\left(T_{\text{air}}^{\text{n-1}} - T_{\text{e}}^{\text{n}}\right) - H_{\text{tr}}\left(T_{\text{air}}^{\text{n-1}} - T_{\text{e}}^{\text{n}}\right)}{H_{\text{sa}}} \tag{H.3}$$

H.2.2 Heat balance for internal surfaces

Heat balance for internal surfaces temperature node includes thermal capacity, indicating transient heat transfer and thus is represented by ordinary differential equation (H.4) and is shown in figure H.3(b).

$$C_{\text{m}}\frac{dT}{d\tau} = H_{\text{sa}}\left(T_{\text{air}}^{\text{n}} - T_{\text{si}}^{\text{n-1}}\right) \tag{H.4}$$

C_{m}	Thermal capacity of the building zone, $\left[{}^{\text{Wh}}\!/\!{}_{\circ\text{C}}\right]$
τ	Time step, [h]

The solution of foregoing ordinary differential equation is based on forward (explicit) Euler method scheme considering a time step of one hour. Applying forward Euler scheme to equation (H.4) with assumption of time step equal to one hour, equation (H.5) is obtained.

$$C_{\text{m}}\frac{\left(T_{\text{si}}^{\text{n}} - T_{\text{si}}^{\text{n-1}}\right)}{\Delta\tau} = H_{\text{sa}}\left(T_{\text{air}}^{\text{n}} - T_{\text{si}}^{\text{n-1}}\right) \tag{H.5}$$

The calculation of internal surfaces temperature, derived from heat balance in equation (H.5) is shown in equation (H.6).

$$T_{\text{si}}^{\text{n}} = T_{\text{si}}^{\text{n-1}} + \frac{H_{\text{sa}}\,\Delta\tau}{C_{\text{m}}}\left(T_{\text{air}}^{\text{n}} - T_{\text{si}}^{\text{n-1}}\right) \tag{H.6}$$

H.2.3 Operative temperature

The operative temperature is calculated by employing weighted room air and surface temperatures as reflected in equation (H.7), where the room air and internal surfaces fraction in operative temperature are both set to 0.5. Additionally, for the control temperature used for ventilation system regulation, the operative temperature is applied.

$$T_{\text{op}} = 0.5\,T_{\text{air}} + 0.5\,T_{\text{si}} \tag{H.7}$$

T_{op}	Operative temperature, [°C]

Appendix I

Description of BSim models

This appendix serves description of BSim models of different cases, which make a basis for comparison of BSim tool with other reviewed simplified simplified models. Description comprises a general table and detailed explanation of system settings. Furthermore some additional investigations with regards to BSim tool present in this appendix.

Since the current thesis focus solely on overheating problems, there is no interest in heating system. Although, it should be capable of keeping the minimal operative temperature, which in present case equals to 20 °C. However, the heating system is specified by being capable of heating the room only in the heating season in October to May.

As the heating system will have a heat loss in the heating pipes applied for domestic hot water even when additional heating is not necessary, a fixed part of 5% is implemented in the model.

Reference building								
Heated floor area: 56.813 m^2				**Schedule**				
System	**Description**			**Control**				**Time**
Equipment	**Equipment**			**FullLoad**				**Always**
	Heat load	0.284	kW	100% 1-24				
	Part to air	0.5	-					
Infiltration	**Infiltration**			**FullLoad**				**Always**
	Basic airchange	0.473	/h	100% 1-24				
	TmpFactor	0	/h/K					
	TmpPower	0	-					
	WindFactor	0	s/m/h					
Venting	**Venting**			**VentingCtrl**				**Always**
	Basic airchange	2.367	/h	SetPoint	23	°C		
	TmpFactor	-	-	SetP CO2	0	ppm		
	TmpPower	-	-	Factor	1	-		
	WindFactor	-	-					
	Max AirChange	2.367	/h					
	Max Wind	0	m/s					
Heating	**Heating**			**HeatingCtrl**				**HeatingSeason**
	MaxPower	7.5	kW	Factor	1	-		October - May
	Fixed Part	0.05	-	Set Point	20	°C		
	Part To Air	1.0	-	DesignTemp	-12	°C		
				MinPow	0	kW		
				Te min	20	°C		

Table I.1: *Systems implemented in BSim for test case 00.*

I.1 Investigation of time steps influence on output

It was previously declared that BSim model in current project represents reality and thus should be adjusted to produce the most precise output. BSim allows the modeller to vary the number of time steps in order to obtain a balance between simulation speed and precision. In section 6.1 in main report different cases are utilised to check models precision comparing to BSim result. These cases possess varying thermal capacity, solar shading, room height, etc. In this section an analysis of time steps influence on BSim output is executed for cases with different thermal capacity and solar shading as for them is expected to obtain different optimal time steps. Results of this investigation are shown in figure I.1. Cases 1a and 1b are more demanding for number of time steps as they possess very light and light thermal capacity respectively. Although minimum sufficient number of time steps is varying among cases, a choice for all cases is made in favor of 32 time steps per hour.

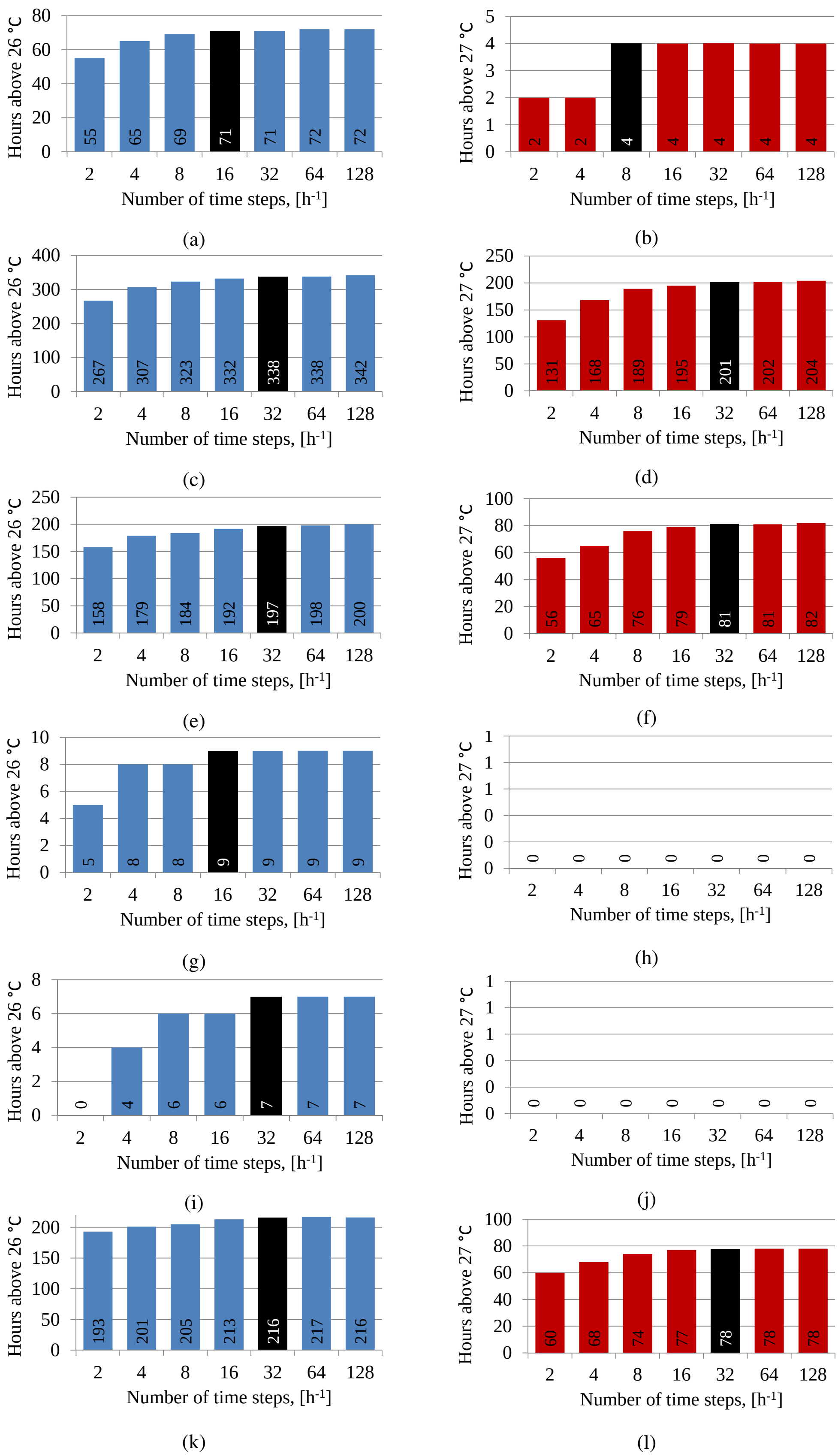


Figure I.1: *Precision of BSim according to number of time steps. Output is expressed in number of hours above 26°C and 27°C for case 0 (a,b), case 1a (c,d), case 1b (e,f), case 1c (g,h), case 2a (i,j), case 2b (k,l).*

Appendix **J**

Sensitivity analysis

This appendix undertakes the description of sensitivity analysis executed in chapter 5.2 in main report as well as gives insight in methodology together with thorough description of input parameters distribution.

J.1 Morris method

The Morris method of sensitivity analysis is based on one-parameter-at-a-time variation, though with global characteristics. Each parameter has number of discrete values, called levels, which are defined withing parameter variation range, [Saltelli et al. 2004, p. 94]. The output of Morris method is expressed with the mean value, μ, determining the degree of influence of input parameter on output variable and standard deviation, σ, determining interactions of input parameter with other input parameters and all nonlinear effects. The Morris method is based on elementary effect (EE), defined as the change in output according to change in input and calculated by means of equation (J.1), [Saltelli et al. 2004, p. 94].

$$EE_{\mathrm{i}} = \frac{y\left(x_1, \ldots, x_{\mathrm{i-1}}, x_{\mathrm{i}} + \Delta, x_{\mathrm{i+1}}, \ldots, x_{\mathrm{n}}\right) - y(x))}{\Delta} \tag{J.1}$$

y	Output
x	Input parameter
x_{i}	Modified input parameter
Δ	Change in input parameter x_{i}

J.2 Methodology

The description of an approach applied for sensitivity analysis conducted in the current thesis is described below, i.e. the basic six steps that include the following, [Heiselberg and Brohus, p. 2]:

1. *Identify the purpose of analysis and the output variable(s).* The purpose is to determine the most important input parameters contribution to output uncertainty for designed, but yet not built dwelling. EN ISO 13790, Bo Adamson and SBi simplified models possess number of hours with operative temperature above 26°C and 27°C as the main output, which, in fact, is required according to summer comfort requirement in BR2015.

2. *Determine input parameters included in SA*. Due to diversity of input parameters and boundary conditions for different simplified models, cf. section 4.3, these parameters are in focus in SA, which can identify the most optimal ones to be utilised by all three models in further comparison. Note, that both user and model input parameters comprise the input parameters in the current SA.

3. *Assign probability density functions (PDF) to each selected input parameter*. The PDF of all input parameters are deeply investigated and presented in appendix J.3.

4. *Generate samples matrix by means of an appropriate sampling method*. In current work this step is executed in SimLab[1]software by means of Morris sampling method. The maximum number of executions is chosen, i.e. 310, as the required computational time is quite low.

5. *Calculate an output distribution based on the generated samples matrix*. This step is proceeded in three simplified models, namely EN ISO 13790, Bo Adamson and SBi. It should be noted that unlike SBi simplified model, which is represented by a tool with all implemented boundary conditions, EN ISO 13790 and Bo Adamson simplified models have only some recommended boundary conditions to be applied. It was therefore decided for both EN ISO 13790 and Bo Adamson simplified models to use internal heat gains patterns and solar heat gains calculation algorithm stated in [EN ISO 13790 2008], together with ventilation settings of SBi simplified model.

6. *Assess the degree of influence of each input parameters on the output variable*. This step is likewise conducted in SimLab software by means of Morris method and elementary effects.

The above mentioned steps 3-6 of SA are illustrated in figure J.1.

[1]SimLab - simulation environment for uncertainty and sensitivity analysis.

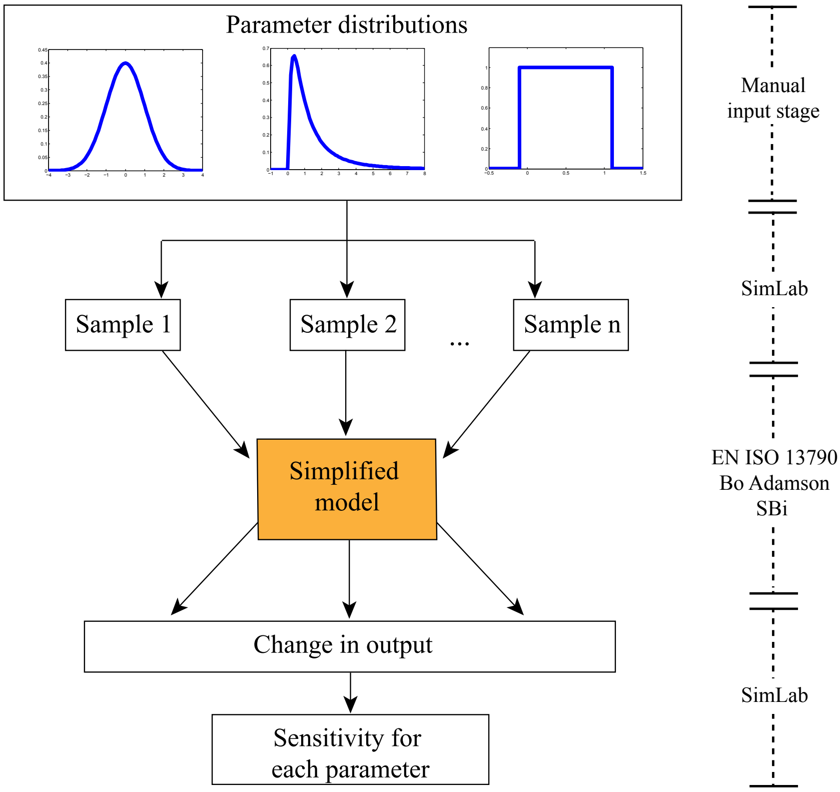


Figure J.1: *Structure of sensitivity analysis applied for simplified models.*

J.3 Probability density function

The uncertain input parameters are often expressed in terms of probability density function (PDF) or probability distribution. A PDF has two properties, [Ekstrom 2005, p. 7]:

1. It is always positive;
2. Its integral over entire range of values is equal to one.

The probability of a random variable x, which falls within a given range can be determined by means of PDF as expressed in equation (J.2):

$$P(c < x < d) = \int_c^d f(x)dx \tag{J.2}$$

P	Probability
$f(x)$	PDF

There are various PDF used in sensitivity and uncertainty analysis, e.g. normal, log-normal, uniform, log-uniform, exponential, BETA, Weibull and other distributions. However, only the first three mentioned distributions are used in current thesis.

J.3.1 Normal distribution

Normal distribution is one of the most widely used of all distributions. It is symmetric, bell shaped and specified by mean value, μ, and standard deviation, σ, [Williams 2004, p. 1]. The PDF of normal distribution is defined via equation (J.3) and illustrated in figure J.2.

$$f(x;\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-0.5(x-\mu)^2/\sigma^2} \tag{J.3}$$

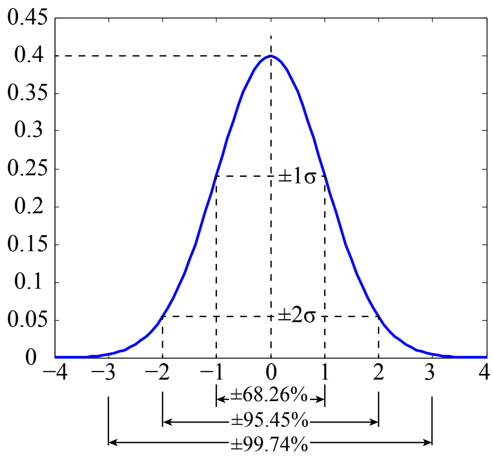


Figure J.2: *Normal distribution with μ=0 and σ=1. Redrawn from Williams [2004, p. 1].*

For this distribution a three-sigma rule is valid. It states that for normal distribution almost all values are within three sigmas, i.e. 68.26% of values are within $\mu \pm 1\,\sigma$, 95.45% of values are within $\mu \pm 2\,\sigma$ and 99.74% of values are within $\mu \pm 3\,\sigma$, cf. figure J.2.

J.3.2 Log-normal distribution

Log-normal distribution is often used when the majority of values occur near the minimum or the lower end of the range, [Ekstrom 2005, p. 8]. It is defined by equation (J.4) and illustrated in figure J.3.

$$f(x;\mu,\sigma) = \frac{1}{x\,\sigma\,\sqrt{2\pi}} e^{-0.5(log\,x-\mu)^2/\sigma^2} \tag{J.4}$$

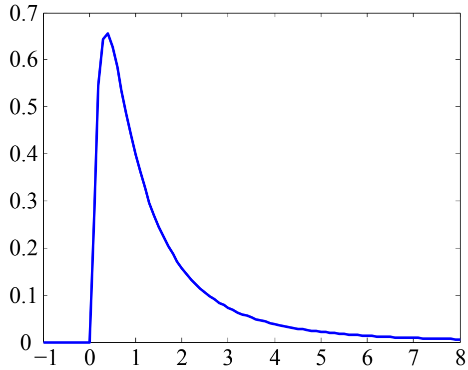


Figure J.3: *Log-normal distribution with* μ*=0 and* σ*=1.*

J.3.3 Uniform distribution

Uniform distribution is the simplest of distributions. If only minimum and maximum values, i.e. a and b respectively, for the parameter are known, then uniform distribution is appropriate. All values in uniform distribution are equally sampled, [Ekstrom 2005, p. 9]. It is defined by equation (J.5) and illustrated in figure J.4.

$$f(x) = \begin{cases} \frac{1}{b-a}, & x \in (a,b). \\ 0, & x \notin (a,b). \end{cases} \tag{J.5}$$

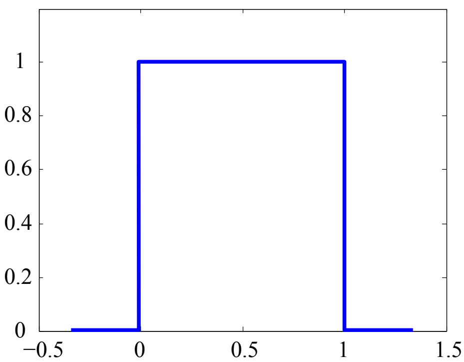


Figure J.4: *Uniform distribution with a=0 and b=1.*

J.4 Overview of applied input parameters

All applied input parameters are divided into four category:

1. Building geometry parameters;
2. Envelope thermal properties parameters;
3. Windows solar properties parameters;

4. Occupants behaviour related parameters;

In current thesis probability distributions are established assuming 95% confidence interval.

J.4.1 Building geometry parameters

Regarding the uncertainties in building geometry, it is possible to distinguish between the different phases of the building process. In the preliminary design phase, uncertainties are often related to technical drawings, especially if these are performed manually. The construction of the building can also lead to uncertainties in the execution phase as well as insufficient communication in between architects, engineers and contractors.

In order to gather information regarding maximum allowable deviations for building geometry, tolerances, tolerance classes and control methods in the workmanship of building are used. As not all building projects have the same demands for tolerances, an uncertainty is linked to the following objectives. However, as 80% of all building projects are asummed to apply normal tolerances, these are used in the determination of maximum allowable deviations and it is assumed that 95% of deviations are within these intervals, [Dansk Byggeri 2007]:

- $\pm$50 mm for each wall caused by deposits of the foundation;
- $\pm$10 mm in height for a brickwork;
- $\pm$10 mm for each dimension in an external wall cavity.

The tolerances imply a maximum allowable deviations varying between $\pm$2.8 - $\pm$3.2 m^2 for external constructional areas respectively. The window areas are relatively smaller compared to the other building construction areas, which is reflected in its maximum allowable deviation of $\pm$0.16 m^2. The maximum allowable deviations for linear thermal length around external wall and windows are likewise determined according to tolerances with a magnitude of 0.310 m and 0.186 m respectively.

Deviations in the window orientation are mainly related to the construction of the building and the building site properties and conditions, which may lead to deposits in the ground. Due to lack of information regarding maximum allowable deviations, an estimation of $\pm 2°$ from the starting-point is specified as maximum deviation for the window orientation. The probability distributions related to building geometry are illustrated in figure J.5 and reflected in table J.1.

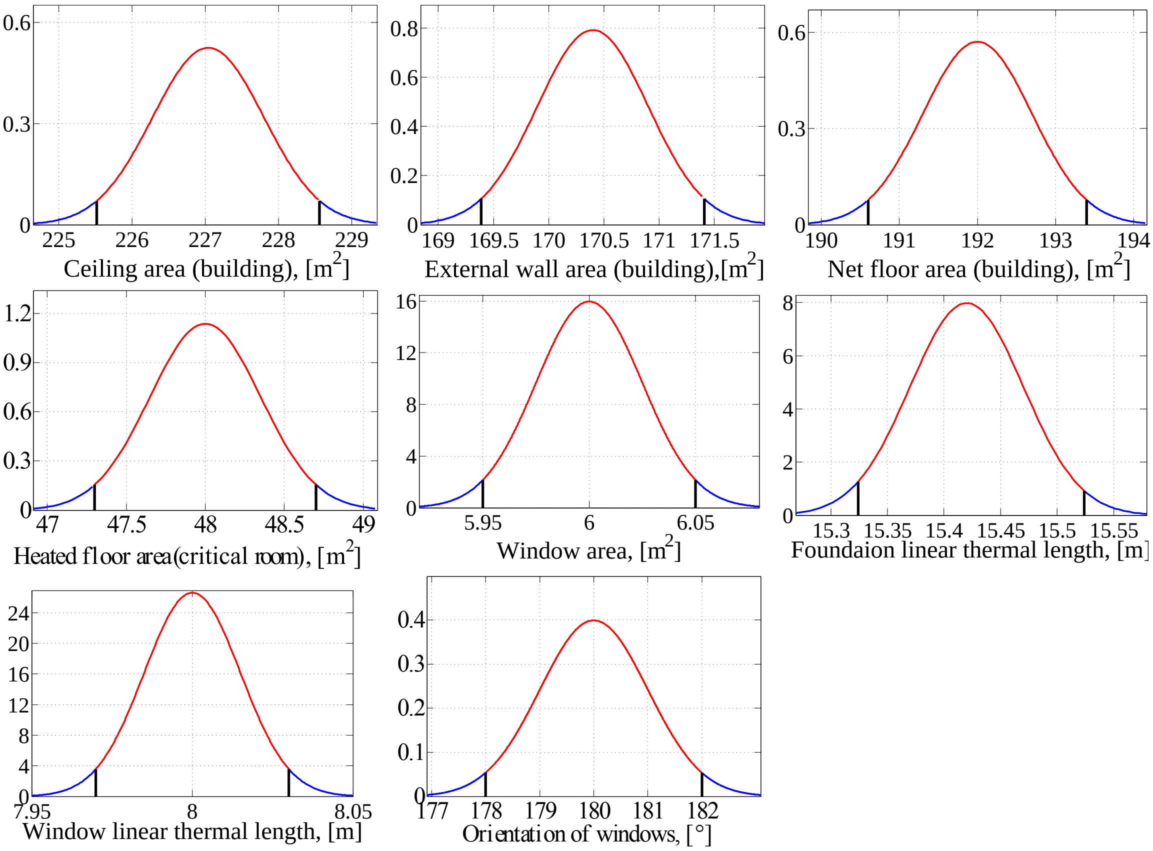


Figure J.5: *Probability distributions of building geometry parameters. Blue color indicates truncated values.*

No.	Parameter	Unit	Type	Mean value μ	Standard deviation σ	Variation coefficient δ	Expected interval *min* *max*
1	Ceiling area (building)	[m^2]	N	227.0	0.76	0.3%	225.5 - 228.6
2	External wall area (building)	[m^2]	N	170.4	0.50	0.3%	169.4 - 171.4
3	Net floor area (building)	[m^2]	N	192.0	0.70	0.4%	190.6 - 193.4
4	Heated floor area (critical room)	[m^2]	N	48.0	0.35	0.7%	47.3 - 48.7
5	Window area	[m^2]	N	6.0*	0.03	0.4%	5.95 - 6.05
6	Foundations linear thermal length	[m]	N	29.8	0.05	0.2%	29.3 - 29.3
7	Window linear thermal length	[m]	N	8.0*	0.02	0.2%	7.97 - 8.03
8	Orientation of windows	[°]	N	180	1.00	0.6%	178 - 182

Table J.1: *Probability distributions of building geometry parameters. Following distribution type is used: N - normal. *Related to one window.*

J.4.2 Envelope thermal properties parameters

The envelope thermal properties are often calculated based on information from the manufacturer regarding materials thermal properties. The related uncertainties can by caused by wrong determination of material parameters, mistakes in the calculation or in the practical workmanship of the building construction elements. For the determination of thermal transmittances deviations, the following assumptions are applied. As it is possible that more than one deviation happens at the same time, larger variations may occur. This is taken into account by assuming that 95% of deviations are within these intervals.

- ± 0.02 $^{m^2 {}^\circ C}/_{W}$ for surface resistances facing internal or external conditions;
- ± 0.50 $^{m^2 {}^\circ C}/_{W}$ for external surface resistance facing ground;
- ± 0.003 $^{W}/_{m {}^\circ C}$ for thermal conductivity of insulation;
- ± 0.100 $^{W}/_{m {}^\circ C}$ for thermal conductivity of tiles;
- ± 0.100 $^{W}/_{m {}^\circ C}$ for thermal conductivity of concrete;
- ± 0.100 $^{W}/_{m {}^\circ C}$ for thermal conductivity of brick;
- ± 0.050 $^{W}/_{m {}^\circ C}$ for thermal conductivity of wood;
- ± 10 mm for thickness of insulation;
- ± 5 mm for thickness of concrete, light-weight concrete, brick and wood.

The implementation of these assumed individual deviations implies a total deviation of 0.013 - 0.015 $^{W}/_{m^2 {}^\circ C}$ for the external constructional thermal transmittances, namely external ceiling, wall and floor. The window thermal transmittance is depending on the manufacture of the window and the determination of the window parameters, which is assumed cause 10% deviation.

Linear thermal transmittance for foundation is depending on the structure of the foundation and the surrounding external floor. Due to lack of information, the foundation linear thermal transmittance and external floor thermal transmittance are assumed to have a similar variation coefficients. Thus, the standard deviation for linear thermal transmittance for foundation is determined according to equation (J.6).

$$\sigma = \delta \cdot \mu \tag{J.6}$$

σ	Standard deviation, $\left[^{W}/_{{}^\circ C\, m}\right]$
δ	variation coefficient, $\left[^{W}/_{{}^\circ C\, m}\right]$
μ	Mean value, $\left[^{W}/_{{}^\circ C\, m}\right]$

The deviations of the linear thermal transmittance for windows is assumed to have a magnitude of ± 0.01 $^{W}/_{m {}^\circ C}$, which corresponds to a variation of ± 10 mm of the insulation thickness in the thermal bridge.

Estimation of thermal capacity uncertainty is based on evaluation of six houses from *The Comfort Houses* project, [Larsen et al. 2012e]. The thermal capacity of six comfort houses in Be10 is approximately set to values from 80 to 120 $^{\text{Wh}}/_{\text{°C m}^2}$. Furthermore, these values correspond to two adjacent input values of thermal capacity in Be10, which means that the input variation in Be10 is within 40 $^{\text{Wh}}/_{\text{°C m}^2}$. It was decided to assign uniform probability to thermal capacity input parameter ranging from 80 to 120 $^{\text{Wh}}/_{\text{°C m}^2}$ with equal probability of being within this range.

The distribution factors related to the envelope thermal properties are illustrated in figure J.6 and reflected in table J.2.

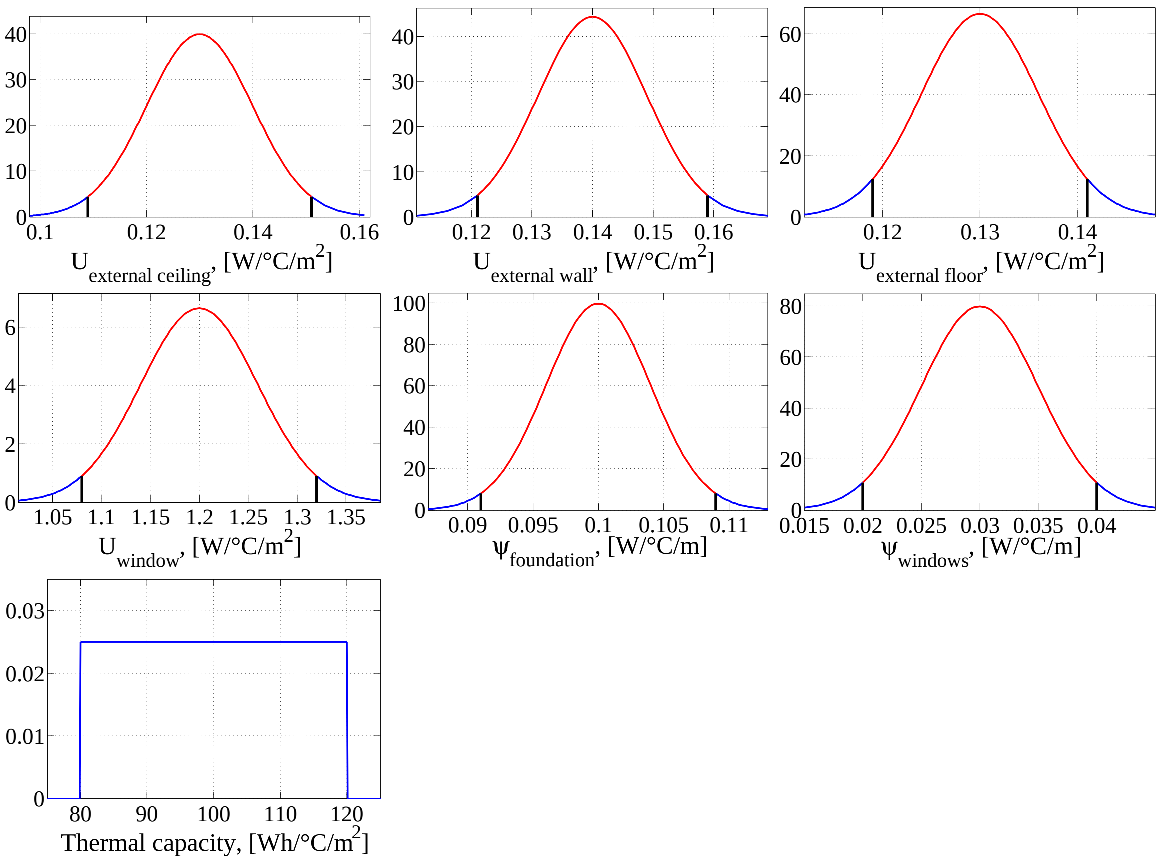


Figure J.6: *Probability distributions of envelope thermal properties parameters. Blue color indicates truncated values.*

No.	Factor	Unit	Type	Mean value μ	Standard deviation σ	Variation coefficient δ	Expected interval *min* *max*
9	External ceiling thermal transmittance	$\left[{}^{W}/_{\circ C\,m^2}\right]$	N	0.13	0.010	8.0%	0.11 - 0.15
10	External wall thermal transmittance	$\left[{}^{W}/_{\circ C\,m^2}\right]$	N	0.14	0.009	6.7%	0.12 - 0.16
11	External floor thermal transmittance	$\left[{}^{W}/_{\circ C\,m^2}\right]$	N	0.13	0.006	4.4%	0.12 - 0.14
12	Windows thermal transmittance	$\left[{}^{W}/_{\circ C\,m^2}\right]$	N	1.20	0.060	5.0%	1.08 - 1.32
13	Foundation linear thermal transmittance	$\left[{}^{W}/_{\circ C\,m}\right]$	N	0.10	0.004	4.4%	0.09 - 0.11
14	Window linear thermal transmittance	$\left[{}^{W}/_{\circ C\,m}\right]$	N	0.03	0.005	16.7%	0.02 - 0.04
15	Thermal capacity	$\left[{}^{Wh}/_{\circ C\,m^2}\right]$	U	-	-	-	80 - 120

Table J.2: *Probability distributions of envelope thermal properties parameters. Following distribution type is used: N - normal, U - uniform.*

J.4.3 Windows solar properties parameters

The different shadow angles, and subsequently also their respective deviations, are strongly dependent on the size of the objects causing the different shadows on the window, but also the window orientation and specific location in the building envelope have an influence. The partial shadow factor for horizon angles takes into account shadows from other buildings or topography. These can change significantly during the building service life, which is why substantial uncertainty is associated with the horizon angle in the building preliminary design phase. Thus, the distribution of the horizon angle is assumed to be uniform in a range going from 0 - 30° to take into account these possible variations.

The shadow factor is further dependent on overhang and side fins, both intended for passive cooling of the building or just other elements of the concerned building causing shadows on the conditioned window. The uncertainty relating to these shadow angles is estimated to $\pm 2°$. The partial shadow factor for wall cavity describes the relative depth of window compared to the smallest window dimensions. Thus, this ratio and its possible uncertainty depends on window dimensions and workmanship of the building which are estimated to be in a magnitude of $\pm 0.5\%$.

The solar energy transmittance at normal incidence, often referred to as the *g*-value, is often informed by the manufacturer of the window and depends solely on the structure of the glazing element, more specifically the number of panes in the glazing along with type of coating and filling, as it specifies the solar energy transmitted through the glazing element. As a glazing element thickness can maximum vary ± 1.0 mm for double glazed glazing and ± 1.5 mm for triple glazed glazing, [EN 1279-1 2006, section 5], the uncertainty is estimated to be rather insignificant. Thus, the solar energy transmittance is assumed to be able to vary in between the interval $0.57 - 0.63$.

The shading factor describes the solar shading potential in the applied shading devices and depends on the whether the shading device is external, internal or integrated in the window along with the type of shading device, e.g. venetian blind, roller blind, curtain, shutter, etc. The shading factor is often determined according to predefined values, such as By og Byg Anvisning 202 [2002, table 8.6], which can bring some uncertainty regarding correct estimations when determining this value along with the manufacturing of the shading devices. The shading factor is assumed to be able to vary ±0.15.

The distribution factors related to window properties are illustrated in figure J.7 and reflected in table J.3.

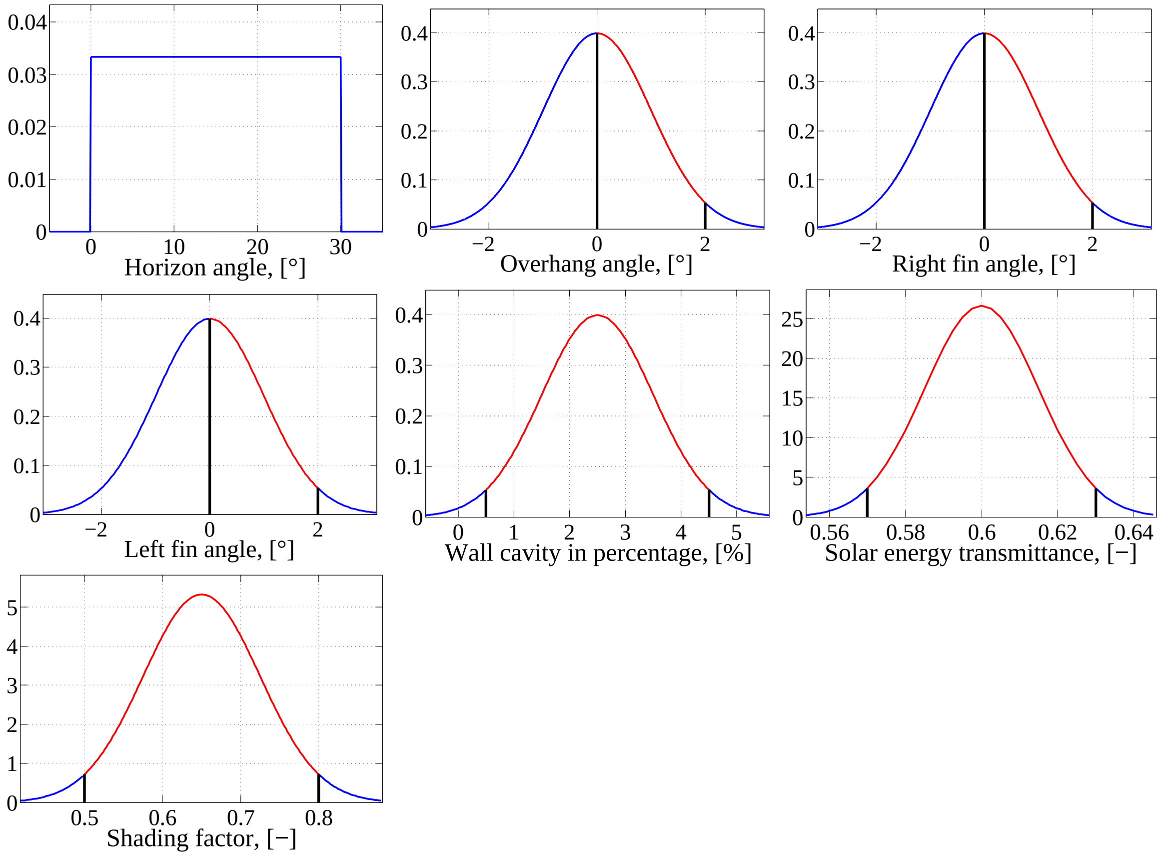


__Figure J.7:__ Probability distributions of window solar properties parameters. Blue color indicates truncated values.

No.	Factor	Unit	Type	Mean value μ	Standard deviation σ	Variation coefficient δ	Expected interval *min max*
16	Horizon angle	[°]	U	-	-	-	0 - 30
17	Overhang angle	[°]	N	0	1.00	-	0 - 2
18	Right fin angle	[°]	N	0	1.00	-	0 - 2
19	Left fin angle	[°]	N	0	1.00	-	0 - 2
20	Wall cavity in percentage*	[%]	N	2.5	0.25	10.0%	2 - 3
21	Solar energy transmittance	[−]	N	0.60	0.015	2.5%	0.57 - 0.63
22	Shading factor	[−]	N	0.65	0.075	11.5%	0.50 - 0.80

Table J.3: *Probability distributions of window solar properties parameters. Following distribution types are used: N - normal, U - uniform. *Not applicable in EN ISO 13790 and Bo Adamson simplified models.*

J.4.4 Occupants behaviour related parameters

Current subsection contains more distinct input parameters, which are separately described.

Internal heat gains

Although non of the simplified models distinguish between occupants and appliances with regard to internal heat gains, a separation of theses is kept in order to obtain rather reliable distributions. Furthermore, this separation exists in Be10 tool, which SBi simplified model is a part of. A default average value for internal heat gains by occupants of 1.5 $^{W}/_{m^2}$ in dwellings is applicable in Be10 tool, [SBi-anvisning 213 2008, p.63]. It is assumed to be an average of one person and four persons in a dwelling of 150 m^2, corresponding to 90 W and 360 W respectively. For the same detached house a default average value for appliances is 3.5 $^{W}/_{m^2}$. It is an average of 210 W and 840 W, corresponding to one person and four persons presented in a dwelling with the same floor area.

The internal heat supply is noticeably depending on the occupancy, which is rather difficult to determine in the building design phase. In order to obtain reliable distributions, the number of occupancy in the seven comfort houses along with their heated floor areas were used as listed in table J.4. The sensible heat load corresponding to adult is set to 100 W and a child has 60% of adult heat production, [Hyldgård et al. 2001, p. 18]. Nevertheless, residents are assumed to be present in their dwelling 16.4 hours per weekday and 19.9 hour per day in the weekend, [Kristensen and Jensen 2011, p. 5]. The standard deviation of normal distribution is calculated for a 95% confidence interval.

Comfort house	Adults	Children	Total hourly heat load	Heated floor area	Internal heat flow rate from occupants
	[−]	[−]	[W]	$[m^2]$	$[W/m^2]$
12	2	1	189	177.0	1.06
28	2	2	232	163.0	1.42
37	2	3	276	169.0	1.63
39	2	1	189	179.0	1.05
43	2	0	145	214.0	0.68
45	2	2	232	224.0	1.04
47	2	2	232	165.0	1.41
49	2	2	232	198.0	1.17
Mean value, μ					**1.18**
Standard deviation, σ					**0.28**

Table J.4: *Samples of internal heat flow rate from occupants in seven comfort houses, used to calculate probability distribution for sensitivity analysis. Only sensible heat load from occupants is presented.*

Similar approach was applied for determination of the distribution for internal heat gains from appliances, by considering the electricity consumption, i.e. domestic appliances and lighting, of four comfort houses with available results.

Comfort house	Lighting	Domestic appliances	Hourly heat load	Heated Floor area	Internal heat flow rate from appliances
	$[kWh/year]$	$[kWh/year]$	[W]	$[m^2]$	$[W/m^2]$
12	4369	202	522	177.0	2.95
28	2423	775	365	163.0	2.24
37	2455	886	381	169.0	2.26
39	3172	1115	489	179.0	2.73
Mean value, μ					**2.54**
Standard deviation, σ					**0.31**

Table J.5: *Samples of internal heat flow rate from appliances in four comfort houses, used to calculate probability distribution for sensitivity analysis*

Ventilation set-point temperature

The ventilation set-point temperature, for which additional air exchange starts by means of natural ventilation in order to cope with excessive indoor temperatures, is a very uncertain input parameter, as it is depending on the preferences of each particular individual. As ventilation is the major contributor to space cooling it should be enabled before the operative temperature exceeds the maximum allowed temperature, which according to EN 15251 [2007, p. 26] for category II and SBi-anvisning

213 [2008, p. 19] is 26°C for living spaces for summer season. The recommended set-point temperature for ventilation for cooling is 23°C, [SBi-anvisning 213 2008, p. 29]. The uncertainty of this parameter involves probability of rather higher temperatures, which is why the log-normal distribution type is selected. With the mean value of 0.5°C, standard deviation of 0.6°C and distribution displacement with respect to X axis to 21.01°C the highest probability of starting natural ventilation corresponds to 23°C.

Proportional band

The purpose of a proportional band is to gradually increase ventilation rate when it is required. It is implemented due to the fact that occupants are not fully opening windows, instead they open them partly, when experience overheating, [Mortensen 2012-2013]. The proportional band is embedded in SBi simplified model with default value of 1°C, which is not possible to modify, read detailed explanation of proportional band in appendix N.2.1. The uniform distribution with interval of 0°C to 2°C is applied to this parameter due to lack of data of its possible variation range.

Basic ventilation rate

Basic ventilation rate accounts for the minimum fresh air supply required in dwellings independently of the type of ventilation system and equals to 0.3 $^{l}/_{s\,m^2}$, [SBi-anvisning 213 2008, p. 59]. Unlike mechanically ventilated dwellings for naturally ventilated ones infiltration is incorporated in basic ventilation rate. Basic ventilation rate is variable due to occupants behaviour and can reach either lower magnitude when occupants are absent or higher magnitude depending on occupants activity level. The normal distribution is applied to this parameter. There is a probability of having an infiltration rate alone when occupants are absent resulting in 0.1 $^{l}/_{s\,m^2}$, see equation (5.1), which corresponds to the maximum allowed level of tightness according to Danish BR2015 for future low-energy buildings. Since normal distribution assumes symmetrical variation, the highest magnitude of basic ventilation rate is set to 0.5 $^{l}/_{s\,m^2}$. The standard deviation is equal to 0.1 $^{l}/_{s\,m^2}$ corresponding to 95% confidence interval, whereas the mean value is set to 0.3 $^{l}/_{s\,m^2}$.

Summer ventilation rates

By summer ventilation an additional natural ventilation intended to cope with overheating in dwellings is assumed. It is proposed to use an estimated value of 0.9 $^{l}/_{s\,m^2}$ for dwellings with manual windows opening corresponding to 75% of windows opening time, which is considered as a maximum time of having windows open, [SBi-anvisning 213 2008, p. 60]. The ventilation rate is related to effective opening area equal to 1.5% of floor area for cross ventilation and, in case if the effective opening area has larger area, then ventilation rate, 0.9 $^{l}/_{s\,m^2}$, can be proportionally increased, [SBi-anvisning 213 2008, p.60-61]. The effective opening area in the reference building is 4%, which leads to the increased ventilation rate 2.4 $^{l}/_{s\,m^2}$. However this value can dramatically vary depending on occupants behaviour and conditions for natural ventilation, e.g. site properties, windows orientation and location with respect to each other, weather conditions etc. As the summer natural ventilation rate has normally at least the values of winter ventilation rate, cf. SBi-anvisning 213 [2008, p. 58], the minimum ventilation rate is set to 0.5 $^{l}/_{s\,m^2}$. Since a normal distribution is applied to current parameter, the maximum summer ventilation rate is set symmetrically to 4.3 $^{l}/_{s\,m^2}$. Then according to 95% confidence interval the standard deviation is calculated to 0.95 $^{l}/_{s\,m^2}$.

It should be noted that in EN ISO 13790 and Bo Adamson simplified models there is implemented summer ventilation separation into daytime, evening and night ventilation by analogy to SBi simplified model. However, as only one daily ventilation rate is proposed by SBi-anvisning 213 [2008, p. 60] then it is used in all three aforementioned periods of the day.

Solar shading set-point

Solar shading is a significantly uncertain parameter, which includes:

1. Input data uncertainty when the proper shading factor for solar shading device should be chosen, see subsection J.4.3;
2. Occupants behaviour related uncertainty regarding the actual usage of solar shading device.

The EN ISO 13790 simplified model possesses the control of solar shading usage, which depends on solar incidence. The recommended value used in BSim tool, which, in turn, is employed for building simulations in Denmark, is 150 $^{W}/_{m^2}$ on inner surface of the window. The minimum value of set-point is assumed to be 0 $^{W}/_{m^2}$, which possibly occurs when occupants leave the shading devices enabled during their absence. Since a normal distribution is applied to current parameter, the maximum set-point for shading is set to 300 $^{W}/_{m^2}$. For 95% confidence interval the standard deviation is calculated to 75 $^{W}/_{m^2}$.

It should be mentioned that SBi simplified model incorporates solar calculation algorithm of Be10 tool, which possesses calculated by BSim tool monthly coefficients both for shadow and shading based on DRY. It is, however, not explained which algorithm and assumptions are used for these coefficients establishment. Nevertheless, it is not possible to check the influence of solar shading set-point on the SBi simplified model output. The input parameters related to occupants behaviour are illustrated in figure J.8 and reflected in table J.6.

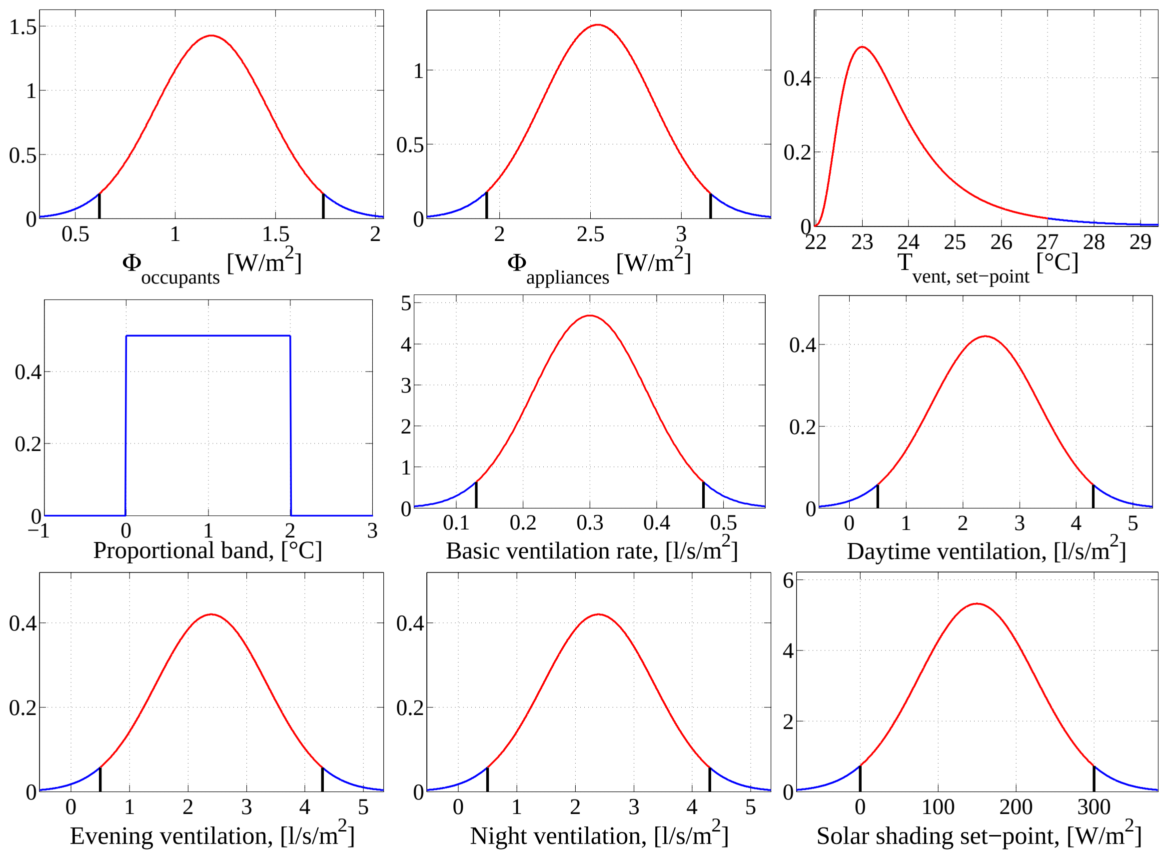


Figure J.8: *Probability distributions of occupants behaviour related parameters. Blue color indicates truncated values.*

No.	Factor	Unit	Type	Mean value μ	Standard deviation σ	Variation coefficient δ	Expected interval *min* *max*
23	Internal heat gains from occupants	$[W/m^2]$	N	1.18	0.28	23.5%	0.62 - 1.74
24	Internal heat gains from appliances	$[W/m^2]$	N	2.54	0.31	12.0%	1.93 - 3.16
25	Ventilation set-point temperature	[°C]	L	0.89*	0.45	-	22 - 27
26	Proportional band	[°C]	U	-	-	-	0 - 2
27	Basic ventilation rate	$[l/s\,m^2]$	N	0.3	0.10	33.3%	0.1 - 0.5
28	Daytime ventilation rate	$[l/s\,m^2]$	N	2.40	0.95	39.6%	0.50 - 4.30
29	Evening ventilation rate	$[l/s\,m^2]$	N	2.40	0.95	39.6%	0.50 - 4.30
30	Night ventilation rate	$[l/s\,m^2]$	N	2.40	0.95	39.6%	0.50 - 4.30
31	Solar shading set-point**	$[W/m^2]$	N	150	75	50.0%	0 - 300

Table J.6: *Probability distributions of occupants related input parameters. Following distribution types are used: N - normal, L - log-normal, U - uniform. *Displaced with respect to X axis by 21.01°C. **Not applicable in SBi simplified model.*

J.5 Output data from SimLab

No.	Factor	EN ISO 13790		Bo Adamson		SBi	
		μ^*, [h]	σ^*, [h]	μ^*, [h]	σ^*, [h]	μ^*, [h]	σ^*, [h]
1	Ceiling area (building)	1	1.1	2	2.5	0.8	1
2	External wall area (building)	0.8	1.4	1	1.4	1	1.1
3	Net floor area (building)	10.4	9.4	7.2	5.9	10.8	6.1
4	Heated floor area (critical room)	18.3	14.8	17.1	16.7	17.0	15.1
5	Window area	4.4	3.5	4.4	3.2	7.8	5.3
6	Foundations linear thermal length	0	0	0	0	0	0
7	Windows linear thermal length	0	0	0.4	1.3	0	0
8	Orientation of windows	4.2	3.5	4	2.8	41.6	24.7
9	External ceiling thermal transmittance	16	29.4	13	20.2	16.8	23.4
10	External wall thermal transmittance	15.4	27.6	15.8	25.9	13.2	18.5
11	External floor thermal transmittance	5.6	8.4	4.8	6.1	8.4	13.8
12	Window thermal transmittance	37.4	59.5	31.2	51.9	30.2	46.8
13	Foundation linear thermal transmittance	1.6	2.5	1.2	1.9	2.6	4.2
14	Windows linear thermal transmittance	1.2	1.4	2.8	4.4	0.8	1.4
15	Building thermal capacity	48.6	15.7	70.8	22.9	98.8	45.4
16	Horizon angle	4.4	6.2	8.2	11.5	18.6	20.8
17	Overhang angle	13.2	12.2	8.4	5.6	15	9.4
18	Right fin angle	9.6	7.5	10.2	8.6	2.6	1.9
19	Left fin angle	2.8	2.3	5	3.8	2	1.6
20	Wall cavity in percentage	0	0	0	0	4.6	3.5
21	Solar energy transmittance	35.8	33.3	42.2	29.2	53.8	28.9
22	Shading factor	139	94.7	157	72.9	77.6	34.5
23	Internal heat gains from occupants	37.2	27.5	44	24.4	42.4	29.2
24	Internal heat gains from appliances	45.6	36.4	58	31	52.8	24.9
25	Ventilation set-point temperature	1330	1640	1190	1280	1350	1380
26	Proportional band	128	92.1	139	93.2	192	151
27	Basic ventilation rate	210	495	176	366	192	409
28	Daytime ventilation (9-16)	73.6	61.6	94	78.1	203	135
29	Evening ventilation (17-24)	170	171	237	189	195	112
30	Night ventilation (1-8)	99	98.5	111	87.3	141	119
31	Solar shading set-point	150	147	159	110	0	0

Table J.7: *Output data regarding the influence of hours with operative temperature above 26°C in considered simplified models.* **Output mean value and standard deviation.*

No.	Factor	EN ISO 13790		Bo Adamson		SBi	
		μ^*, [h]	σ^*, [h]	μ^*, [h]	σ^*, [h]	μ^*, [h]	σ^*, [h]
1	Ceiling area (building)	0.8	1.9	0	0	0.8	1.7
2	External wall area (building)	0.4	0.8	0.4	0.8	0.6	1
3	Net floor area (building)	6.8	9	6.2	6.1	6.8	6.1
4	Heated floor area (critical room)	8.9	12.0	8.1	7.6	8.3	6.9
5	Window area	1.8	3.2	3.2	2.3	5.4	3.3
6	Foundations linear thermal length	0	0	0	0	0.2	0.6
7	Windows linear thermal length	0	0	0	0	0	0
8	Orientation of windows	3.4	4.3	4	3.3	19.2	13
9	External ceiling thermal transmittance	3.8	6.1	3	4.2	7.8	12.1
10	External wall thermal transmittance	4	6.5	5.6	10.5	3	4.9
11	External floor thermal transmittance	1.4	3.8	3.6	7.6	1.8	1.8
12	Window thermal transmittance	11.8	24	13.2	23.9	8.6	13.8
13	Foundation linear thermal transmittance	1	1.7	0.8	1.4	0.8	1.4
14	Windows linear thermal transmittance	0	0	1	1.4	1.2	1.4
15	Building thermal capacity	21.8	16.1	49.6	16.2	65.8	34.1
16	Horizon angle	0.6	1	1.6	3.2	6	10.1
17	Overhang angle	7.8	8.4	8.8	7	7	6.1
18	Right fin angle	5.8	7	6.4	5.5	1	1.1
19	Left fin angle	1.4	1.6	1.6	2.1	1	1.4
20	Wall cavity in percentage	0	0	0	0	3.8	3.8
21	Solar energy transmittance	13.4	16	19.2	18.8	28.6	18.7
22	Shading factor	62	68	94.2	64.4	38.2	25.9
23	Internal heat gains from occupants	17.6	16.3	22	13.5	21	13.7
24	Internal heat gains from appliances	12.6	11.9	25.8	18	27	14.9
25	Ventilation set-point temperature	321	431	362	425	422	458
26	Proportional band	36.8	36	45.4	27.5	61.4	38.7
27	Basic ventilation rate	29.4	74.8	40.8	101	54.4	125
28	Daytime ventilation (9-16)	41	79	62.2	62.7	112	175
29	Evening ventilation (17-24)	56.6	67.2	119	101	97	58
30	Night ventilation (1-8)	34	42.9	55.4	49.2	96.2	83.6
31	Solar shading set-point	72.4	130	101	122	0	0

Table J.8: *Output data regarding the influence of hours with operative temperature above 27°C in considered simplified models.* **Output mean value and standard deviation.*

Appendix **K**

Factorial design

K.1 Methodology

The factorial design method is able to quantify correlations among the input parameters simply by determining the effect of changing one single input parameter. The concept of factorial design was introduced in 1978, [Box et al. 1978]. Back then, the power of computational simulations was rather limited compared to its ability nowadays, and a clear and simplified approach was developed out of necessity. Although, this implies a limited usage for practical applications of the factorial design method as it requires n^k simulations, of which n corresponds to number of chosen possible values, or levels, for each input parameter and k specifies the amount of considered input parameters. This simply means that the investigation easily requires exponential high number of simulations. Usually each input parameters are indicated by two levels, a minimum(-) and a maximum(+) level, in a predefined variation intervals with equal probability. However, if it is favourable to quantify the uncertainty among the chosen input parameters with regards to nonlinearity, the variation interval can be divided into several levels.

As the method easily becomes to complex in case of larger amount of input parameters and levels, some organization methods are invented in order to organize a factorial design, [Box et al. 1978, p. 322]. One of them is the contrast coefficient table shown in table K.1 in order to give a comprehensive view of the approach in factorial design. As the correlation between three input parameters each with two levels are investigated, the factorial design requires 2^3 = 8 simulations. The contrast coefficient table specifies for each simulation whether the minimum(-) or maximum(+) level is needed for each particular input parameter (x_1, x_2, x_3) in order to obtain an output, Φ.

Simulation	1st order			2nd order			3rd order	Mean	Output
	x_1	x_2	x_3	x_1x_2	x_1x_3	x_2x_3	$x_1x_2x_3$		
1	-	-	-	+	+	+	-	+	Φ_1
2	+	-	-	-	-	+	+	+	Φ_2
3	-	+	-	-	+	-	+	+	Φ_3
4	+	+	-	+	-	-	-	+	Φ_4
5	-	-	+	+	-	-	+	+	Φ_5
6	+	-	+	-	+	-	-	+	Φ_6
7	-	+	+	-	-	+	-	+	Φ_7
8	+	+	+	+	+	+	+	+	Φ_8
Divisor	4	4	4	4	4	4	4	8	

Table K.1: *Contrast coefficient table applied for factorial design with use of three input parameters, [Saltelli et al. 2000, p. 55].*

The contrast coefficient table is further extended in order to contain signs for each correlation between two and three input parameters along with the average value. The sign for the 1st order effect is specified for each particular simulation. The signs for the 2nd and 3rd order effects are determined by multiplication of the sign for the applied input parameters in the given simulation. The divisors are determined according to the sum of each sign in the columns. The principle of factorial design is illustrated in figure K.1 in which the output is indicated by bullets in each corner.

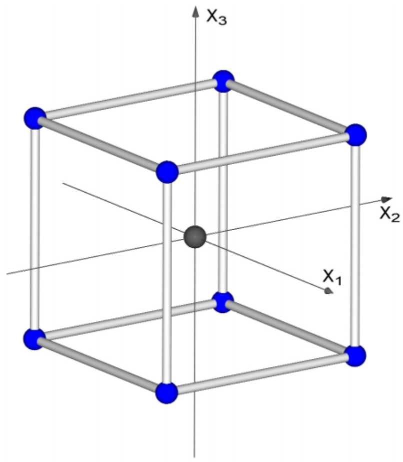


Figure K.1: *Graphical representation of factorial design principle with three input parameters.*

K.2 Calculation procedure

As the sensitivity analysis was conducted prior to the factorial design, it is possible to reduce the amount of considered input parameters and select the most important ones and investigate in details their mutual correlation. From this knowledge can be obtained regarding the optimal combination of the investigated input parameters and reduces the overall uncertainty of the simplified models. In this thesis it is chosen to further investigate three input parameters each by two levels with regards to their correlation. These three investigated input parameters are determined according to the most important input parameters in the sensitivity analysis and are listed in table K.2 along with their respectively minimum and maximum levels based on a 95% confidence interval.

	No.	**Factor**	**Unit**	**Variation interval**	
				(−)	(+)
x_1	25	Ventilation set-point temperature	[°C]	22	27
x_2	29	Evening ventilation rate (17-24)	$[{}^{l}/_{s\,m^2}]$	0.5	4.3
x_3	31	Solar shading set-point	$[{}^{W}/_{m^2}]$	0	300

Table K.2: *The three most important input parameters of total 31 input parameters determined in the sensitivity analysis.*

The output regarding hours above 26°C and 27°C for the 8 simulations in both EN ISO 13790 and Bo Adamson simplified model are listed in table K.3 along with the conditions for each particular simulation. As the SBi simplified model does not include the solar shading set-point as an input data, the factorial design is omitted for this simplified model.

Simulation	Input matrix			Hours above 26°C		Hours above 27°C	
	$T_{ve,set}$	$q_{ve,eve}$	$f_{c,set}$	EN ISO 13790	Bo Adamson	EN ISO 13790	Bo Adamson
	[°C]	[$^{l}/_{s\,m^2}$]	[$^{W}/_{m^2}$]	[h]	[h]	[h]	[h]
1	22	0.50	0	48	182	2	50
2	27	0.50	0	2584	2469	1285	1318
3	22	4.30	0	2	23	0	0
4	27	4.30	0	2365	2105	791	764
5	22	0.50	300	254	431	76	227
6	27	0.50	300	3550	3313	2136	2106
7	22	4.30	300	25	83	2	23
8	27	4.30	300	3160	2718	1336	1233

Table K.3: *Output of factorial design simulations for EN ISO 13790 and Bo Adamson simplified model along with their respective conditions.*

K.3 Determination of 1st order effect

The calculation for the 1st order effect, corresponding to the individual variations of each applied parameters which is contributing to the simplified models uncertainty, are illustrated by means of a cube in figure K.2 by having two opposite surfaces in a cube.

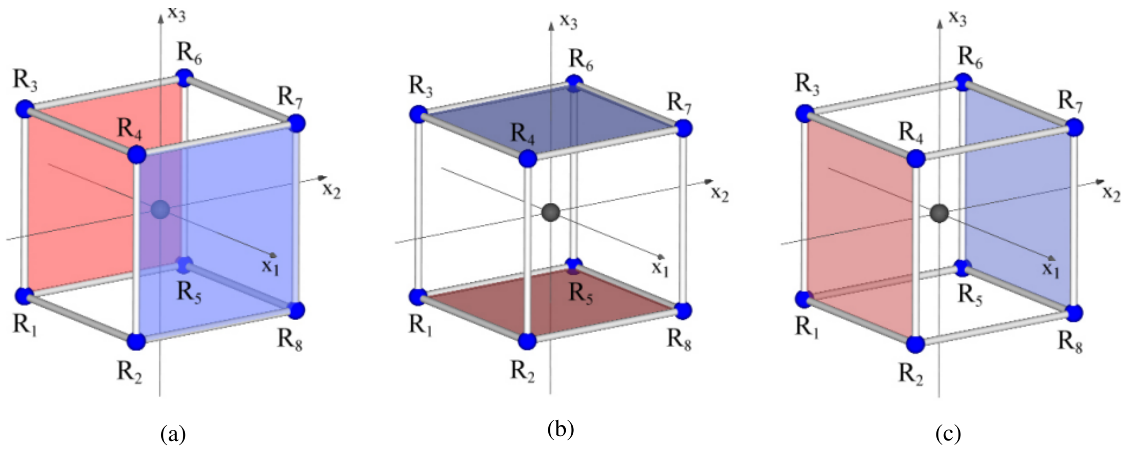


Figure K.2: *Illustration by means of a cube for 1st order effect for x_1 (a), x_2 (b) and x_3 (c), [Saltelli et al. 2000, p. 54].*

The 1st order effect is determined by summing the outputs for (+) and (-) in the column of the considered parameter and divided by the allocated divisor. Thus, the 1st order effect is considered as the direct exchange between two surfaces. The calculation of the main effect of the 1st order effect is specifed by equation (K.1) and is exemplary shown in equation (K.2) for x_1.

$$R_{1\text{st}} = \frac{\overline{\Phi_+} - \overline{\Phi_-}}{4} \tag{K.1}$$

$$R_{x_1} = \frac{-\Phi_1 + \Phi_2 - \Phi_3 + \Phi_4 - \Phi_5 + \Phi_6 - \Phi_7 + \Phi_8}{4} \tag{K.2}$$

R_{x_1}	Main effect of x_1, [h]
Φ_{1-8}	Output for each of performed simulation, [h]

	Evening ventilation rate (17-24) [l/s m²]	Solar shading set-point [W/m²]	Hours above 26°C EN ISO 13790 [h]	Hours above 26°C Bo Adamson [h]	Hours above 27°C EN ISO 13790 [h]	Hours above 27°C Bo Adamson [h]
$\Phi_2 - \Phi_1$	0.50	0	2536	2287	1283	1268
$\Phi_4 - \Phi_3$	4.30	0	2363	2082	791	764
$\Phi_6 - \Phi_5$	0.50	300	3296	2882	2060	1879
$\Phi_8 - \Phi_7$	4.30	300	3135	2635	1334	1210
Average:			2833	2472	1367	1280

***Table K.4:** Determination of 1st order effect for x_1 = ventilation set-point temperature.*

	Ventilation set-point [°C]	Solar shading heat gains [W/m²]	Hours above 26°C EN ISO 13790 [h]	Hours above 26°C Bo Adamson [h]	Hours above 27°C EN ISO 13790 [h]	Hours above 27°C Bo Adamson [h]
$\Phi_3 - \Phi_1$	22	0	-46	-159	-2	-50
$\Phi_4 - \Phi_2$	27	0	-219	-364	-494	-554
$\Phi_7 - \Phi_5$	22	300	-229	-348	-74	-204
$\Phi_8 - \Phi_6$	27	300	-390	-595	-800	-873
Average:			-221	-367	-343	-420

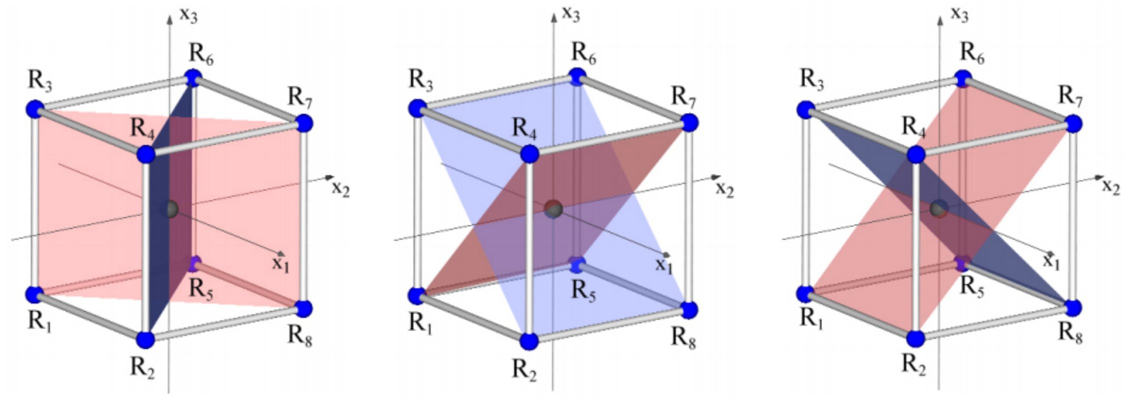
***Table K.5:** Determination of 1st order effect for x_2 = evening ventilation rate (17-24).*

	Ventilation set-point [°C]	Evening ventilation rate (17-24) [l/s m²]	Hours above 26°C EN ISO 13790 [h]	Hours above 26°C Bo Adamson [h]	Hours above 27°C EN ISO 13790 [h]	Hours above 27°C Bo Adamson [h]
$\Phi_5 - \Phi_1$	22	0.50	206	249	74	177
$\Phi_6 - \Phi_2$	27	4.30	966	844	851	788
$\Phi_7 - \Phi_3$	22	0.50	23	60	2	23
$\Phi_8 - \Phi_4$	27	4.30	795	613	545	469
Average:			498	442	368	364

***Table K.6:** Determination of 1st order effect for x_3 = solar shading set-point.*

K.4 Determination of 2nd order effect

The 2nd order effect describes the correlation between two parameters and is cubical illustrated in figure K.3 by having the exchange between two diagonal surfaces in a cube.



(a) (b) (c)

Figure K.3: *Illustration by means of a cube for the 2nd order effect for x_1x_2 (a), x_1x_2 (b) and x_2x_3 (c), [Saltelli et al. 2000, p. 54].*

	Hours above 26°C		**Hours above 27°C**	
	EN ISO 13790	**Bo Adamson**	**EN ISO 13790**	**Bo Adamson**
	[h]	[h]	[h]	[h]
$\Phi_1 - \Phi_2$	-2536	-2287	-1283	-1268
$\Phi_3 - \Phi_4$	-2363	-2082	-791	-764
$\Phi_6 - \Phi_5$	3296	2882	2060	1879
$\Phi_8 - \Phi_7$	3135	2635	1334	1210
Average:	383	287	330	264

Table K.7: *Determination of the 2nd order effect for x_1x_2.*

	Hours above 26°C		**Hours above 27°C**	
	EN ISO 13790	**Bo Adamson**	**EN ISO 13790**	**Bo Adamson**
	[h]	[h]	[h]	[h]
$\Phi_1 - \Phi_2$	-2536	-2287	-1283	-1268
$\Phi_4 - \Phi_3$	2363	2082	791	764
$\Phi_5 - \Phi_6$	-3296	-2882	-2060	-1879
$\Phi_8 - \Phi_7$	3135	2635	1334	1210
Average:	-84	-113	-305	-293

Table K.8: *Determination of the 2nd order effect for x_1x_3.*

	Hours above 26°C		Hours above 27°C	
	EN ISO 13790	Bo Adamson	EN ISO 13790	Bo Adamson
	[h]	[h]	[h]	[h]
$\Phi_1 - \Phi_3$	46	159	2	50
$\Phi_2 - \Phi_4$	219	364	494	554
$\Phi_7 - \Phi_5$	-219	-348	-74	-204
$\Phi_8 - \Phi_6$	-390	-595	-800	-873
Average:	-89	- 105	-95	-118

Table K.9: *Determination of the 2nd order effect for x_2x_3.*

K.5 Determination of 3rd order effect

The 3rd order effect describes the correlation between two parameters and is illustrated by means of a cube in figure K.4 by having the exchange between two diagonal surfaces in a cube. tetrahedron

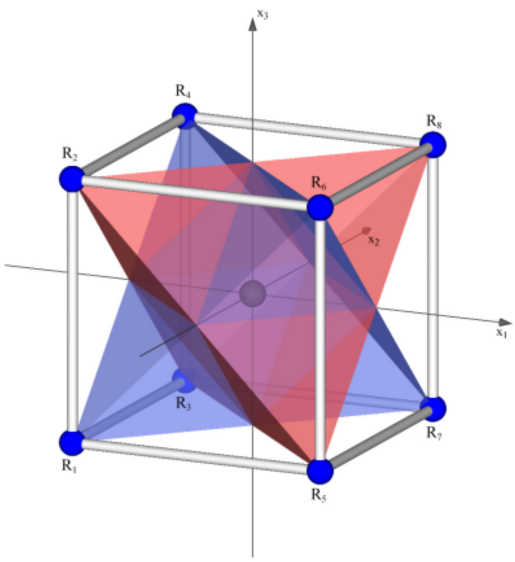


Figure K.4: *Illustration by means of a cube for 3rd order effect for $x_1x_2x_3$, [Saltelli et al. 2000, p. 55].*

K.6 Result of factorial design

The results of the factorial design are obtained by organizing the output into the contrast coefficient table. For the three input parameters the final results for hours with operative temperature exceeding 26°C and 27°C are illustrated in figure K.5 and K.6 respectively for the 1st order, 2nd order and 3rd order effect along with the mean value.

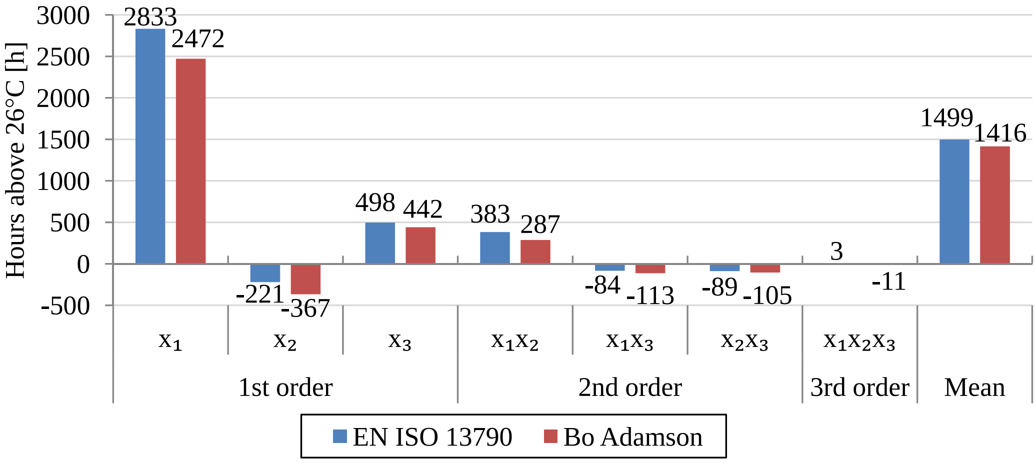


Figure K.5: *Results of factorial design expressed by hour with operative temperature exceeding 26°C.*

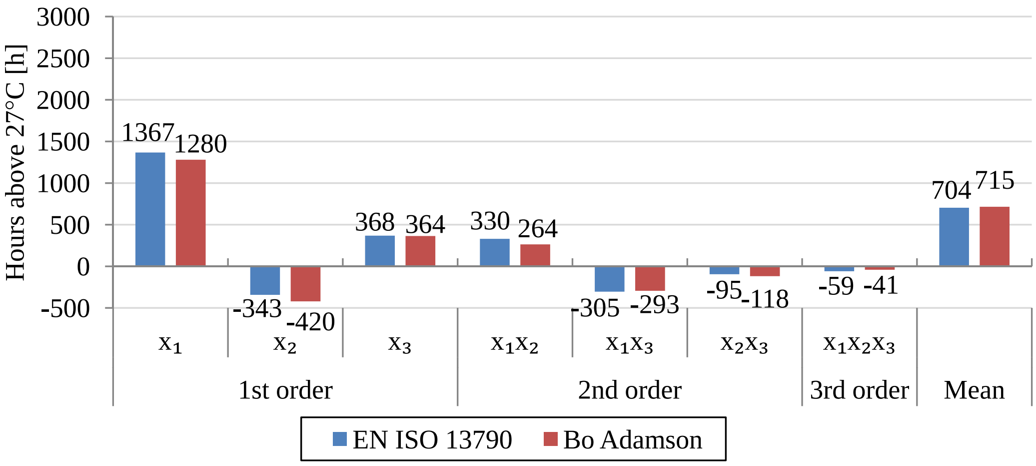


Figure K.6: *Results of factorial design expressed by hour with operative temperature exceeding 27°C.*

In general, the EN ISO 13790 conducts higher values, but the two considered simplified simplified models obtains the same tendency among results in the factorial design for the three input parameters, as only the variations of the model output for the ventilation set-point temperature causes deviations. The first three groups of columns presents the results for the variation of the model output by changing one single input parameter (1st order effect). As the ventilation set-point temperature was particularly the most important input parameter in Morris-method for all three simplified simplified models, this factor implies the highest variations of the model output. The following two groups of columns presents the results for correlation between two and three input parameters based on their variations (2nd order effect and 3rd order effect). The biggest correlation occurs between the ventilation set-point temperature and evening ventilation rate (x_1x_2). This can be explained by the fact that both of these factors are connected to the ventilation heat transfer, but also that they affects mainly the room air temperature whereas the solar shading set-point affects the internal surfaces temperature.

Appendix **L**

Thermal capacity

This appendix contains a theoretical description of thermal capacity calculations for a thermal zone, which are utilised for the establishment of simplified models.

L.1 Thermal energy storage

Thermal energy storage is a favourable passive cooling and heating solution in buildings, as the thermal mass' ability to absorb and liberate considerable amounts of energy enables a lowered risk of overheating, and additionally a lowered cooling demand resulting in a lowered energy consumption as well. In general, a high thermal mass absorbs energy when its temperature is lower than the surfaces temperature, which provides attenuation of peaks due to delay of discharged heat. Conversely, energy will be liberated when the thermal mass temperature is higher than the surfaces temperature, which decreases the heating demand during night in the winter. [Heiselberg 2008b, p. 14-15].

The thermal mass of a thermal zone depends mainly on the internal materials thermal properties. Thus, the choice of material thermal properties is rather important in order to obtain a passive cooling solution to the building. Table L.1 consists of materials thermal properties for often used materials.

	Density ρ, $\left[{}^{\text{kg}}/_{\text{m}^3}\right]$	Specific heat capacity c_p, $\left[{}^{\text{kJ}}/_{\text{kg}\,^\circ\text{C}}\right]$	Thermal conductivity λ, $\left[{}^{\text{W}}/_{\text{m}\,^\circ\text{C}}\right]$	Thermal Diffusivity α, $\left[{}^{\text{mm}^2}/_{\text{s}}\right]$
Concrete	2385	0.8	1.60*	0.84
Light-weight concrete	1200	1.0	0.35	0.29
Brick	1850	0.8	0.68	0.46
Tiles	2100	1.0	1.50	0.71
Gypsum (plaster board)	881	1.0	0.20	0.23
Wood on concrete	1440	1.2	0.53	0.31
Wood	950	1.8	0.14	0.08
Sapwood	470	1.8	0.12	0.14
Linoleum	1200	1.4	0.17	0.10
Stone wool	21	0.8	0.039**	3.32
Polystyrene, fill	21	0.8	0.050	2.98
Leca, fill	325	0.8	0.21	0.81

Table L.1: *Materials thermal properties based on BSim predefined values. *For reinforced concrete the thermal conductivity is changed to 2.1* ${}^{\text{W}}/_{\text{m}\,^\circ\text{C}}$*, **The thermal conductivity varies between 34, 37 and 39* ${}^{\text{mW}}/_{\text{m}\,^\circ\text{C}}$*,* The capacity of the heat storage depends on the thermal diffusivity coefficient, α, given by equation (L.1), as it describes how quickly the heat dissipation happens. Thus, it considers the materials ability to transfer energy compared to its ability to store energy, [D. Wangsøe 2004, p. 20].

$$\alpha = \frac{\lambda}{\rho \cdot c_p} \tag{L.1}$$

α	Thermal diffusivity coefficient, $[\text{m}^2/\text{s}]$
λ	Thermal conductivity, $[\text{W}/\text{m}\,^\circ\text{C}]$
ρ	Density, $[\text{kg}/\text{m}^3]$
c_p	Specific heat capacity, $[\text{J}/\text{kg}\,^\circ\text{C}]$

The thermal diffusivity coefficients are calculated for the materials listed in table L.1 and graphically illustrated in figure L.1.

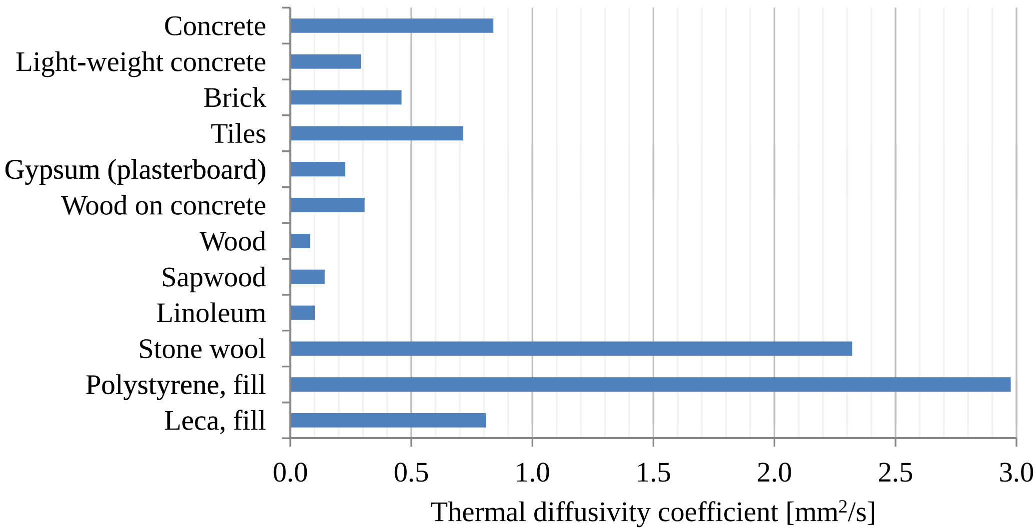


Figure L.1: *Thermal diffusivity for different building materials.*

When the internal surfaces are affected by a heat supply for a longer period, the internal surface temperature increases and heat will be transmitted into the material. This temperature fluctuation attenuates the longer it reaches into the material. As heat accumulation only is possible when the temperature is changing over time, this limits the part of construction which is included as thermal mass. This so-called periodic penetration depth is depending on the materials thermal properties and the exposures duration, [D. Wangsøe 2004, p. 19-21].

Insulating materials with a thermal diffusivity, $\alpha \geq 1.0 \times 10^{-6}$ m^2/s, have a negligible thermal conductivity and heat storage capacity due to their open structure, [EN ISO 13786 2007, p. 12]. Thus, insulating materials are not included in the thermal mass, which limits the periodic penetration depth as well. The determination of the thickness of thermal mass varies among the different simplified model as they apply different methods and assumptions.

L.2 Calculation algorithm

There are two mentioned approaches in this appendix for determination of the thermal capacity of the thermal zone. The first approach is simply based on the predefined values, listed in table L.2 for different guidances and European standards, depending on the type of building constructions. However, there is no description provided for different building construction elements and subsequently the thermal capacity in *EN ISO 13790* standard.

Building class	**Description***	**Thermal capacity** **SBi 213** C_m, $[Wh/°C\,m^2{-}floor]$	**Thermal capacity** **EN ISO 13790** C_m, $[Wh/°C\,m^2{-}floor]$
Very light	Only light materials (e.g. Wood)	40	22
Middle Light	Few heavy materials (e.g. concrete deck with wood/light-concrete walls)	80	31
Medium	-	-	46
Middle Heavy	Lot of heavy materials (e.g. concrete deck with tiles and brick walls)	120	72
Very heavy	Only heavy materials (e.g concrete, bricks and tiles)	160	103

Table L.2: *Guidance for determining thermal capacity SBi 213 and EN ISO 13790 standard, [SBi-anvisning 213 2008, p. 33], [EN ISO 13790 2008, p. 68]. Description is valid for SBi 213.*

The second approach is based on calculation of the thermal capacity of a thermal zone by taking into account for material thermal properties of the internal building elements by using equation (L.2). *The thermal capacity of doors and windows are assumed negligible, [Danvak ApS 1987, p. 102].

$$C_m = \sum_{j=1}^{n} A_j \cdot d \cdot \rho \cdot c_p \qquad \text{(L.2)}$$

C_m	Thermal capacity of a thermal zone, $[Wh/°C]$
A_j	Area of the building element j, $[m^2]$
d_a	Thickness of internal layer, [m]

The models calculation procedure for determine the thermal capacity of the thermal zone differs from each other as different methods and assumptions for determination of the characteristics are applied.

L.2.1 EN ISO 13786 simplified method

This method is referred to in the EN ISO 13790 standard and hence applied for the EN ISO 13790 simplified model. It is proposed to use either detailed or simplified method for calculation of building element thermal capacity, [EN ISO 13786 2007, p. 1]. However, this section solely describe the simplified method, as it is used in the EN ISO 13790 simplified model, which is based on different scenario depending the layer thickness and periodic penetration depth ratio, ξ, which is calculated according to equation (L.3).

$$\xi = \frac{d}{\delta} \tag{L.3}$$
$$\delta = \sqrt{\frac{\lambda \cdot T}{\pi \cdot \rho \cdot c_p}}$$

ξ	Layer thickness and periodic penetration depth ratio, [-]
δ	Periodic penetration depth of a heat wave in a material, [m]
λ	Thermal conductivity, $\left[{}^{W}/_{m\,^\circ C}\right]$
T	Period of variations, [s]
ρ	Density, $\left[{}^{kg}/_{m^3}\right]$
c_p	Specific heat capacity $\left[{}^{J}/_{kg\,^\circ C}\right]$

Different approximations and methods should be applied depending on layer thickness and penetration length ratio.

Case A (ξ<0.5)
If the first layer of building element has thickness less than half of its penetration length and following layer is insulation, then areal thermal capacity of construction element is approximated by means of equation (L.4).

$$\kappa_j = d \cdot \rho \cdot c_p \tag{L.4}$$

κ_j	Areal thermal capacity of the construction element j, $\left[{}^{J}/_{m^2\,^\circ C}\right]$

Case B (0.5<ξ<2.0)
Here the effective thickness method is utilised, which implies a convectional thermal diffusivity, $\alpha = 0.7 \cdot 10^{-6}\ {}^{m^2}/_{s}$. The effective thickness of one side of a construction element is the minimum value of the following:

1. Half of thickness of the building element;

2. The thickness of the material between surface of interest and first thermal insulation layer, without taking into account coating;

3. A maximum effective thickness which for one day period of vibrations equals to 100 mm.

As the thermal diffusivity for usual building materials, except insulating materials ranges from $\alpha = 0.12 \cdot 10^{-6}\ ^{m^2}/_{s}$ to $\alpha = 1 \cdot 10^{-6}\ ^{m^2}/_{s}$, actual effective thickness can then range from 40% to 120% of conventional value, [EN ISO 13786 2007, p. 12]. The areal heat capacity is then calculated by equation (L.5).

$$\kappa_j = d_T \cdot \rho \cdot c_p \tag{L.5}$$

d_T	Effective thickness, [m]

Case C (2.0<ξ)
If the first layer of construction element has a thickness larger than twice of its penetration length, then thermal capacity of construction element is approximated by means of equation (L.6).

$$\kappa_j \cong \frac{\delta \cdot \rho \cdot c_p}{\sqrt{2}} \tag{L.6}$$

L.2.2 Bo Adamson calculation method

This calculation method of thermal capaticy of a thermal zone is applied for the Bo Adamson simplified model. It simply determines the depth for which temperature deviation caused by thermal capacity is negligible and thus the thickness of the thermal mass layer depending on the following criteria specified in Danvak ApS [1987, p. 101-102]:

- Internally located in front of light insulation material;
- The thermal transmittance for the heat accumulating layer must be $\geq 2.00\ ^{W}/_{m^2 \cdot {}^\circ C}$;
- Distance from internal surface is less than 50 mm for light-weight materials and less than 100 mm for heavy-weight materials;
- Distance from internal surface is half of the wall thickness for internal walls;
- The time constant of the each internal surface can not vary more than a factor three compared to the time constant of the thermal zone or exceed a daily oscillation, cf. equation (L.7).

$$\frac{1}{3}\,\tau_0 \leq \frac{C_{m,j}}{H_{ms,j}} \leq \max \begin{cases} 3 \cdot \tau_0 \\ 24\ \mathrm{h}/(2\,\pi) = 3.8\ \mathrm{h} \end{cases} \tag{L.7}$$

L.3 Investigation of calculation algorithms

	Extra light		Light		Heavy		Extra heavy	
	Material	d, [m]	Material	d, [m]	Material	d, [m]	Material	d, [m]
Ceiling	Wood	0.030	Wood	0.030	Wood	0.020	Concrete	0.100
	Stone wool 39	0.270	Stone wool 39	0.270	Stone wool 39	0.280	Stone wool 39	0.200
	Roofing	0.010	Roofing	0.010	Roofing	0.010	Roofing	0.010
	Total	**0.310**	**Total**	**0.310**	**Total**	**0.310**	**Total**	**0.310**
External wall	Gypsum	0.030	Light concrete	0.100	Brick	0.108	Brick	0.108
	Stone wool 39	0.320	Stone wool 39	0.250	Stone wool 39	0.242	Stone wool 39	0.242
	Brick	0.108	Brick	0.108	Brick	0.108	Brick	0.108
	Total	**0.458**	**Total**	**0.458**	**Total**	**0.458**	**Total**	**0.458**
Internal wall	Gypsum	0.030	Gypsum	0.030	Brick	0.108	Brick	0.108
	Stone wool 39	0.040	Stone wool 39	0.040	Stone wool 39	0.075	Stone wool 39	0.075
	Gypsum	0.030	Gypsum	0.030	Brick	0.108	Brick	0.108
	Total	**0.100**	**Total**	**0.100**	**Total**	**0.291**	**Total**	**0.291**
Floor	Wood	0.030	Wood	0.010	Tiles	0.010	Tiles	0.010
	Stone wool 39	0.180	Concrete	0.150	Concrete	0.150	Concrete	0.150
	Concrete	0.190	Polystyrene fill	0.240	Polystyrene fill	0.240	Polystyrene fill	0.240
	Total	**0.400**	**Total**	**0.400**	**Total**	**0.400**	**Total**	**0.400**

Table L.3: *Material layers for different building construction elements. Light concrete corresponds to light-weight concrete.*

L.4 Uncertainties in thermal capacity determination for SBi summer comfort model

	Case 1		Case 2		Case 3		Case 4	
	Material	d, [m]	Material	d, [m]	Material	d, [m]	Material	d, [m]
Ceiling	Tiles	0.030	Light concrete	0.100	Light concrete	0.100	Light concrete	0.100
	Stone wool 39	0.270	Stone wool 39	0.200	Stone wool 39	0.200	Stone wool 39	0.200
	Roofing	0.010	Roofing	0.010	Roofing	0.010	Roofing	0.010
	Total	**0.310**	**Total**	**0.310**	**Total**	**0.310**	**Total**	**0.310**
External wall	Light concrete	0.100	Light concrete	0.100	Light concrete	0.100	Light concrete	0.100
	Stone wool 39	0.250	Stone wool 39	0.250	Stone wool 39	0.250	Stone wool 39	0.250
	Brick	0.108	Brick	0.108	Brick	0.108	Brick	0.108
	Total	**0.458**	**Total**	**0.458**	**Total**	**0.458**	**Total**	**0.458**
Internal wall	Gypsum	0.030	Gypsum	0.030	Gypsum	0.013	Light concrete	0.100
	Stone wool 39	0.040	Stone wool 39	0.040	Light concrete	0.100	Stone wool 39	0.075
	Gypsum	0.030	Gypsum	0.030	Gypsum	0.013	Light concrete	0.100
	Total	**0.100**	**Total**	**0.100**	**Total**	**0.126**	**Total**	**0.275**
Floor	Tiles	0.010	Tiles	0.010	Tiles	0.010	Tiles	0.010
	Concrete	0.090	Concrete	0.090	Concrete	0.090	Concrete	0.150
	Polystyrene fill	0.300	Polystyrene fill	0.300	Polystyrene fill	0.300	Polystyrene fill	0.240
	Total	**0.400**	**Total**	**0.400**	**Total**	**0.400**	**Total**	**0.400**
Thermal capacity, $\left[{}^{Wh}/_{{}^\circ C\ m^2-floor}\right]$	89		95		102		120	

Table L.4: *Material layers for different building construction elements corresponding to middle heavy building class. Light concrete corresponds to light-weight concrete. Thermal capacity was calculated by means of EN ISO 13786 detailed method.*

	Case 4		Reference building	
	Material	d, [m]	Material	d, [m]
Ceiling	Light-weight concrete	0.100	Wood	0.020
	Stone wool 39	0.200	Stone wool 39	0.280
	Roofing	0.010	Roofing	0.010
	Total	**0.310**	**Total**	**0.310**
External wall	Light-weight concrete	0.100	Brick	0.108
	Stone wool 39	0.250	Stone wool 39	0.242
	Brick	0.108	Brick	0.108
	Total	**0.458**	**Total**	**0.458**
Internal wall	Light-weight concrete	0.100	Brick	0.108
	Stone wool 39	0.075	Stone wool 39	0.075
	Light-weight concrete	0.100	Brick	0.108
	Total	**0.275**	**Total**	**0.291**
Floor	Tiles	0.010	Tiles	0.010
	Concrete	0.150	Concrete	0.150
	Polystyrene fill	0.300	Polystyrene fill	0.300
	Total	**0.460**	**Total**	**0.460**

Table L.5: *Material layers for different building construction elements corresponding to the total thermal capacity of 120* $^{Wh}/_{^\circ C\ m^2-floor}$.

Appendix **M**

Specific heat transfer by transmission

This appendix contains a theoretical description of specific heat transfer by transmission for a building zone. The calculation algorithm is utilised for the establishment of simplified models.

M.1 Calculation algorithm

The specific heat transfer by transmission through opaque constructions and windows/doors is calculated according to equation (M.1). The specific heat transfer by transmission through opaque envelope elements, $H_{tr,opa}$, covers all heat transfers by transmission to the external environment, the ground and adjacent (un)conditioned rooms, [EN ISO 13790 2008, p. 34].

$$H_{tr} = H_{tr,opa} + H_{tr,w} = b\left[\sum_{j=1}^{n} U_j \cdot A_j + \sum_{i=1}^{n} \psi_i \cdot l_i + \sum_{k=1}^{n} \chi_k\right] \quad (M.1)$$

H_{tr}	Total specific heat transfer by transmission, $\left[{}^{W}/_{{}^\circ C}\right]$
$H_{tr,opa}$	Specific heat transfer by transmission through opaque envelope elements, $\left[{}^{W}/_{{}^\circ C}\right]$
$H_{tr,w}$	Specific heat transfer by transmission through windows and doors, $\left[{}^{W}/_{{}^\circ C}\right]$
b	Temperature factor, $[-]$
U_j	Thermal transmittance of envelope element j, $\left[{}^{W}/_{{}^\circ C\,m^2}\right]$
A_j	Area of envelope element j, $\left[m^2\right]$
ψ_i	Linear thermal transmittance of linear thermal bridge i, $\left[{}^{W}/_{{}^\circ C\,m}\right]$
l_i	Linear thermal length of linear thermal bridge i, $[m]$
χ_k	Point thermal transmittance of point thermal bridge k, $\left[{}^{W}/_{{}^\circ C}\right]$

The impact of point thermal transmittance, χ, as a result from intersection of linear thermal bridges. can be neglected, [EN ISO 14863 2005, p. 3]. The remaining transmission heat transfer elements are thorough explained in the following sections.

M.2 Temperature factor

The temperature factor, b, specifies whether the temperature in the unheated adjacent space is lower than the internal temperature, compared to the temperature difference between internal and external conditions. It is different from 1.0, when the temperature on the external part of envelope element is different from external air temperature as well as when the temperature on internal part of envelope element is different from internal air temperature, [SBi-anvisning 213 2008, p. 39].

$$b = \frac{H_{\text{tr,adj}}}{H_{\text{adj}} + H_{\text{tr,adj}}} \tag{M.2}$$

$H_{\text{tr,adj}}$	Specific heat transfer by transmission from adjacent rooms to external conditions, $[{}^{\text{W}}/{}_{^\circ\text{C}}]$
H_{adj}	Specific heat transfer by transmission to adjacent room, $[{}^{\text{W}}/{}_{^\circ\text{C}}]$

The temperature factor is determined in steady-state conditions by using equation (M.2). In case of underfloor heating, a correction for temperature factor, Δb, is added to the temperature factor. This is due to an additional heat transfer as a consequence of increased temperature.

$$\Delta b = \frac{T_{\text{f}} - T_{\text{air}}}{T_{\text{air}} - T_{\text{e}}} \tag{M.3}$$

T_{f}	Floor temperature in level of heating pipes, [°C]
T_{air}	Room air temperature, [°C]
T_{e}	External temperature, [°C]

To avoid additional input parameters for description of building envelope constructions and simplify the calculation process, predefined values of temperature factor are shown in table M.1. A correction for temperature factor of +0.3 is applied for a flow temperature of 35 °C.

Conditions	**Temperature factor** $b, [-]$
Building components towards indoor conditions	0.0
External floor without underfloor heating	0.7
Basement floor without underfloor heating	0.7
Basement wall lower than 2 meters compared to ground level	0.7
Basement wall beneath the building	0.7
Basement foundation lower than 2 meters compared to ground level	0.7
Basement foundation beneath the building	0.7
Building components towards outdoor conditions	1.0
Including underfloor heating	+0.3

Table M.1: *Temperature factor for building components at different conditions, [SBi-anvisning 213 2008, p. 39].*

M.3 Thermal transmittance

As an indicator of the building elements thermal performance, the thermal transmittance is calculated based on thermal resistances according to equation (M.4).

$$\frac{1}{U} = R = R_{si} + \sum_{i=1}^{n} \frac{d_i}{\lambda_i} + R_{se} \tag{M.4}$$

R	Thermal resistance, $\left[{}^{m^2\,{}^\circ C}/_{W}\right]$
R_{si}	Internal surface resistance, $\left[{}^{m^2\,{}^\circ C}/_{W}\right]$
R_{se}	External surface resistance, $\left[{}^{m^2\,{}^\circ C}/_{W}\right]$
d_i	Thickness of material layer i, [m]
λ_i	Thermal conductivity of material layer i, $\left[{}^{W}/_{m\,{}^\circ C}\right]$

Surface resistances should not be applied to surfaces in contact with another opaque material, only when they are in contact with air. The surface resistances specifies the convective and radiative heat transfer to air and other surfaces of the thermal zone respectively, [EN ISO 6946 2007, p. 3, 12-13]. Determination of them applies equation (M.5) for detailed analysis.

$$R_s = \frac{1}{\alpha_{conv} + \alpha_{rad}} \tag{M.5}$$

$$\alpha_{rad} = 4 \cdot \varepsilon \cdot \sigma \cdot T_s^3 \tag{M.6}$$

R_s	Surface resistance, $\left[{}^{m^2\,{}^\circ C}/_{W}\right]$
α_{conv}	Convective thermal transmittance, $\left[{}^{W}/_{m^2\,{}^\circ C}\right]$
α_{rad}	Radiative thermal transmittance, $\left[{}^{W}/_{m^2\,{}^\circ C}\right]$
ε	Hemispherical emissivity of the surfaces, [−]
σ	The Stefan-Boltzmann constant equal to $5.67 \cdot 10^{-8}$, $\left[{}^{W}/_{m^2\,{}^\circ C^4}\right]$
T_s	Mean thermodynamic temperature of the surface and its surroundings, [°C]

In the absence of specific information regarding the boundary conditions, design values are applicable. Table M.2 specifies design values for plane surfaces.

	Upwards $\left[{}^{m^2\,{}^\circ C}/_{W}\right]$	**Horizontal** $\left[{}^{m^2\,{}^\circ C}/_{W}\right]$	**Downwards** $\left[{}^{m^2\,{}^\circ C}/_{W}\right]$
R_{si}	0.10	0.13	0.17
R_{se}	0.04	0.04	0.04

Table M.2: *Conventional surface resistances dependent of the direction of heat flow valid for a horizontal surface, [EN ISO 6946 2007, p. 4].*

The surface resistance for building elements in external floor facing ground ±0.5 meter from ground level is determined to 1.5 ${}^{m^2\,{}^\circ C}/_{W}$, [DS 418 2011, p. 37].

The calculations of thermal transmittances based on equation (M.4) associated with total thicknesses for the building elements of the reference building (case 0) are described and listed in table M.3.

Building element	Material	Thickness d,[m]	Thermal conductivity $\lambda, [\mathrm{W}/\mathrm{m}\,°\mathrm{C}]$	Thermal resistance $R, [\mathrm{m}^2\,°\mathrm{C}/\mathrm{W}]$	Thermal transmittance $U, [\mathrm{m}^2\,°\mathrm{C}/\mathrm{W}]$
External ceiling	Surface resistance			0.10	**0.13**
	Wood	0.020	0.140	0.14	
	Stone wool 39	0.280	0.039	7.18	
	Roofing	0.010	0.048	0.21	
	Surface resistance			0.04	
	Total	**0.310**		**7.67**	
External wall	Surface resistance			0.13	**0.15**
	Brick	0.108	0.680	0.16	
	Stone wool 39	0.242	0.039	6.21	
	Brick	0.108	0.680	0.16	
	Surface resistance			0.04	
	Total	**0.458**		**6.69**	
Internal wall	Surface resistance			0.13	**0.40**
	Brick	0.108	0.680	0.16	
	Stone wool 39	0.075	0.039	1.92	
	Brick	0.108	0.680	0.16	
	Surface resistance			0.13	
	Total	**0.291**		**2.50**	
External floor	Surface resistance			0.17	**0.15**
	Tiles	0.010	1.5	0.01	
	Concrete	0.150	1.600	0.09	
	Polystyrene, fill	0.240	0.050	4.80	
	Surface resistance			1.50	
	Total	**0.400**		**6.57**	

Table M.3: *Thermal calculation of building construction elements of the reference building.*

M.4 Linear thermal transmittance

The linear thermal transmittance, ψ, is an indicator of the linear thermal transfer for thermal bridge, which occurs due to difference between internal and external areas near junctions, and can be calculated according to equation (M.7). The linear thermal transfer often occurs around windows/doors and foundations, [EN ISO 14863 2005].

$$\psi = L^{2\mathrm{D}} - \sum_{\mathrm{i}=1}^{n} l_{\mathrm{i}}\, U_{\mathrm{i}} \tag{M.7}$$

L^{2D}	Thermal coupling coefficient , $\left[{}^{W}/_{m\,^{\circ}C}\right]$
l_i	Length within the two-dimensional component i, [m]
U_i	Thermal transmittance of the one-dimensional component i, $\left[{}^{W}/_{m^2\,^{\circ}C}\right]$

The thermal coupling coefficient is obtained by considering the component separating the internal and external environment in a two-dimensional geometrical model. In any calculation of the linear thermal transmittance, the system of dimensions for the considered component must be specified, [EN ISO 14863 2005, p. 4-5].

M.5 Thermal transmission areas and linear lengths

The different kinds of dimension systems for determination of thermal transmission areas and linear lengths for elements of the building envelope may be determined at national levels, [EN ISO 13790 2008, p. 20]. Thus, all thermal transmission areas and linear lengths are determined according to DS 418 standard. The building elements which are included as heat accumulating constructions, but not a part of the building envelope, e.g. internal walls, are incorporated by having internal dimensions.

The thermal transmission areas for the building envelope are determined according to figure M.1. Subdivisions are made for building elements containing different types of construction. However, internal doors are not considered separately, but as a connecting wall surfaces. For windows and doors, the thermal transmission area is determined according to the dimensions of the external wall cavity, [DS 418 2011, p. 15].

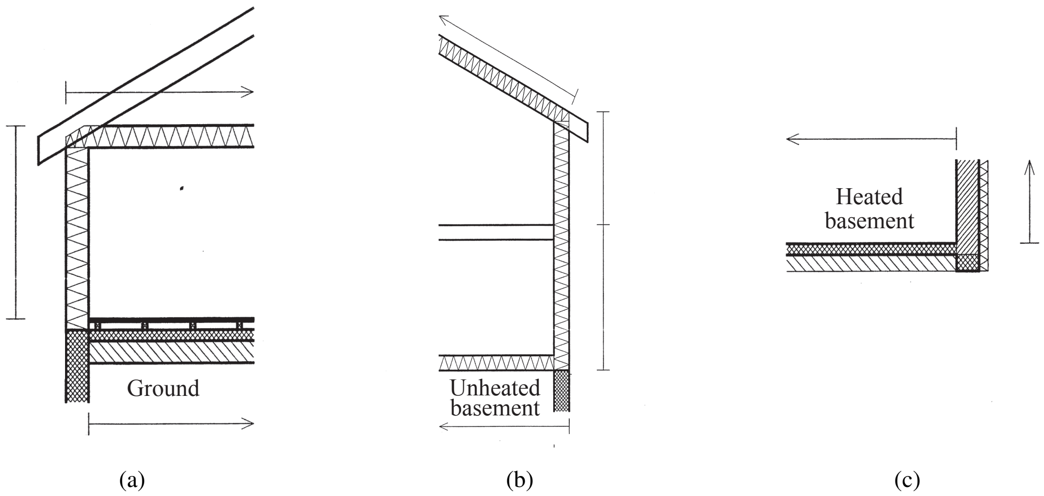


Figure M.1: *Determination of thermal transmission areas for buildings with attic and ground deck (a), inclined roof and unheated basement (b) heated basement (c). Redrawn from DS 418 [2011, p. 16].*

The thermal linear length for windows and doors is determined according to the dimensions of external wall cavities. However, only the top and sides are included. For the foundations, the thermal linear length is determined according to its outer perimeter, [DS 418 2011, p. 17].

Appendix **N**

Specific heat transfer by ventilation

N.1 Basic ventilation rate

Infiltration rate through the constructions should be specified as basic ventilation rate, which usually is a default value of 0.3 $^{l}/_{s}$ per m^2 floor area, [SBi-anvisning 213 2008, p.57]. In case, a measured infiltration loss is achieved from a blowerdoor test, this should be applied as basic ventilation rate and substitute the default value.

N.2 Models calculation procedures

The specific heat loss by ventilation is determined based on equation (N.1) and is valid for all models.

$$H_{ve} = \rho \cdot c_p \cdot q_{ve} \tag{N.1}$$

H_{ve}	Specific heat loss by ventilation, $\left[{}^{W}/_{^\circ C}\right]$
ρ	Air density, $\left[{}^{kg}/_{m^3}\right]$
c_p	Specific air heat capacity, $\left[{}^{J}/_{kg\,^\circ C}\right]$
q_{ve}	Air volume flow, $\left[{}^{m^3}/_{s}\right]$

By assuming fixed values for air density and specific air heat capacity the only one variable of foregoing equation is the air volume flow, which, in turn, depends on type of ventilation system and its control system. Both natural and mechanical ventilation are available in EN ISO 13790 and Bo Adamson models, whereas SBi model utilises solely natural ventilation. No specific description of ventilation system was found neither in EN ISO 13790 [2008] nor in Danvak ApS [1987], therefore ventilation system of only SBi model is described in this appendix.

N.2.1 SBi model

The specific heat loss by ventilation is determined on hourly basis based on the supply air flow rate, using equation (N.1).

The air exchange in current model is utilised only by natural ventilation hence assuming neither applied preheating of the supply air nor use of mechanical forces for air transportation. In addition, as illustrated in figure N.1, the natural ventilation is controlled via time period and control temperature, T_{ctr}, which is the operative temperature for the previous time step. For daytime, evening and night periods random ventilation rates are set up in the figure for demonstration purpose. Proportional band and limit temperature are described further in the text.

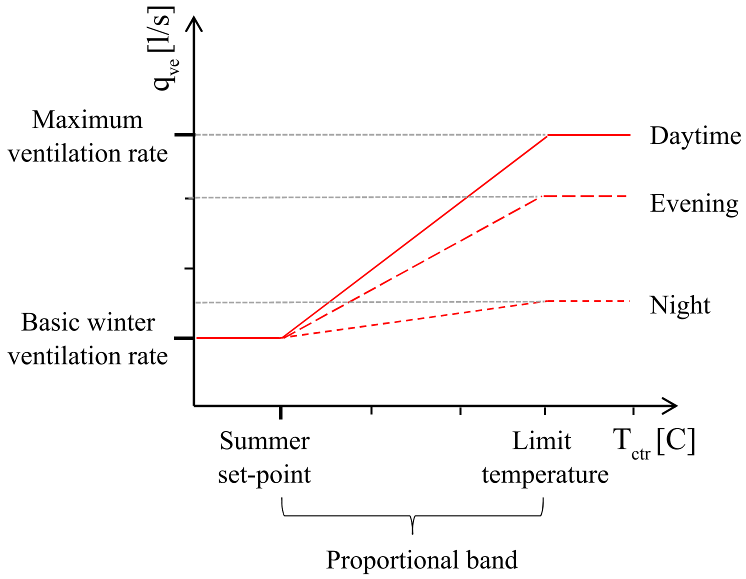


Figure N.1: *Control of ventilation system in SBi model.*

There is a basic winter ventilation rate, q_b, which according to the Danish Building Regulation is the minimum ventilation rate and accounts for infiltration. It is used during the entire year. Together with basic winter ventilation rate, for the following time periods the maximum ventilation rate should be specified:

- Daytime ventilation rate, q_{day} (9^{th} - 16^{th} hour);
- Evening ventilation, $q_{evening}$ (17^{th} - 24^{th} hour);
- Night ventilation, q_{night} (1^{st} - 8^{th} hour).

Thus, the ventilation rate will increase from a specified basic ventilation rate when the control (operative) temperature raises above a certain set-point temperature, $T_{ve,set}$, until a maximum ventilation rate is obtained or the calculated control temperature is below the set-point temperature. This increase will happen gradually, during a specified proportional band, T_{prop}, which is explained in figure N.2. The maximum ventilation rate is reached when the control temperature equals the limit temperature, which is the sum of summer set-point temperature and proportional band.

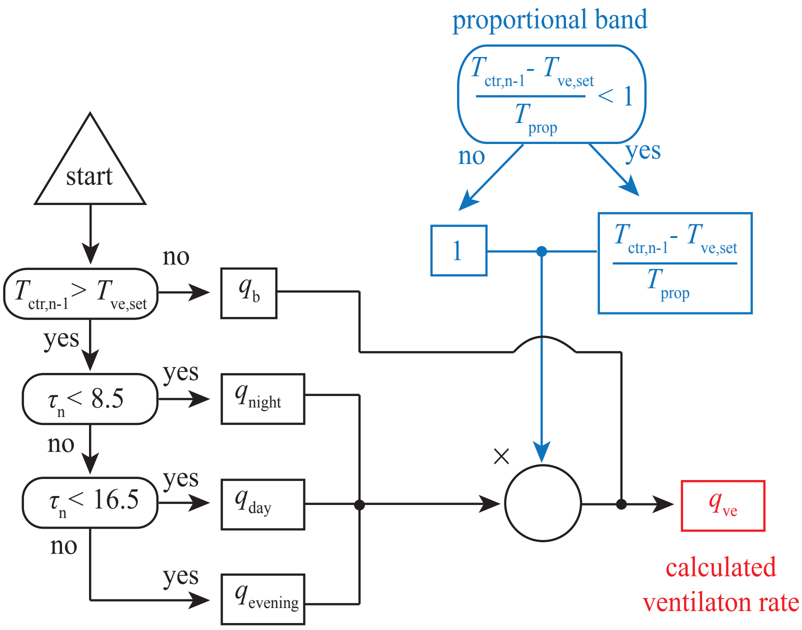


Figure N.2: *Scheme of ventilation system's control algorithm.*

N.3 Models calculation procedures

N.3.1 EN ISO 13790 - simple hourly method

Typical occupancy-related data for residential buildings are provided by EN ISO 13790 [2008] and illustrated in table N.1. It is expected that other conditioned areas are intended for sleeping, like nurseries and bedrooms due to the peak of heat production during the night.

Days	**Hours**	**Living room + Kitchen** [$^{W}/_{m^2}$]	**Other conditioned areas** [$^{W}/_{m^2}$]
Workdays	07.00 to 17.00	8.0	1.0
	17.00 to 23.00	20.0	1.0
	23.00 to 07.00	2.0	6.0
	Daily average	**9.0**	**2.67**
Weekend	07.00 to 17.00	8.0	2.0
	17.00 to 23.00	20.0	4.0
	23.00 to 07.00	2.0	6.0
	Daily average	**9.0**	**3.83**
Weekly average		**9.0**	**3.0**

Table N.1: *Heat flow rate from occupants and appliances valid for residential buildings, [EN ISO 13790 2008, p. 122].*

N.3.2 SBi model

The internal thermal load is set by means of Be10 for entire building, where people and equipment loads are summed up together. Default values for dwellings are equal to 1.5 $^{W}/_{m^2}$ and 3.5 $^{W}/_{m^2}$ respectively for people and equipment. Then the total internal thermal load of critical room is calculated by multiplying 5 $^{W}/_{m^2}$ of the heated floor area of the critical room. Although for energy calculation the internal heat load can be varied for entire building in Be10, for excessive temperatures calculation no variations are possible for critical room, i.e. 5 $^{W}/_{m^2}$ is the fixed internal heat load, [Mortensen 2012-2013].

N.4 Investigation of internal heat gains

This section contains material used for determination of internal heat gains in subsection 5.3.3.

Internal heat gains from occupants

To analyse the internal heat gains from occupants a daily occupancy profile should be established. Before applying it to a particular type of room a general one, applicable for entire house should be determined. The magnitude of internal heat gains from occupants is dependent on the number of residents as well as their activity level, which is studied later in the report. In order to develop a profile, which is representative of a majority of houses an average number of residents and average net building area should be considered. A study which encompass all detached houses in Denmark, [Wittchen 2004], revealed an average number of residents equals to 2.62. Furthermore, six low-energy houses from The Comfort Houses project were investigated to find the average areas of living room/kitchen and other types of rooms. This choice is explained by the fact that these dwellings are good representatives of future low-energy houses in Denmark which must comply with overheating requirement coming into effect in 2015, cf. table 1.1. The average net dwelling area resulted in 182 m^2, which comprises the average net floor area of living room/kitchen, i.e. 80 m^2, and the average floor net area of other rooms, 103 m^2, see figure N.3.

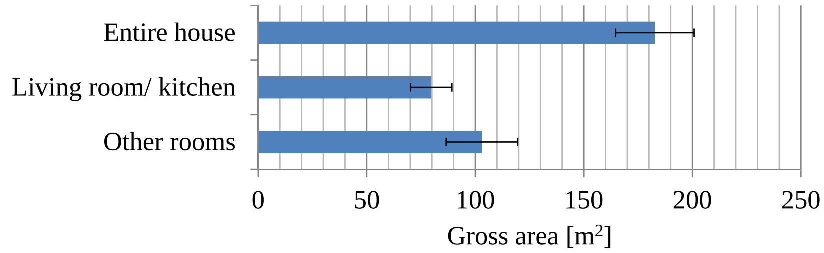


Figure N.3: *Average areas plus/minus standard deviation of different room types of six low-energy houses.*

It is a complex task to create an averaged occupancy profile, which encompasses all possible scenarios of residents behaviour. It is therefore assumed that average adult is working during the weekdays and out of home. Aforementioned assumptions are supplemented with following investigation of residence in danish detached houses:

1. An average person resides at home 16.3 hours per weekday. Investigation among 3,543 respondents in an age of 16-74, [Keiding et al. 2003].

2. An average person resides at home 19.9 hours per weekend. Investigation among 40 low-energy buildings, [Knudsen 2010].

3. An average dwelling is empty during approximately 5.4 hours on average day of the week. Investigation among 1,403 residents, [Bergsøe 1994].

The established profiles are evaluated in similar fashion as in Jensen et al. [2011], i.e. based on number of person-hours and the period when dwelling is unoccupied. The profiles are constantly adjusted to make the average values of weekdays, weekends and entire week fit with above mentioned investigations results. The average number of person-hours for entire week is calculated via equation (N.2).

$$\frac{\sum Occupants\ (Monday - Sunday)}{7\ days \times Occupants\ number} \tag{N.2}$$

The occupancy profile for 2.62 residents is shown in table N.2 and profile statistic is compared with demands in table N.3.

Hour	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
1	2.6	2.6	2.6	2.6	2.6	2.6	2.6
2	2.6	2.6	2.6	2.6	2.6	2.6	2.6
3	2.6	2.6	2.6	2.6	2.6	2.6	2.6
4	2.6	2.6	2.6	2.6	2.6	2.6	2.6
5	2.6	2.6	2.6	2.6	2.6	2.6	2.6
6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
7	2.6	2.6	2.6	2.6	2.6	2.6	2.6
8	2.6	2.6	2.6	2.6	2.6	1.7	1.7
9						1.7	1.7
10						1.7	1.7
11						1.7	1.7
12						1.7	1.7
13						1.7	1.7
14						1.7	1.7
15					2.6	1.7	1.7
16					2.6	1.7	1.7
17	2.6	2.6	2.6	2.6	2.6	1.7	1.7
18	2.6	2.6	2.6	2.6	2.6	1.7	1.7
19	2.6	2.6	2.6	2.6	2.6	1.7	1.7
20	2.6	2.6	2.6	2.6	2.6	2.6	2.6
21	2.6	2.6	2.6	2.6	2.6	2.6	2.6
22	2.6	2.6	2.6	2.6	2.6	2.6	2.6
23	2.6	2.6	2.6	2.6	2.6	2.6	2.6
24	2.6	2.6	2.6	2.6	2.6	2.6	2.6
Used	16	16	16	16	18	24	24
Not used	8	8	8	8	6	0	0
Person-hours	41.9	41.9	41.9	41.9	47.2	52.4	52.4

Table N.2: *Weekly occupancy profile of 2.62 persons in dwelling.*

Average	Weekday	Weekend	Weekly		Demand	Deviation
Used	16.4	24	18.6	1)	16.3	-0.1
Not used	7.6	0	5.4 3)	2)	19.9	-0.1
Person-hours	16.4 1)	20 2)	17.4	3)	5.4	0.0

Table N.3: *Evaluation statistic of 2.62 persons occupancy profile in dwelling and comparison with demands.*

The occupancy profile presented in table N.2 is valid for the entire house. It should be then distributed among different room types. A separation of entire house into two categories, i.e. living room/kitchen and other rooms seems to be optimal as the former represents spaces with high internal heat gains during non-sleeping time, whereas the latter are assumed to be occupied mainly during the night. Furthermore living room and kitchen are often coupled together, it is therefore reasonable to include them into the same category. An analysis of CO_2 level in living room/kitchen in seven comfort houses during the winter time was performed. Additionally a simplified occupancy profile was established based on CO_2 level dynamic, i.e. the decrease of CO_2 level indicates occupants absence, whereas the increase of CO_2 level indicates occupants activity. Based on obtained simplified profile a sleeping time comprises eight hours in total and occurs from 22.00 till 6.00, see figure N.4. Living room/kitchen were additionally unoccupied during the daytime when residents are assumed to be at work/school. Although obtained profile from CO_2 measurements indicates an occupancy pattern, it cannot be used as a final profile, because for an airflow movement the house is considered as one zone and measured CO_2 level in one particular space, e.g. living room, is affected by CO_2 level from other adjacent spaces. The airflow movement between zones during sleeping time is significantly dependent on the doors opening between different rooms.

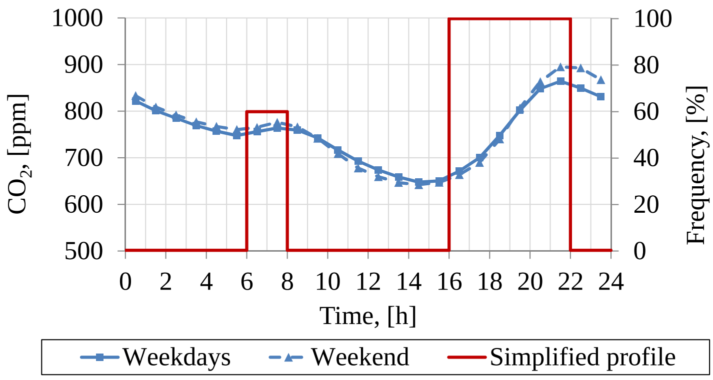


Figure N.4: *CO_2 measurements conducted in seven comfort houses for living room and established simplified occupancy profile.*

Another analysis of CO_2 level in bedrooms and nurseries in seven comfort houses shows that there is some activity during evening time. It is thus evident that during non-sleeping time residents do not spend all their time in living room/kitchen, though the major part of it. Based on aforementioned observations it is assumed that residents spend 70% of non-sleeping time in living room/kitchen, while the rest 30% of non-sleeping time and the time intended for sleeping occupants spend in other rooms. Table N.2 hence transforms into occupancy profile for living room/kitchen and other rooms during weekdays and weekend respectively, see figure N.5. Friday occupancy from 15:00 to 16:00 is equally distributed among weekdays.

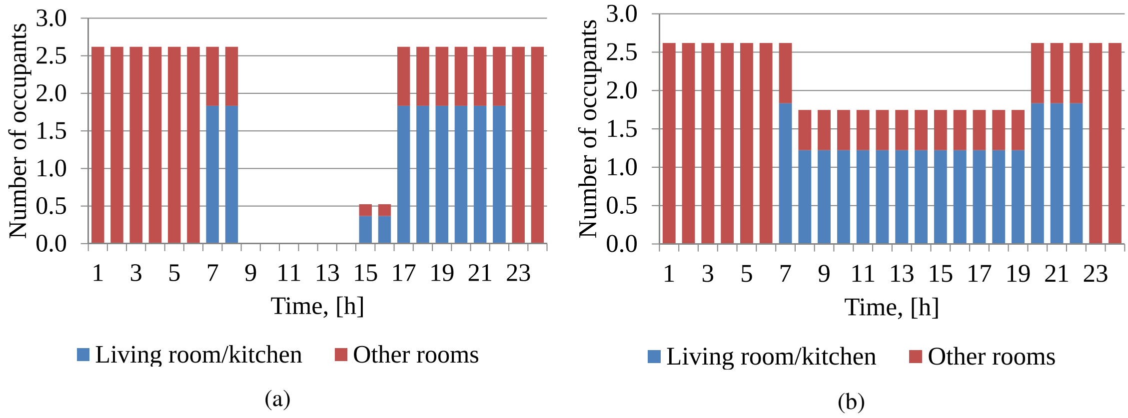


Figure N.5: *Occupancy profile of 2.62 persons in dwelling for two types of rooms during: weekdays (a) weekend (b).*

In order to obtain internal heat load from occupants it is necessary to know the heat production of people in dwellings. Standard EN 15251 [2007] states that for living spaces in residential buildings a metabolic heat rate of 1.2 can be used, corresponding to 70 W of sensible heat per m^2 of body area. However it is varying significantly depending on activity and more precise data is essential. There is a list of activities common for dwellings with corresponding metabolic heat generation rates proposed by AHSRAE, see table N.4. An estimate was made to determine the average occupant's heat production for entire house, living room/kitchen and other rooms, by applying dwelling related activities proposed by ASHRAE, see subsection N.4.1. Result is shown in figure N.6.

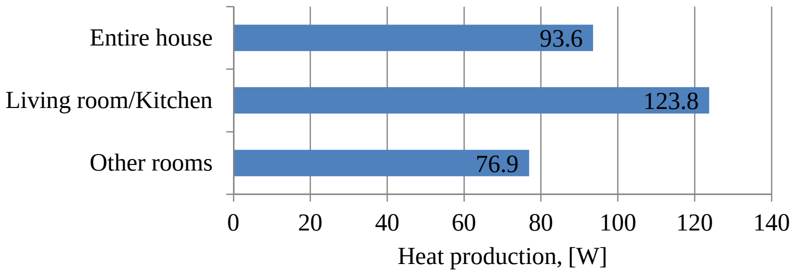


Figure N.6: *Adult occupant heat production depending on the spaces occupied.*

Calculated occupant heat production for entire house, 93.6 W, is very close to 90 W proposed in Sbi 213 for energy calculation, [SBi-anvisning 213 2008, p.63]. Using calculated occupant heat production and established occupancy profiles the average values of heat gains from occupants are calculated and illustrated in figure N.7. Data regarding areas of six comfort houses, cf. figure N.3, were used to calculate heat gains per square meter of area.

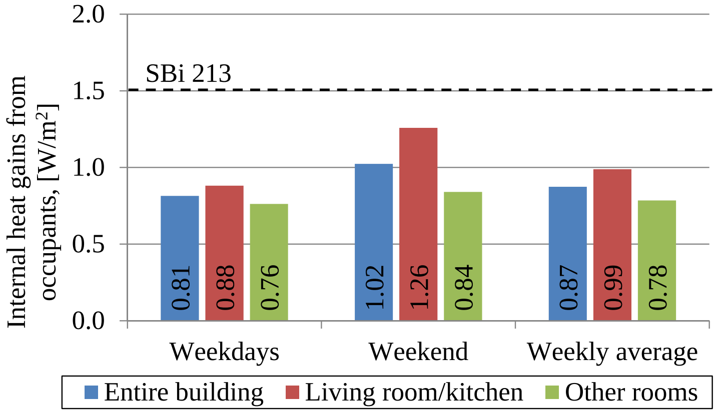


Figure N.7: *Average internal heat gains from occupants depending on the spaces occupied. Profiles are based on average areas of six comfort houses.*

Obtained average internal heat gains are compared solely with SBi 213 values as only total internal heat gains are specified in EN ISO 13790 standard without distinction on occupants and appliances. Although weekly average values for both living room/kitchen and other rooms are slightly lower than SBi 213 values, the difference between these two types of spaces is rather small.

Internal heat gains from appliances

In order to obtain data of internal heat gains magnitude from appliances an annual electricity consumption of detached houses in Denmark should be investigated. Only appliances and lighting are of interest assuming that 100% of consumed electricity is turned into internal heat gains, [SBi-anvisning 213 2008, p.63]. Another assumption is that electricity consumption of appliances and lighting and consequently internal heat gains are equally distributed throughout the area of dwelling.

In Gram-Hanssen [2005, p.10] 8500 detached houses in Denmark were analysed and based on that an equations was developed, i.e. equation (N.3). It is used for calculation of annual electricity consumption of detached house based on information about number of residents and dwelling net floor area.

$$Q = 530\ ^{\text{kWh}}/_{\text{year}} + A_{\text{f}} * 12\ ^{\text{kWh}}/_{\text{m}^2\ \text{year}} + N * 350\ ^{\text{kWh}}/_{\text{person year}} \tag{N.3}$$

Q	Annual electricity consumption, $\left[{}^{\text{kWh}}/_{\text{year}}\right]$
A_{f}	Dwelling net floor area, $\left[\text{m}^2\right]$

Calculated annual electricity consumption via equation (N.3) for the family with 2.62 residents equals to 3934 kW. An average internal heat gains are thus calculated to 3.06 $^{\text{W}}/_{\text{m}^2}$, which is slightly lower than ones used in SBi 213, i.e. 3.5 $^{\text{W}}/_{\text{m}^2}$. There was not found information regarding different electricity consumption of appliances during weekdays and weekdays. Analysis of electricity measurements of five houses from The Comfort Houses project also indicates a very similar behaviour during weekdays and weekdays. It is thus decided to use 3.06 $^{\text{W}}/_{\text{m}^2}$ for weekly average internal heat gains.

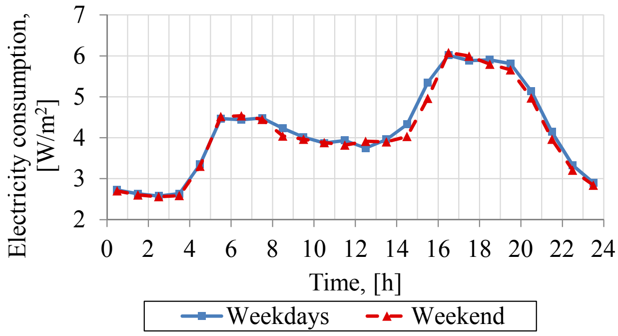


Figure N.8: *Electricity consumption measurements of appliances conducted in five comfort houses which are valid for entire house.*

Total internal heat gains

By combining previously calculated internal heat gains from occupants and appliances new profiles are established, for living room/kitchen during weekdays and weekend and for other rooms respectively. Comparison of average internal heat gains for living room/kitchen and other rooms between new profile, EN ISO 13790 standard and SBi 213 values is illustrated in figure N.9. Internal heat gains of new profile and SBi 213 look similar for both types of residential spaces, whereas EN ISO 13790 values are significantly varying, i.e. around 100% larger than the rest in case of living room/kitchen and around 50% smaller comparing to the rest in case of other rooms.

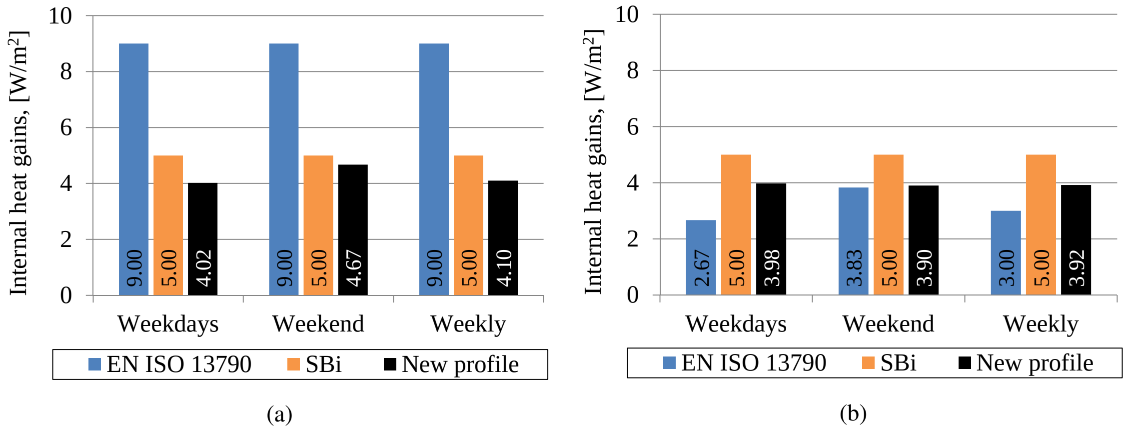


Figure N.9: *Comparison of average values of internal heat gains for: living room/kitchen (a), for other rooms (b).*

N.4.1 Heat production from people and equipment

An activity list with corresponding sensible metabolic heat generation proposed by ASHRAE is shown in table N.4.

Activity		Heat production	
Group	Subgroup	$[^{W}/_{m^2}]$	[met]
Resting	Sleeping	40	0.7
	Reclining	45	0.8
	Seated, quiet	60	1.0
	Standing, relaxed	70	1.2
Office activities	Typing	65	1.1
Miscellaneous	Cooking	95-115	1.6-2.0
Occupational Activities	Housecleaning	115-200	2.0-3.4

Table N.4: *Typical metabolic heat generation for various activities, [ASHRAE 2009, p.8.7]. 1 met = 58.2* $^{W}/_{m^2}$.

A quick estimation of person heat production is done depending the space he is occupying, see tables N.5 - N.7. An adult person is assumed with a body surface area of 1.7 m^2, which is an average of male and female as it is assumed that they are proportionally distributed in dwellings. Furthermore, for miscellaneous occupational activities an average heat productions of proposed ranges are used.

Estimations are based on different activities, which likely occur in particular type of residential space without taking into account the difference between weekdays and weekend. The total time spent in particular space is limited by following assumptions:

1. An average occupant spend 16.3 hours per weekday in detached house in Denmark, [Keiding et al. 2003];
2. A sleeping time is equal to 8 hours;
3. An average occupant spend 70% of non-sleeping time in living room/kitchen according to subsection 5.3.3 ((16.3-8.0)*0.7 = 5.8 h);
4. An average occupant spend 30% of non-sleeping time and all time intended for sleeping in other rooms according to subsection 5.3.3 ((16.3-8.0)*0.3 + 8.0 = 10.5 h).

Activity	**Time**	**Area of body**	**Heat production**		
	[h]	$[m^2]$	[met]	$[W/m^2]$	[W]
Sleeping	8	1.7	0.7	40	544
Reclining	1	1.7	0.8	45	77
Seated, quiet	3	1.7	1.0	60	306
Typing	2	1.7	1.1	65	221
Standing, relaxed	1	1.7	1.2	70	119
Cooking (average)	1	1.7	1.8	105	179
Housecleaning (average)	0.3	1.7	2.7	158	80
Total	16.3				1525
Hourly average					94

Table N.5: *Calculation of weighted average hourly heat production of a person in dwelling.*

Weighted average hourly heat production of a person is calculated by dividing total heat production with total time.

Activity	**Time**	**Area of body**	**Heat production**		
	[h]	$[m^2]$	[met]	$[W/m^2]$	[W]
Sleeping	0	1.7	0.7	40	0
Reclining	1	1.7	0.8	45	77
Seated, quiet	1.5	1.7	1.0	60	153
Typing	1	1.7	1.1	65	111
Standing, relaxed	1	1.7	1.2	70	119
Cooking (average)	1	1.7	1.8	105	179
Housecleaning (average)	0.3	1.7	2.7	158	80
Total	5.8				718
Hourly average					124

Table N.6: *Calculation of weighted average hourly heat production of a person in living room/kitchen.*

Activity	**Time**	**Area of body**	**Heat production**		
	[h]	$[m^2]$	[met]	$[W/m^2]$	[W]
Sleeping	8	1.7	0.7	40	544
Reclining	0	1.7	0.8	45	0
Seated, quiet	1.5	1.7	1.0	60	153
Typing	1	1.7	1.1	65	111
Standing, relaxed	0	1.7	1.2	70	0
Cooking (average)	0	1.7	1.8	105	0
Housecleaning (average)	0	1.7	2.7	158	0
Total	10.5				808
Hourly average					77

Table N.7: *Calculation of weighted average hourly heat production of a person in other rooms.*

Appendix O

Solar heat gains

This appendix contains a theoretical description of solar energy supply in a thermal zone along with a treatment of solar algorithms, which are utilised as boundary conditions for simplified models.

O.1 Solar position algorithm

Predicting the thermal indoor environment in buildings, and hereby the effect of solar energy arriving at a building surface, requires rather detailed calculations and detailed knowledge of the sun's behaviour, as the sun is responsible for this heat gain. The position of the sun is specified as in figure O.1 by a solar azimuth angle, γ_s, and solar altitude angle, α_s.

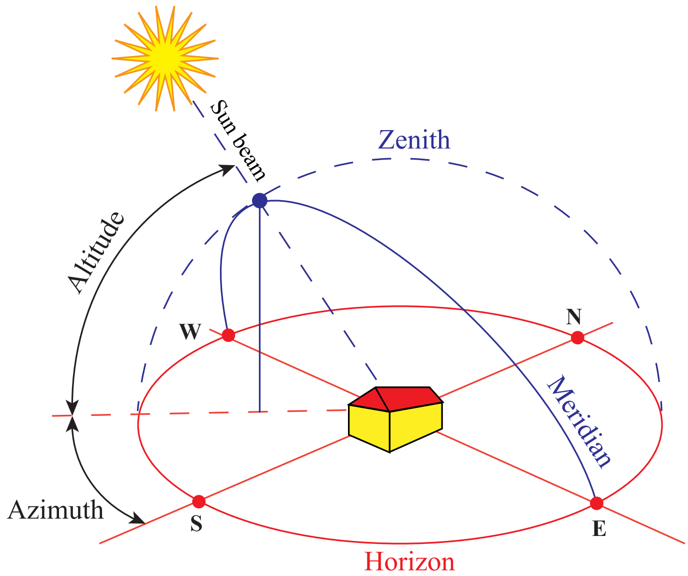


Figure O.1: *Definition of azimuth and altitude in terms of spherical astronomy. Redrawn from Heiselberg [2008a, p. 4].*

As a definition, altitude is the angle from the horizon to the vertical location of the sun, whereas azimuth is the angle from straight south to the horizontal location of the sun, with negative values towards east and positive values towards west, [Heiselberg 2008a, p. 26].

O.1.1 Solar altitude angle

Equation (O.1) is applied for calculation of the altitude of the sun. For the Danish Reference Year, DRY, the latitude and longitude are defined as 55.46 ° and 12.19 ° respectively, [SBi 2009].

$$\sin(\alpha_s) = \cos(\phi)\cos(\delta)\cos(\varpi) + \sin(\phi)\sin(\delta) \tag{O.1}$$

α_s	Solar altitude angle, [°]
ϕ	Latitude, [°]
δ	Earth declination angle, [°]
ϖ	Hour angle, [°]

The Earth declination angle, δ, is solely varying during the year, and specifies the angle between the equatorial plane and the vertical location of the sun when it is in zenith, [Heiselberg 2008a, p. 25]. The Earth declination angle can be calculated from equation (O.2).

$$\delta = 23.45 \sin\left(\frac{(284+N)\,360^\circ}{365}\right) \tag{O.2}$$

N	Day number of the year, [−]

Meanwhile, the hour angle, ϖ, is varying during the day as it is defined as the angle between the meridian plane of a specific location and the sun beam. The hour angle will be negative before 12 o'clock and positive afterwards. Hereby it needs to be calculated, as a function of solar time, τ_s, as the sun has an apparent speed of 15 ° per hour, cf. equation (O.3). Solar time can be calculated from local time based on the longitude and time meridian of the location, [Heiselberg 2008a, p. 25].

$$\varpi = 15(\tau_s - 12) \tag{O.3}$$

τ_s	Solar time for a specific location, [h]

O.1.2 Soalr azimuth angle

The solar azimuth angle can be calculated as a function of the solar pseudo azimuth angle, γ_s', by using equation (O.4).

$$\gamma_s = C_1 C_2 \gamma_s' + C_3\left(\frac{1 - C_1 C_2}{2}\right) \cdot 180^\circ \tag{O.4}$$

$$sin(\gamma_s') = \frac{sin(\varpi)cos(\delta)}{cos(\alpha_s)}$$

γ_s	Solar azimuth angle, [°]
γ_s'	Solar pseudo azimuth angle, [°]
C_1, C_2, C_3	Calculation constants, [−]

The constants, C_1 - C_3, are determined according to the following equations (O.5) - (O.7).

$$C_1 = \begin{cases} 1 & \text{for} \quad |\varpi| \leq \varpi_{ew} \\ -1 & \text{for} \quad |\varpi| > \varpi_{ew} \end{cases} \tag{O.5}$$

$$\cos(\varpi_{ew}) = \frac{\tan(\delta)}{\tan(\phi)}$$

$$C_2 = \begin{cases} 1 & \text{for} \quad (\phi - \delta) \geq 0 \\ -1 & \text{for} \quad (\phi - \delta) < 0 \end{cases} \tag{O.6}$$

$$C_3 = \begin{cases} 1 & \text{for} \quad \varpi \geq 0 \\ -1 & \text{for} \quad \varpi < 0 \end{cases} \tag{O.7}$$

O.2 Solar incidence

The solar radiation arriving at a building surface consists of direct, diffuse and reflected components as well, all of which are calculated by means of BSim and its Perez algorithm by applying DRY weather data.

$$I_{sol} = I_{dir} + I_{dif} + I_{ref} \tag{O.8}$$

I_{sol}	Total solar incidence, $[W/m^2]$
I_{dir}	Direct solar radiation, $[W/m^2]$
I_{dif}	Diffuse solar radiation, $[W/m^2]$
I_{ref}	Reflected solar radiation, $[W/m^2]$

The direct solar radiation is characterized by directly penetrating the atmosphere. In this way the intensity varies depending on the distance through the atmosphere and the sky conditions. The part of solar radiation which is scattered among dust particles, water drops in the Earth's atmosphere results in diffuse solar radiation, which arrives at a building surface even on a cloudless day, although its magnitude will not be significant compared to the direct solar radiation, [Heiselberg 2006, p. 2-3]. Finally, the building surfaces may also receive a considerable amounts of solar radiation reflected from surrounding surfaces and ground, which in calculations can be considered as diffuse solar radiation, [ASHRAE 2009, p. 30.41].

O.3 Solar heat gain elements

Predicting the thermal indoor environment in buildings requires further knowledge of window properties. Indeed, windows let daylight entering the building and provide visual contact with outdoors. But more important in this thesis, they transmit solar energy, which can affect the energy consumption or lead to overheating. In terms of the latter, a particular attention will be paid on the following characteristics of solar heat gains illustrated in figure O.2.

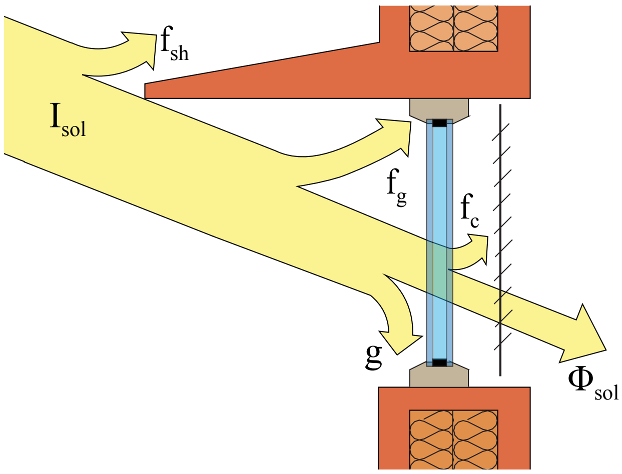


Figure O.2: *Characteristics of incident solar radiation through transparent construction and the related solar heat gain elements.*

The present appendix considers the solar heat gain algorithm described in EN ISO 13790 [2008] on hourly basis along with additional configurations incorporated in the monthly solar calculation in Be10, used in SBi simplified model, which is based on solar heat gain algorithm of EN ISO 13790 [2008]. The total solar heat gain transmitted into a room can be calculated as in equation (O.9) by summing up solar energy transmitted through each collecting element, [EN ISO 13790 2008, p. 54]. Notice that equation (O.9) appears as a simplified version as it neglects thermal radiation to the sky from the building elements.

$$\Phi_{sol} = \sum_{j=1}^{n} I_{sol} \cdot A_w \cdot g_{gl} \cdot f_g \cdot f_c \cdot f_{sh} \tag{O.9}$$

Φ_{sol}	Solar heat gains in a thermal zone, [W]
A_w	Area of a window element, $[m^2]$
g_{gl}	Solar energy transmittance of transparent part of collective element, [−]
f_g	Glazing area fraction, [-]
f_c	Shading factor, [-]
f_{sh}	Shading factor, [−]

Windows are composed of different components, namely glazing with accompanying coating and gas filling along with spacer and frame. The noticeable difference is that the spacer and frame are not transparent, whereby the energy is not significantly transmitted through these components, which will decrease the solar heat gains. Thus, a considered window with the area, A_w, will be multiplied with a glazing area fraction, f_g, in order to obtain the glazing area of which the incident solar radiation on the surface will penetrate.

O.3.1 Shadow factor

The shadow factor, f_{sh}, defines a reduction of the solar radiation arriving at a building surface by means of obstructions from other buildings, topography and other elements of the concerned building as well as external wall cavity, [By og Byg Anvisning 202 2002, p. 47]. This can be calculation by using equation (O.10).

$$f_{sh} = f_{hor} \cdot f_{ov} \cdot f_{fin} \cdot f_{wc} \tag{O.10}$$

f_{hor}	Partial shadow correction factor for the horizon, $[-]$
f_{ov}	Partial shadow correction factor for overhangs, $[-]$
f_{fin}	Partial shadow correction factor for side fins, $[-]$
f_{wc}	Partial shadow correction factor for wall cavity, $[-]$

The shadow angles are often determined at the center of the glazing element, cf. figure O.3, in order to reduce the amount of input data for computational calculation purposes, and thus neglects specification of window dimensions and distances between window edges and obstructions causing shadow. The partial shadow correction factor for side fins takes into account other vertical elements of the concerned building, which are causing shadows on the particular window as well. Hereby, a distinction is made of whether the shadows occur from right or left side construction, as it will have different influence on hourly basis and only one will occur at a time due to the solar position.

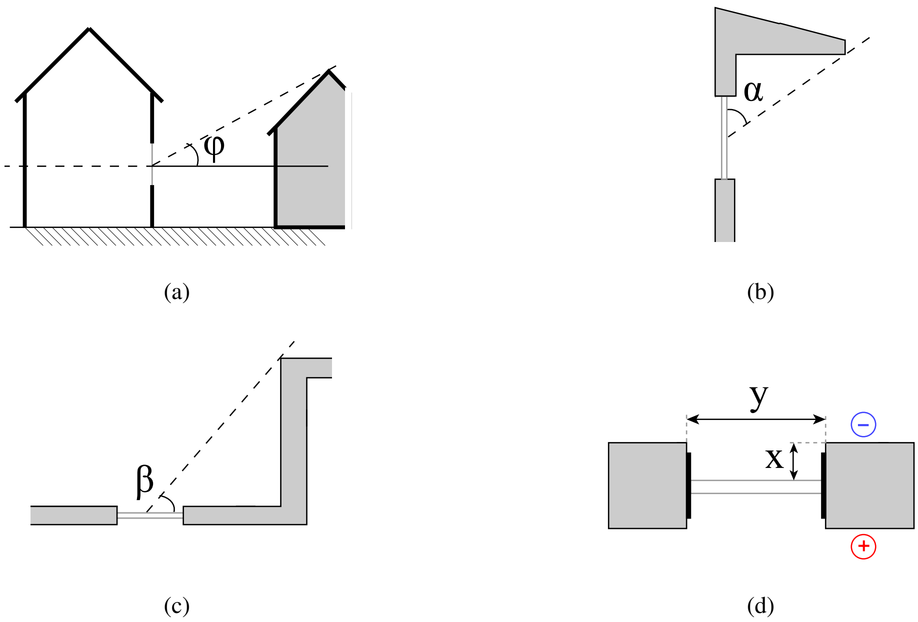
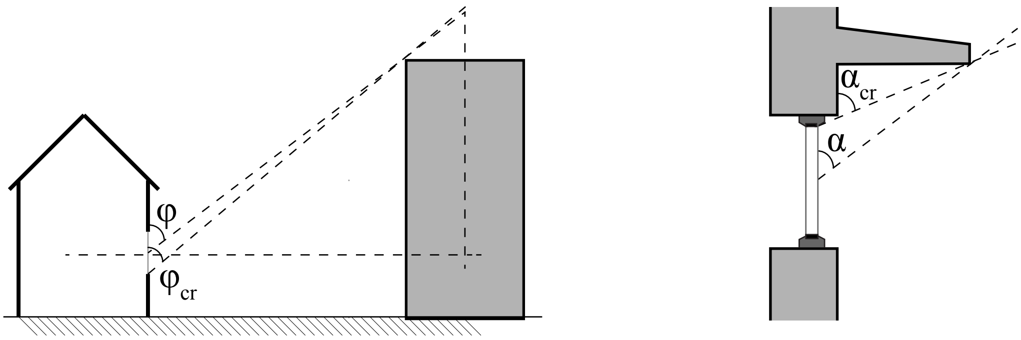


Figure O.3: *Determination of shadows occurring from horizon (a), overhangs (b) side constructions (c) and external wall cavity (d). Redrawn from SBi-anvisning 213 [2008, p. 46-47]. The latter is solely considered in SBi solar algorithm.*

This reduction of input data for computational purposes may increase uncertainty incalculation proecedure. For horizon shadows, it is assumed that no shadows occur on the window if the solar altitude angle exceeds the horizon shadow angle. As it is illustrated in figure O.4(a), this is incorrect for solar altitude angle just above the horizon shadow angle and incorrect solar heat gains will be obtained in these few particular hours.

A possible error occurs for shadows from overhangs as well, as the solar calculation algorithm assumes that the window remains partly shaded when the solar altitude is less than $(90° - \alpha_{cr})$. As illustrated in figure O.4(b), this is only applicable if the overhang is located at the window edges and the error increases along with the distance between the window edges and overhang. This objective is valid for shadows from external obstructions as well.



(a) (b)

Figure O.4: *Differences in the calculation of the shadow factors.*

These errors in determination of shadows occurring on the window have an insignificant magnitude on a yearly basis. Although, It should be noted that a rather considerable errors could be obtained for buildings with either tall windows facing adjacent buildings or large distances between window edges and external obstruction.

O.3.2 Solar energy transmittance

The solar energy transmittance, g_{gl}, is defined as a ratio of solar radiation that enters a thermal zone through the glazing and the incident solar radiation on the window outer surface. It includes both directly transmitted and absorbed and later reradiated portions. Even though the window optical properties are often quoted for solar incidence perpendicular to the glazing, the glass ability to transmit direct solar radiation depends on a varying solar incidence angle, β, which reduces the solar energy transmittance as a part of the sun beam is reflected, [Nielsen and Svendsen 2003, p. 5-6].

For hourly calculation of solar heat gains, the solar energy transmittance should be determined for each hour depending on sun position along with contribution of diffuse and ground-reflected radiation by taking into account angle dependence of solar incidence. However, for monthly calculation of solar heat gains, utilised in Be10 solar algorithm, a monthly utilisation factor is applied which is taking into account the correlation of monthly solar incidence on external and internal window surface for varying incidence angles.

Angular dependence for hourly calculation

EN ISO 13790 standard presents total solar energy transmittance calculation procedure for monthly method, i.e. time-average total solar energy transmittance, although without guidance regarding hourly calculation. Angle dependence for hourly method was investigated in Karlsson [2001] where different methods were showed. Method A, cf. figure O.5, represents the method with limited complexity, in which the properties of the entire glazing at normal incidence are multiplied with an approximate angular profile, which results in properties at all incidence angles, [Karlsson 2001, p.21].

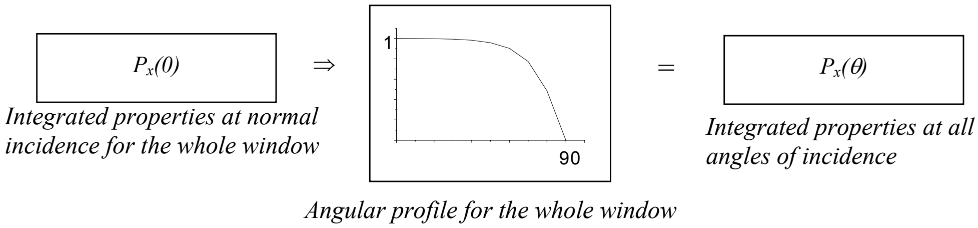


Figure O.5: *Method for obtaining incidence angle depending on thermal properties and construction of a particular window element. Redrawn from [Karlsson 2001, p. 22].*

A common angular function, corresponding to the above mentioned method is shown in equation (O.12), [Nielsen et al. 2000, p. 138], whereas calculation of total and diffuse solar energy transmittance is shown in equations (O.11) and (O.13).

$$g_{\mathrm{gl}} = \frac{I_{\mathrm{dir}} \cdot g_{\mathrm{dir}} + I_{\mathrm{dif}} \cdot g_{\mathrm{dif}}}{I_{\mathrm{sol}}} \tag{O.11}$$

$$g_{\mathrm{dir}} = g \cdot \left[1 - \tan^{p}\left(\frac{\beta}{2}\right)\right] \tag{O.12}$$

$$g_{\mathrm{dif}} = g \cdot f_{\mathrm{dif}} \tag{O.13}$$

g_{dir}	Solar energy transmittance for direct solar radiation, $[-]$
g_{dif}	Solar energy transmittance for diffuse solar radiation, $[-]$
g	Solar energy transmittance for perpendicular solar incidence, $[-]$
p	Angle-dependent factor depending on different types of coatings, $[-]$
β	Incidence angle, $[^\circ]$
f_{dif}	Correction factor for diffuse radiation, $[^\circ]$

Angle-dependent factor, p, is depending on the construction of particular glazing system, e.g. different coating, number of panes, etc and therefore is valid for one particular window. In order to simplify the calculation algorithm, only one angular-dependent function is considered valid for the reference window used in Denmark, [DTU 2006, p. 20]. It is a double pane window (4 mm float glass - 12 mm air - 4 mm float glass), which results in total solar energy transmittance of 0.776. A simulation of this window was performed in "WINDOW 6" tool, [LBNL 2011], in order to find the angle-dependent solar energy transmittance. Different angle-dependent factors are used in angular function, cf. equation (O.12), to fit obtained result from window 6, where p = 3.0 shows the best agreement with window 6 values, see figure O.6.

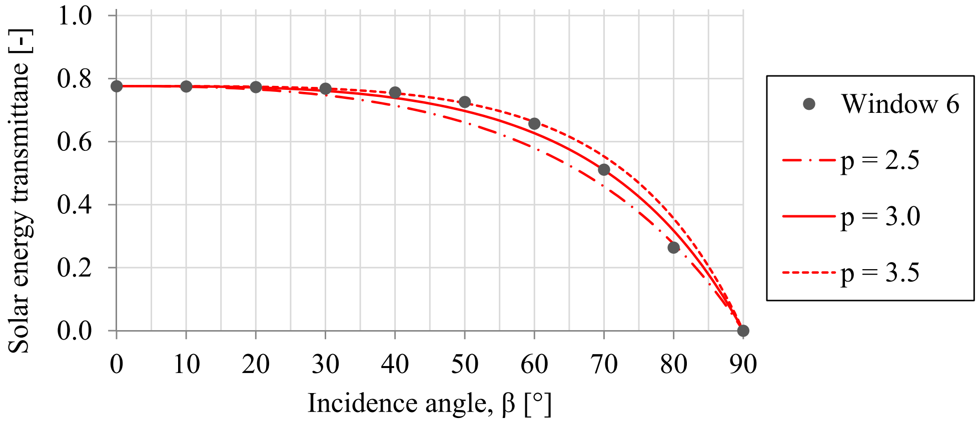


Figure O.6: *Angle-dependent solar energy transmittance simulated by window 6 and adjustment of the curve by means of angular function with different angle-dependent factors for the reference window in Denmark.*

Diffuse solar energy transmittance can be calculated as direct one corresponding to 60°, i.e. $g_{dif} = g_{dir}(60°)$, [DTU 2006, p. 17]. This is also implemented in BSim as a default value for diffuse solar energy transmittance. For the reference window with p = 3.0 correction factor for diffuse radiation, f_{dif} equals to 0.87, which is close to suggested 0.86 in Nielsen et al. [2000, p. 138].

It is noteworthy to mention, that since BSim has rather simple window description possibility it utilises an empirically obtained angular profile, [Larsen 2013], for all windows regardless number of panes and types of coatings, which, in turn, correspond to angular function, equation (O.12), with p = 2.6.

Angular dependence for monthly calculation

To implement this angle-dependent solar energy transmittance for the monthly solar calculations requires further data implemented from BSim. Thus, the correlation factor is given by a fixed value based on national values. As this thesis is considered dedicated to Danish applications, a correlation factor for non-scattering glazing = 0.86 is used, [Nielsen et al. 2003, p. 51].

The angle factor, f_w, describes the correlation for non-scattering glazing and takes into account the reduction of solar incidence transmitted to the room at different incidence angles, which and depends on the time of the year and orientation of windows. When the angle factor is applied for hourly calculations, Roos' algorithm is used for determination of this factor.

$$g_{gl} = g \cdot f_w \cdot \eta \qquad \text{(O.14)}$$
$$\eta = \frac{I_{net}}{I_{sol}} \cdot \frac{1}{g\, f_w}$$

f_w	Angel factor, $[-]$
η	Utilisation factor, $[-]$
I_{net}	Transmitted solar radiation through the glazing element, $[\mathrm{W}/\mathrm{m}^2]$

O.3.3 Shading factor

The shading factor, f_c, defines a reduction of solar heat gain by means of different shading devices. The latter are distinguished regarding the placement, e.g. internal, integrated and external, and regarding the types of shading devices, e.g. venetian blind, roller blind, curtain, shutter, etc. Besides the type of solar shading device, shading factor also depends on the type of glazing as the glass is thermally insulating (e.g. shading) the interior when direct sunlight occurs on the shading device, [By og Byg Anvisning 202 2002, p. 47]. The solar shading is often either manually or automatically controlled with regards to solar incidence or additionally operative temperature.

O.4 Hourly distribution of solar energy

This section is connected to results presented in subsection 5.3.2 and presents the hourly absolute deviation of solar incidence in SBi solar algorithm compared to BSim using Perez' solar algorithm throughout the representative week 23 for a window orientated towards each cardinal direction. Overestimation of SBi simplified solar algorithm is marked with blue colour and underestimation is marked with red colour.

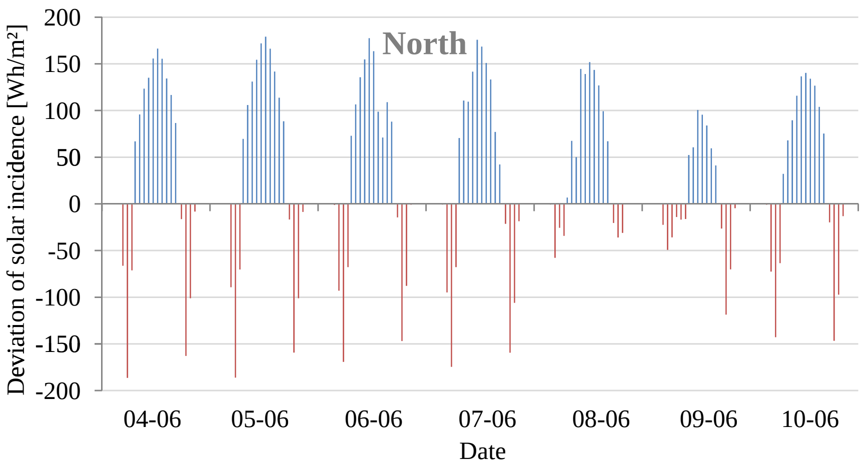


Figure O.7: *Hourly absolute deviation of solar incidences applied in SBi solar algorithm compared with BSim using Perez' solar algorithm on a north-facing window for week 23.*

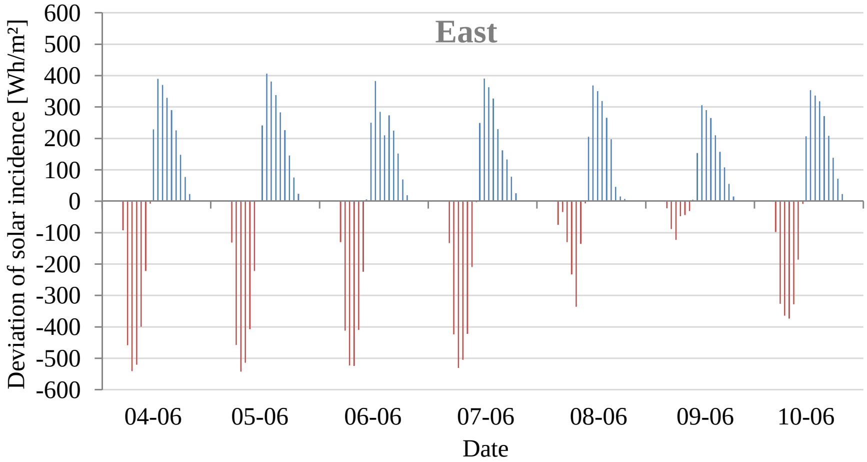


Figure O.8: *Hourly absolute deviation of solar incidences applied in SBi solar algorithm compared with BSim using Perez' solar algorithm on a east-facing window for week 23.*

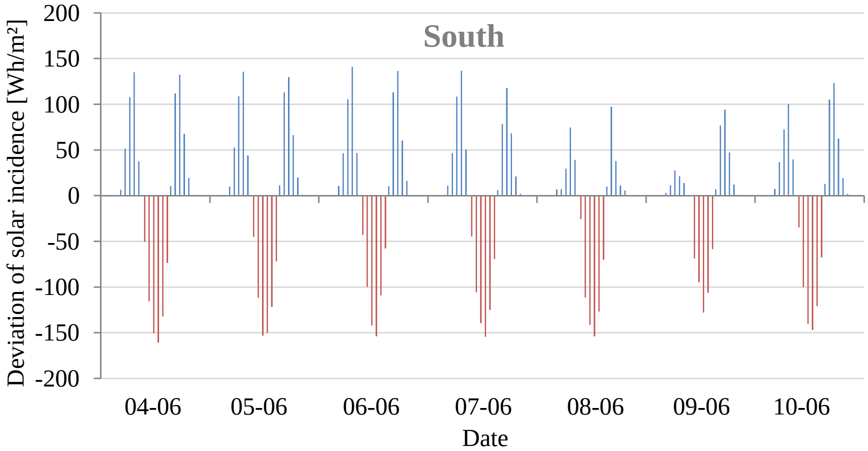


Figure O.9: *Hourly absolute deviation of solar incidences applied in SBi solar algorithm compared with BSim using Perez' solar algorithm on a south-facing window for week 23.*

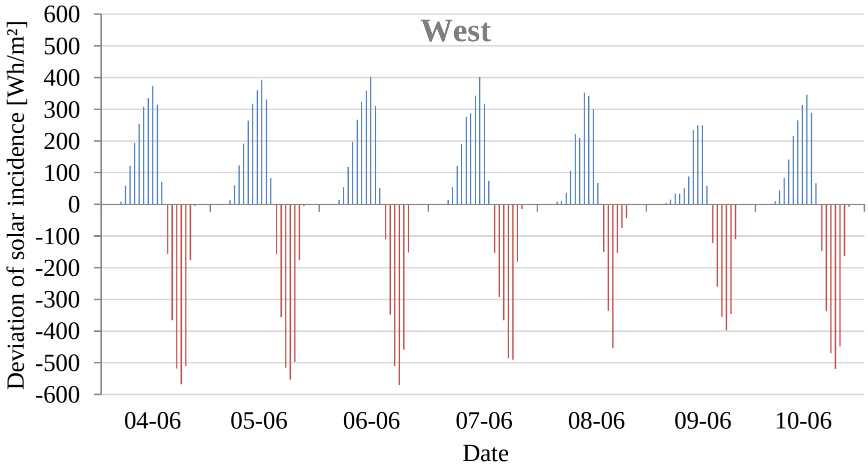


Figure O.10: *Hourly absolute deviation of solar incidences applied in SBi solar algorithm compared with BSim using Perez' solar algorithm on a west-facing window for week 23.*

Appendix **P**

Simplifications of models calculation procedure

intro rc schemes

P.1 Introduction

As was reviewed in section 4.2, simplified models occur in different level of complexity by means of resistance-capacitance schemes representing their physical structure. The differences regarding calculation procedure among review simplified models are listed in table P.1.

	EN ISO 13790	**Bo Adamson**	**SBi summer comfort**
Numerical methods	Crank-Nicolson	Euler (forward)	Euler (forward)
Number of unknown temperature nodes	3 temperature nodes: • Thermal mass • Internal surfaces • Room air	3 temperature nodes: • Thermal mass • Internal surfaces • Room air	2 temperature nodes: • Internal surfaces • Room air
Thermal loads distribution	3 temperature nodes: • Thermal mass • Internal surfaces • Room air	2 temperature nodes: • Internal surfaces • Room air	1 temperature nodes: • Room air
Specific heat transfer distribution	3 temperature nodes: • Thermal mass • Internal surfaces • Room air	2 temperature nodes: • Internal surfaces • Room air	1 temperature nodes: • Room air

Table P.1: *Differences regarding calculation procedure among review simplified models.*

Although, all reviewed simplified models are considered as simplified, EN ISO 13790 simplified model appears to be the most sophisticated comparing to others. Bo Adamson and especially SBi simplified model have more significant simplifications incorporated in their resistance-capacitance schemes with the purpose to narrow their complexity. The analysis will reveal the consequence of individual implementation of these simplifications to the EN ISO 13790 simplified model. Furthermore, as some simplifications have a coherence, combined influences of these are considered as well. For reader's convenience, it should be emphasized that only local trends based on separated simplifications of simplified models are investigated in the present section.

P.2 Numerical methods

As a preliminary distinction between the three simplified models, numerical methods were differently utilised for transient conduction calculation in order to solve the heat balance equations. Crank-Nicolson method is of 2nd-order of accuracy as it primarily calculates the thermal mass temperature based on the average value of the previous and present time step, while substituting room air and internal surfaces temperatures by their respective heat balance equations, cf. appendix F. Euler (forward) method is of 1st-order of accuracy and implies rather simplified transient conduction calculation compared to Crank-Nicolson method, as it solely utilises results of the previous and present time step without sequential calculations of remaining unknown temperatures in present time step.

To investigate the consequence of applying different numerical methods for transient conduction calculation and their impact on the prediction of thermal indoor environment, averaged daily profiles of temperatures in week 23, comprising a representative week in which the largest solar incidences occur, are illustrated in figure P.1(a).

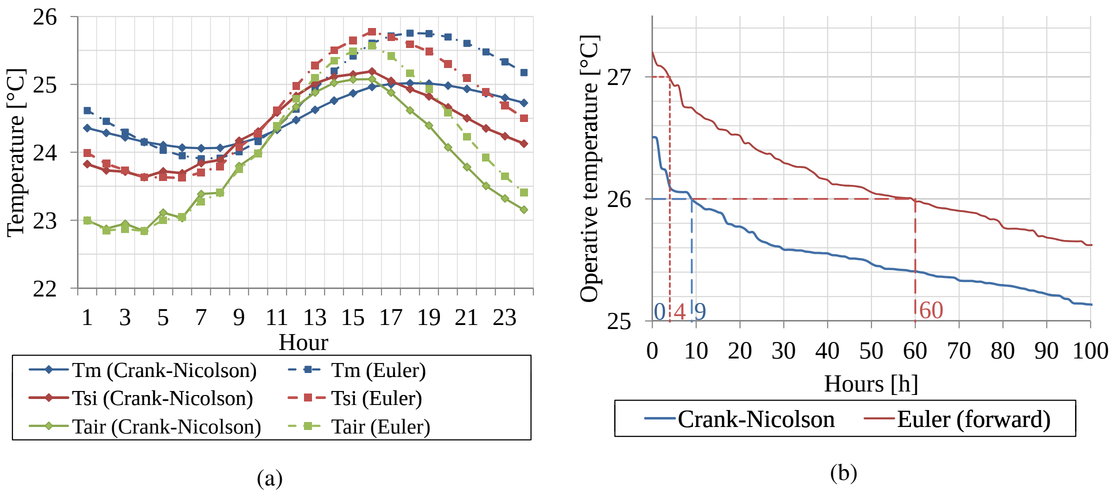


Figure P.1: *Averaged daily profiles of temperatures in week 23 for thermal mass, internal surfaces and room air (a) along with cumulative distribution of operative temperatures (b). The results are valid for the reference building (case 0) when performing calculations in EN ISO 13790 simplified model by utilising different application of numerical methods for transient conduction calculation.*

Usage of the 2nd-order Crank-Nicolson numerical method implies lower temperatures and leads to decreased daily fluctuations of the thermal mass temperature as it implies higher stability compared to a 1st-order Euler (forward) numerical method. These in overall higher thermal mass temperatures will influence the internal surfaces and room air temperature as the heat transfer between them will increase. Higher obtained temperatures by means of Euler (forward) method are reflected on the cumulative distribution of operative temperatures which is illustrated in figure P.1(b). The difference in predicted overheating in a thermal zone for different applied numerical methods is substantial as magnitude of deviations are experienced at 56 and 9 hours with excessive temperatures above 26°C and 27°C respectively.

P.3 Number of unknown temperature nodes

The specific transmission heat transfer between thermal mass and internal surfaces often is based on a rather low thermal resistance, as no insulating materials can be part of the accumulating layer, [EN ISO 13786 2007, p. 12]. Furthermore, since the SBi simplified model solely allocates its thermal loads and specific heat losses to the room air, it seems reasonable to simplify the model even more by considering only two unknown temperature nodes, namely internal surfaces and room air temperature node, as the thermal mass and internal surfaces temperature will be similar. However, to investigate the consequences of this simplification, the two resistance-capacitance schemes in figure P.2 are considered. These differ only in the number of considered unknown temperature nodes, and Bo Adamson simplified model, cf. figure P.2(a), is used as a basic model.

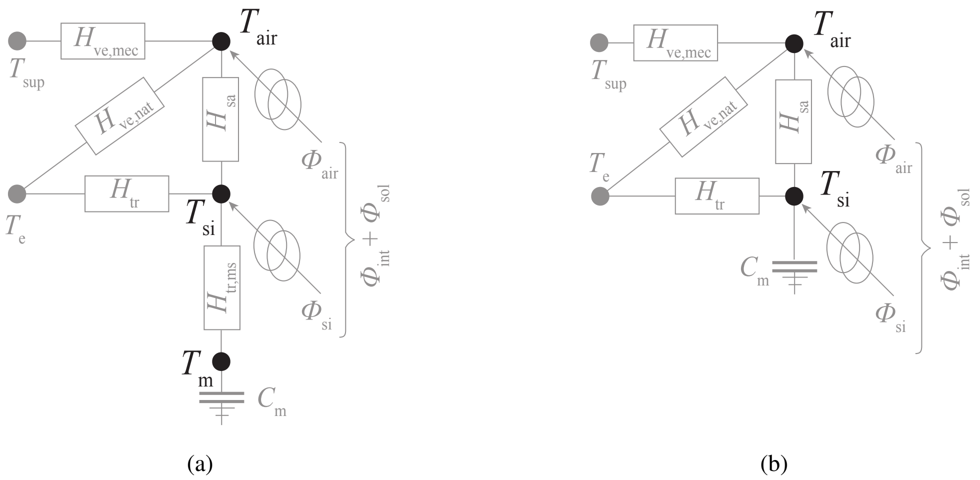


Figure P.2: *Analysis regarding number of unknown temperature nodes by having three (a) and two (b) unknown temperature nodes by utilising resistance-capacitance scheme of Bo Adamson simplified model.*

To define the magnitude of which this simplification is based on, the temperature difference between thermal mass and internal surfaces during the representative week 23 in June is illustrated in figure P.3(a). From here it is evident that a thermal accumulation is observed as the internal surfaces transfer heat to the thermal mass during daytime and opposite during night. Although, the magnitude of the temperature difference is limited, within a scale of ±0.6°C difference.

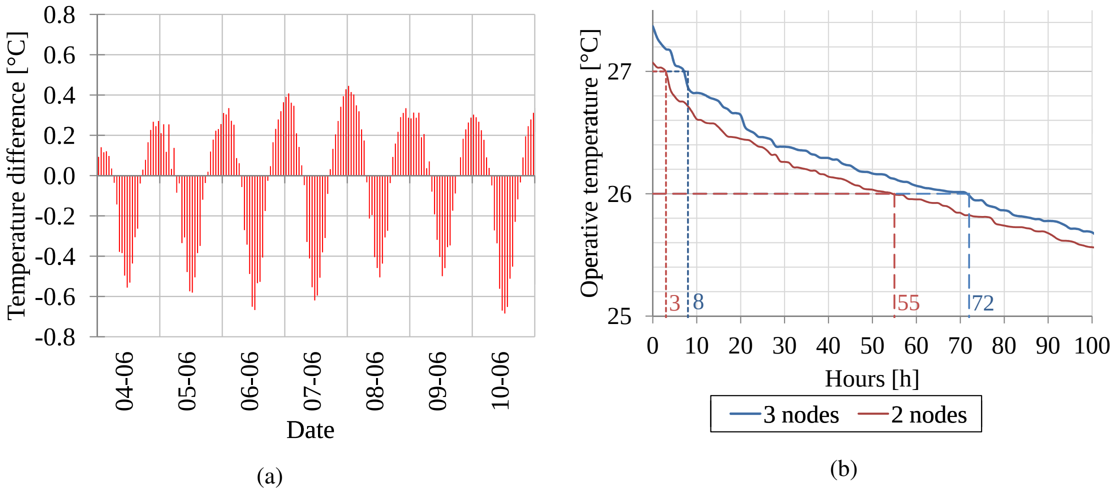


Figure P.3: *Temperature difference between thermal mass and internal surfaces in week 23 (a) along with cumulative distribution of operative temperatures (b). The results are valid for the reference building (case 0) when performing calculations in Bo Adamson simplified model by utilising different number of unknown temperature nodes.*

The rather low temperature difference between thermal mass and internal surfaces is reflected in the cumulative distribution of operative temperatures, which are illustrated in figure P.3(b). The simplifications of considering only two unknown temperature nodes slightly decreases the annual amount of excessive operative temperatures.

P.4 Thermal loads distribution among unknown temperature nodes

Thermal loads occurring from solar and internal heat supply are distributed differently among unknown temperature nodes within different simplified models. It is noteworthy to mention that this is only regarding radiative heat supply, as convective heat supply generated by occupants and appliances is for each simplified model allocated in the room air. The resistance-capacitance schemes applied for investigation regarding distribution of thermal loads are illustrated in figure P.4.

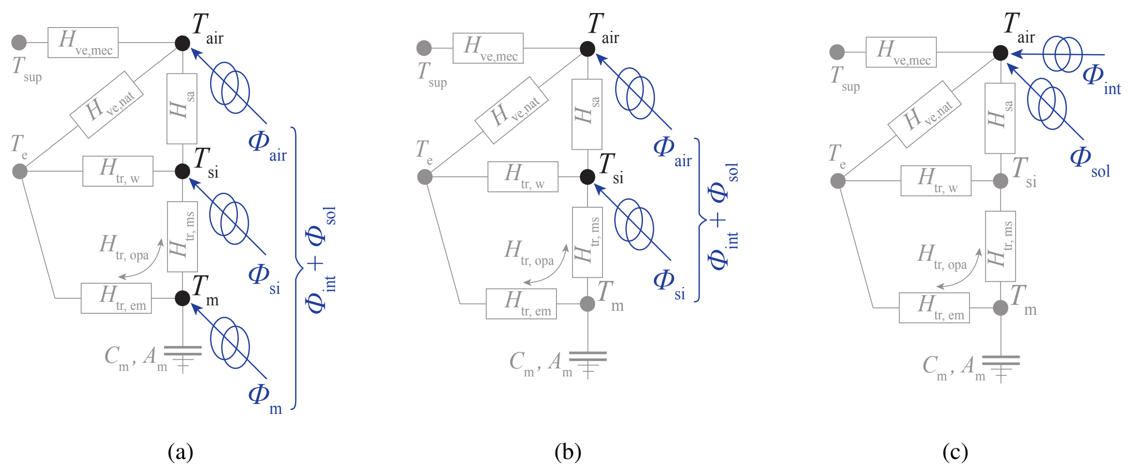
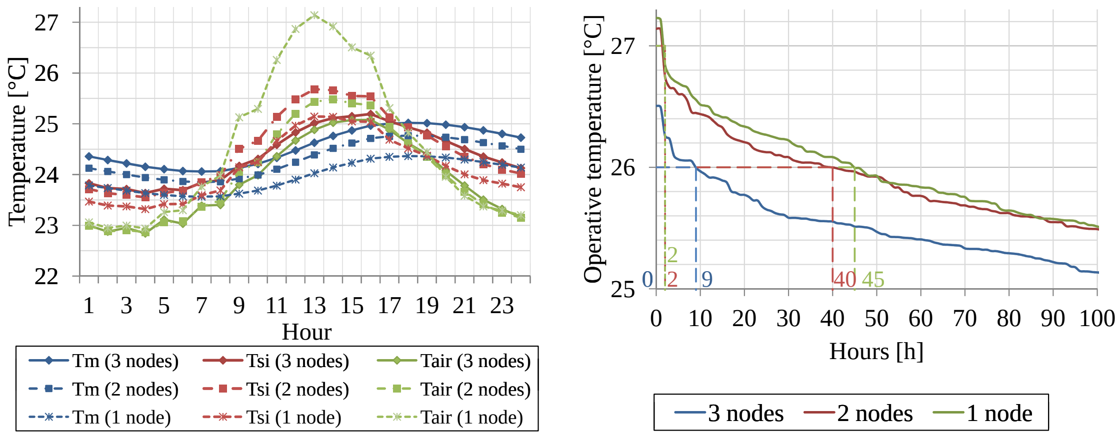


Figure P.4: *Analysis of thermal loads distribution among three (a), two (b) and one (c) unknown temperature node(s) by utilising scheme of EN ISO 13790 simplified model.*

For EN ISO 13790 simplified model illustrated in figure P.4(a) radiative heat is mainly affecting the thermal mass temperature. As doors and windows have a negligible thermal mass, only their internal surfaces is affected by the radiative heat flow and a thermal loss occurs as part of the thermal loads are transmitted through these almost non-accumulating elements to the external environment. By simplifying the distribution of thermal loads into being allocated to only two temperature nodes, namely room air and internal surfaces as illustrated in figure P.4(b), which is utilised in Bo Adamson simplified model, the thermal mass will not be directly affected by thermal loads, and the passive cooling of the room by thermal capacitance is account differently. As a consequence of this, the thermal mass temperature will decrease for sunny days, which is illustrated with blue lines in figure P.5(a). Furthermore, as an increased amount of radiative heat is dedicated to the internal surfaces, this temperature is further affected by solar energy and hence increases during daytime, cf. the red lines in figure P.5(a). Subsequently, the room air indicated by green lines in figure P.5(a) will likewise be increased during daytime as it interacts with the internal surfaces temperature.



(a) (b)

Figure P.5: *Averaged daily profiles of temperatures in week 23 for thermal mass, internal surfaces and room air (a) along with cumulative distribution of operative temperatures (b). The results are valid for the reference building (case 0) when performing calculations in EN ISO 13790 simplified model by utilising different thermal load distributions.*

As the quantity of excessive temperatures is determined according the operative temperature, the room air temperature and in particular the internal surfaces temperature are of highest importance. According to the cumulative distribution of operaitve temperatures stated in figure P.5(b), the simplification of distributing the thermal loads among two temperature nodes will increase the magnitude of excessive temperature, which corresponds to the above mentioned objectives. By further simplifying the distribution of thermal loads into solely affecting the room air as illustrated in figure P.4(c), which is utilised in SBi simplified model, the magnitude of excessive temperature further increases compared to the former mentioned distribution. First of all, as all the thermal loads are solely affecting the room air, this temperature will obtain a substantial increase during daytime and the highest magnitude in operative temperatures. However, as the heat absorbed by the room air is rather quickly removed by ventilation, larger daily fluctuations will appear during each day compared with the previous distribution of the thermal loads among two temperature nodes. These daily fluctuations will imply only a slightly increased amount of hours with operative temperature exceeding 26°C and 27°C for the entire year.

As a conclusion, the distribution of thermal loads among three temperature nodes applied in the EN ISO 13790 simplified model enables higher usage of the thermal building mass as this is directly implemented. In contrary, SBi simplified model assumes that all houses use solar shading, for which the solar heat gains are absorbed by and subsequently solely affects the room air temperature.

P.5 Specific heat transfer distribution among unknown temperature nodes

Another difference between the three simplified models, is their allocation of specific heat transfers caused by transmission and ventilation. Nevertheless, the specific ventilation heat loss is for all three simplified models affecting solely the room air temperature node. EN ISO 13790 simplified model divides the specific heat loss by transmission in two parts, as it distinguishes between building elements with a negligible thermal mass, e.g. doors, windows and other glazed elements of the building envelope, and opaque building elements. Furthermore, the specific transmission heat loss through opaque building elements is divided into two additional losses, one representing the heat transfer between thermal mass and external environment and another one representing the heat transfer between thermal mass and internal surface. The physical schemes applied for investigation regarding distribution of specific heat losses are illustrated in figure P.6.

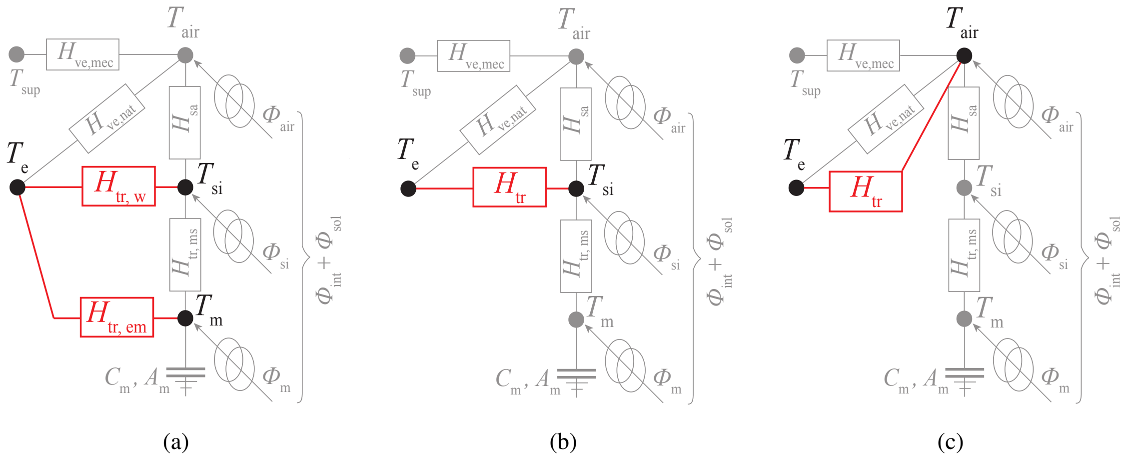
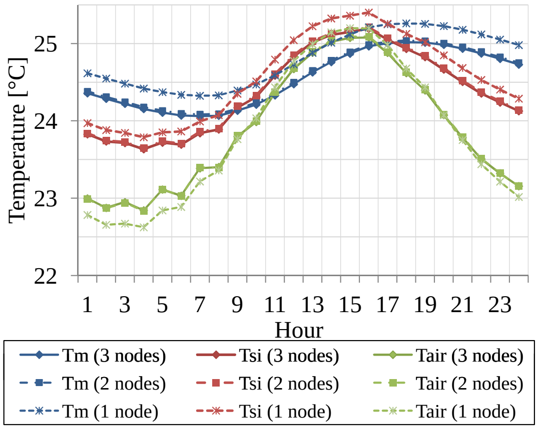
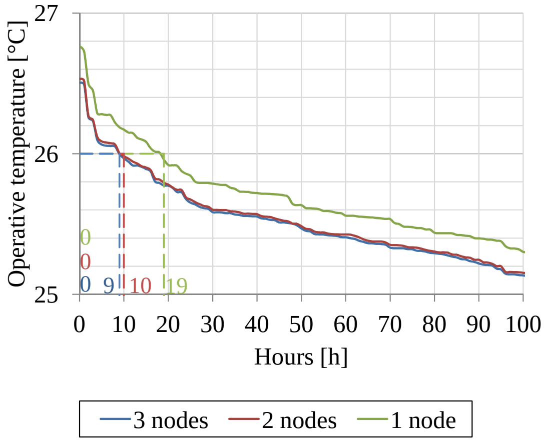


Figure P.6: *Analysis of specific heat transfers distribution among three (a), two (b) and one (c) unknown temperature node(s) by utilising scheme of EN ISO 13790 simplified model.*

The simplification illustrated in figure P.6(b) assumes that direct influence of thermal mass can be neglected. By utilising this simplification the thermal mass will only be indirectly affected by the specific transmission heat loss involving a slightly increased thermal mass temperature, notice the blue lines in figure P.7(a). As stated in figure P.7(b), this will slightly increase the magnitude of excessive operative temperatures.



(a)



(b)

Figure P.7: *Averaged daily profiles of temperatures in week 23 for thermal mass, internal surfaces and room air (a) along with cumulative distribution of operative temperatures (b). The results are valid for the reference building (case 0) when performing calculations in EN ISO 13790 simplified model by utilising different specific heat transfer distributions.*

By further simplification of the allocation of specific transmission heat loss by solely affecting the room air, the magnitude of excessive operative temperatures increases due to neither the internal surfaces is affected by specific heat losses and increase, notice the red lines in figure P.7(a). Thus, the specific transmission and ventilation heat transfer will have a similar behaviours as both of them rather instantly will have an influence on the room air temperature and hence also the operative temperature as the heat is rather quickly removed.

Again, the allocation of specific heat transfer among three temperature nodes applied in the EN ISO 13790 simplified model enables higher usage of the thermal building mass as this is directly implemented, unlike Bo Adamson and especially SBi simplified model which neglects the directly usage of the thermal building mass.

P.6 Combined effect of models simplifications

As the simplifications regarding distribution of thermal loads and specific heat transfers among a reduced number of unknown temperature nodes are often coherent, the combined effect of these two incorporated simplifications contributes with essential results. Basically, the specific heat transfers can be assumed to be allocated among only the unknown temperature nodes affected by thermal loads. Although, distinct results will occur as the building thermal capacity is included differently. This is reflected on the three resistance-capacitance schemes in figure P.8 applied for investigated regarding the combined effect, where each simplified model use Crank-Nicolson method and allocates the same temperature nodes for thermal loads and specific heat losses. The varying number of unknown temperature nodes is not included in the investigation concerning combined effect of models simplifications as its affect on the result was proved insignificant and can be neglected.

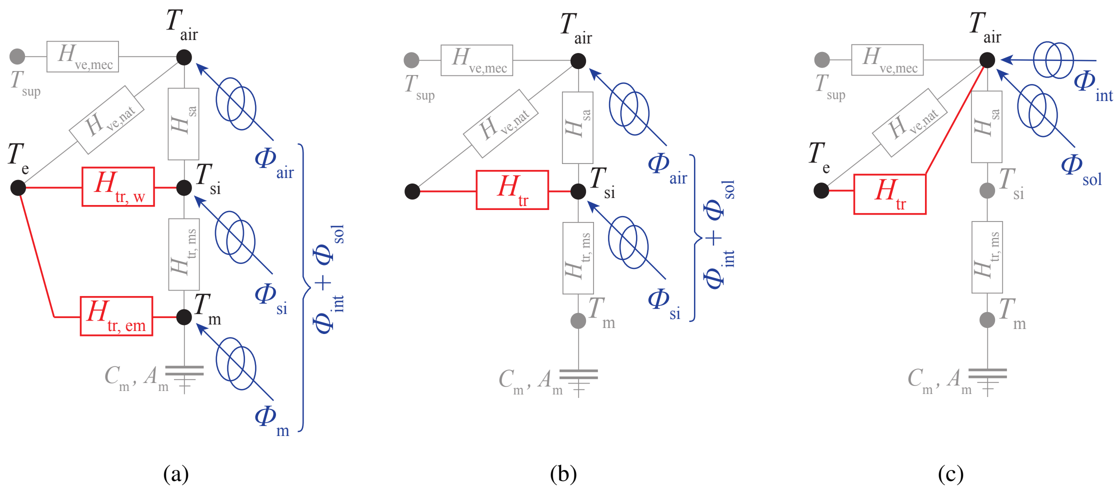


Figure P.8: *Analysis of combined allocation of thermal loads and specific heat transfer among three (a), two (b) and one (c) unknown temperature node(s) by utilising scheme of EN ISO 13790 simplified model.*

The results given as a cumulative distribution of operative temperatures specified in figure P.9(a) states a tendency with increased number of hours with excessive temperatures above 26°C and 27°C when allocating the thermal loads and specific heat losses to two and one temperature node(s).

In order to additionally analyse the combined effect of distribution of thermal loads and specific heat losses with Euler (forward) method applied for transient conduction calculation, similar calculations are illustrated in figure P.9(b) when applying Euler (forward) method.

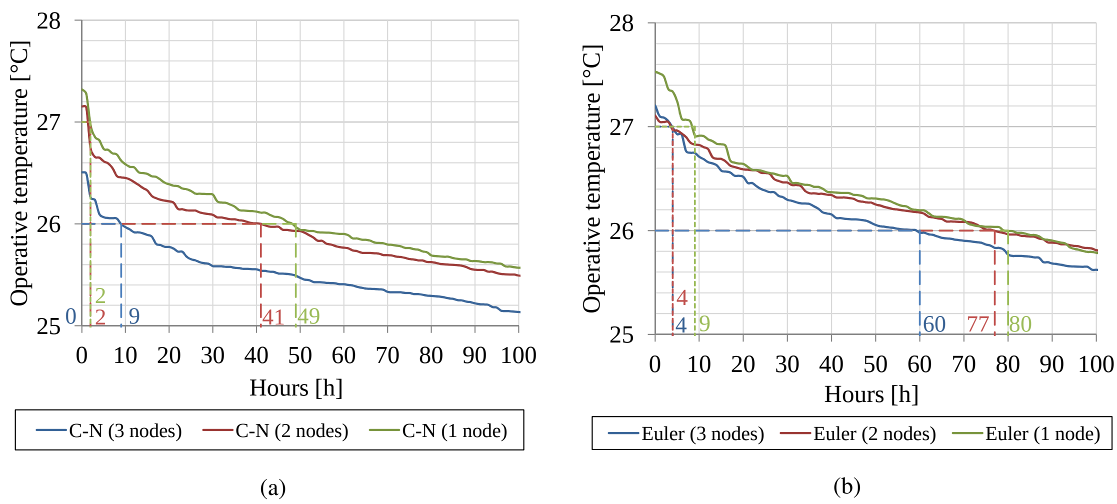


Figure P.9: *cumulative distribution of operative temperatures for different distributions of thermal loads and specific heat losses, more specifically among all three unknown temperature nodes (3 nodes), among internal surfaces and room air temperature nodes (2 nodes) and solely among room air temperature node (1 node). This results are valid for the reference building (case 0) when using Crank-Nicolson method (a) and Euler (forward) method (b) for transient conduction calculation.*

By simplifying into having an indirect influence of building thermal capacity, the thermal zone is rather instantly heated up, and consequently cooled down, resulting in higher operative temperatures, but in shorter time periods when only affecting the room air temperature. Furthermore, by allocating the thermal loads and specific heat losses to only room air temperature node the result are further scattered throughout the summer period.

Appendix **Q**

Description of BESTEST and set up of simplified models

This appendix supplement the description of BESTEST in section 6.2 in main report with additional information regarding input parameters and set up of simplified models and BSim used in BESTEST.

Q.1 Description of BESTEST

An evaluation of the model performance in BESTEST is realised by means of eight advanced programs used for the "reference" results.

Q.1.1 Reference program list

List of selected reference programs, which produced example results of BESTEST, is shown in table Q.1.

Program	**Implemented by**	**Availability**
BLAST 3.0	National Renewable Energy Laboratory (NREL), U.S.A. Politecnico Torino, Italy	Public domain
DOE 2.1D 14	National Renewable Energy Laboratory (NREL), U.S.A.	Public domain
ESP-RV8	De Montfort University, U.K	Research
SERIRES/ SUNCODE 5.7	National Renewable Energy Laboratory (NREL), U.S.A.	Public domain/ Commercial
SERIRES 1.2	Building Research Establishment, U.K.	Public domain
S3PAS	University of Sevilla, Spain	Research
TASE	Tampere University, Finland	Research
TRNSYS 13.1	Building Research Establishment, U.K. Vrije Universiteit Brussels (VUB), Belgium	Commercial

Table Q.1: *Programs used to generate the example results of BESTEST, [NOËL 2004, p.7]*

Q.1.2 Weather data

Description of the weather data and site used in BESTEST is shown in table Q.2. Weather type is cold clear winters and hot dry summers.

Latitude	39.8° north
Longitude	104.9° west
Altitude	1609 m
Time zone	7
Mean annual wind speed	4.02 m/s
Maximum annual wind speed	14.89 m/s
Ground reflectivity	0.2
Ground temperature	10 °C
Mean annual ambient dry-bulb temperature	9.71°C
Minimum annual ambient dry-bulb temperature	-24.39 °C
Maximum annual ambient dry-bulb temperature	35.00 °C
Heating degree days (base 18.3 °C)	3636.2 degree-days
Cooling degree days (base 18.3 °C)	487.1 degree-days
Annual total global horizontal solar radiation	1831.82 kWh/m^2-year
Annual total direct normal solar radiation	2353.58 kWh/m^2-year
Direct horizontal solar radiation	1339.48 kWh/m^2-year
Diffuse horizontal solar radiation	492.34 kWh/m^2-year

Table Q.2: *Site and weather properties used in BESTEST, [Judkoff and Neymark 1995, p.1-4]*

It was necessary to implement calculated by BSim hourly solar incidence radiation into the simplified models as they do not possess the algorithm of calculating direct and diffuse solar incidence radiation on surfaces. BSim calculated solar incidence radiation was compared with results of eight BESTEST reference simulation programs, see figure Q.1. BSim results for a clear day are following the BESTEST average result, cf. figures Q.1(c) and Q.1(d), while for cloudy day the results from BSim are slightly underestimated, especially for west orientation, where BSim result is outside the BESTEST range. Nevertheless, in general BSim result regarding calculated solar incidence radiation demonstrates acceptable precision and is therefore implemented in simplified models.

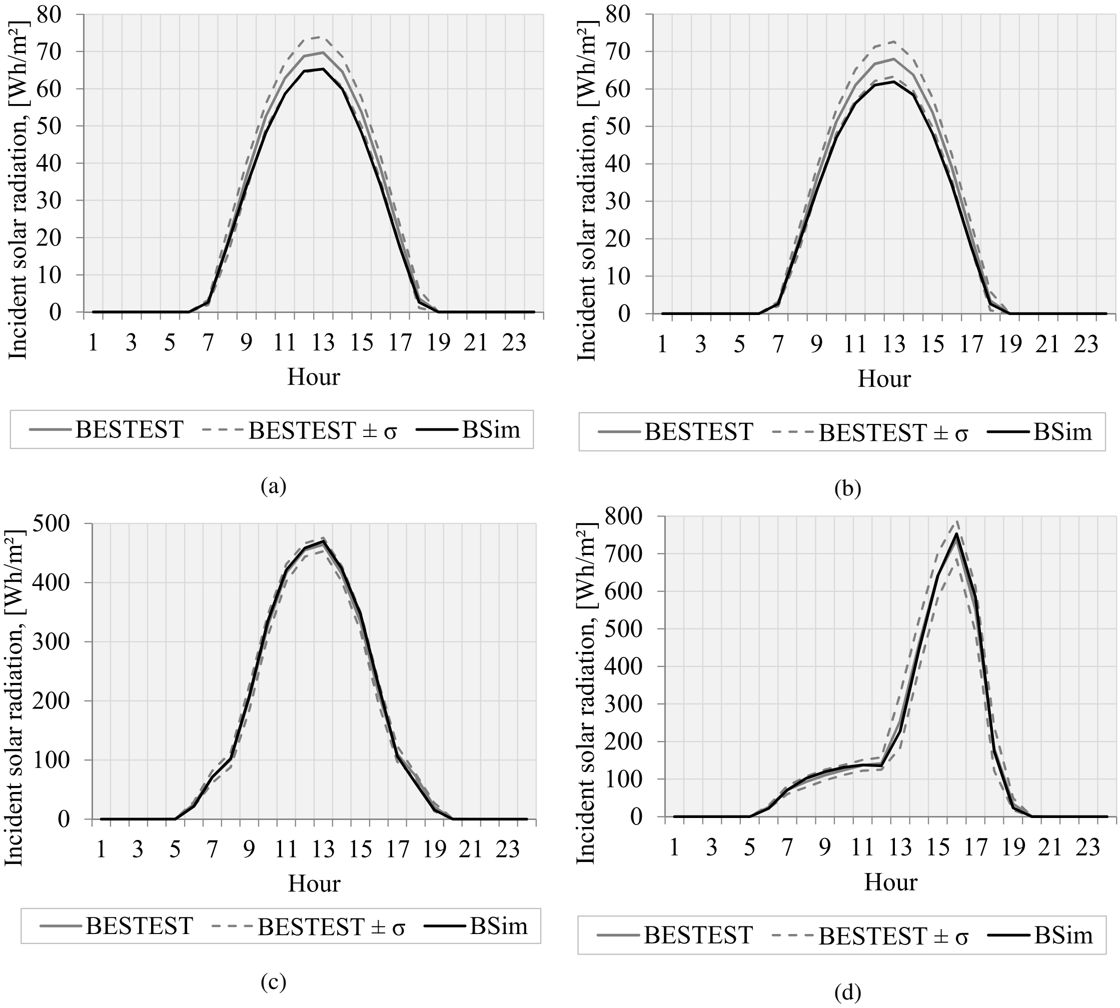


Figure Q.1: *Validation of BSim calculated solar incidence radiation for BESTEST weather data by means of BESTEST reference simulation programs for cloudy day March 5 for south (a) and west (b), clear day July 27 for south (c) and west (d). BESTEST result represents an average result from eight reference simulation programs.*

Q.2 Set up of simplified models and BSim according to test cases

Q.2.1 Building materials

Properties of building materials used in establishment of building construction elements in BESTEST are shown in table Q.3.

Materials	**Density** $\left[{}^{kg}/_{m^3}\right]$	**Specific heat capacity** $\left[{}^{J}/_{kg\cdot C}\right]$	**Conductivity** $\left[{}^{W}/_{m\cdot C}\right]$
Plasterboard	950	840	0.16
Fibreglas quilt	12	840	0.04
Wood Siding	530	900	0.14
Timber flooring	650	1200	0.14
Concrete block	1400	1000	0.51
Insulation	32	800	0.04
Foam insulation	10	1400	0.04
Concrete (slab)	1400	1000	1.13
Roofdeck	530	900	0.14

Table Q.3: *Building materials used in establishment of building construction elements in BESTEST, [NOËL 2004, p.10]*

Q.2.2 Building construction elements

In test cases 600FF and 650FF a lightweight building is used, whereas in cases 900FF and 950FF a heavyweight building is utilised with corresponding construction elements specified in table Q.4. Note that only surface-surface thermal transmittance and resistance are implemented in simplified models, since surface heat transfer coefficient are incorporated in their RC schemes.

Case	Construction element	Material	Thickness [mm]	Thermal transmittance $\left[{}^{W}/{}_{C\cdot m^2}\right]$ air-air	Thermal transmittance surf-surf	Thermal resistance $\left[{}^{C\cdot m^2}/{}_{W}\right]$ air-air	Thermal resistance surf-surf
Lightweight building	Wall	Plasterboard Fibreglas quilt Wood Siding	12 66 9	0.514	0.558	1.944	1.789
	Roof	Plasterboard Fibreglas quilt Roofdeck	10 111.8 19	0.318	0.334	3.147	2.993
	Floor	Timber flooring Insulation	25 1003	0.039	0.040	25.374	25.250
Heavyweight building	Wall	Concrete block Foam insulation Wood Siding	100 61.5 9	0.512	0.556	1.952	1.797
	Roof	The same as for lightweight building					
	Floor	Concrete (slab) Insulation	80 1007	0.039	0.040	25.366	25.246

Table Q.4: *Building construction elements utilised in BESTEST for lightweight and heavy-weight buildings, [NOËL 2004, p.10]*

Q.2.3 Windows

As windows comprise a large part of south facade it is important how precise a program can approximate their performance. Based on this there is a thorough description of window structure in Judkoff and Neymark [1995, table 1-7], which allows the programs to use their precise algorithms, however is unnecessary for simplified models. Thus only short summary is presented in this subsection. The window used in BESTEST is a double pane, i.e. 2mm-13mm-2mm with air between panes. Thermal transmittance is equal to 3.0 ${}^{W}/{}_{C\,m^2}$, solar energy transmittance at normal incidence is equal to 0.787. Angular dependence of solar energy transmittance is shown in table Q.5, where hemispherical solar energy transmittance is equal to 0.686. For free-float cases no shading devices nor shadow are specified.

Angle of incidence	0	10	20	30	40	50	60	70	80	90
Transmittance	0.787	0.786	0.785	0.78	0.767	0.737	0.666	0.518	0.266	0

Table Q.5: *Angular dependence of solar energy transmittance of double pane window used in BESTEST, [Judkoff and Neymark 1995, table 1-22]*

Q.2.4 Combined surface coefficients

This information is implemented only in BSim, since simplified models possess fully prescribed calculation procedure and surface coefficients. Detailed regarding the values of surface coefficients can be found in Judkoff and Neymark [1995, p. 1-5 and 1-6]. Note that interior and exterior infrared emissivity should be set to 0.9 and interior and exterior shortwave absorptivity should be set to 0.6 for free-floating cases

Q.2.5 Infiltration and internal load

An infiltration rate of 0.41 ACH should be used for free-floating cases. Internal load is set to 200 W, from which 60% are radiative part, 40% convective part and all 100% are sensible load.

Q.2.6 Mechanical systems

There is no either heating or cooling systems utilised in free-floating cases, however in test cases 650FF and 950FF venting should be used. The control for venting is:

- 18:00-7:00, fan venting ON;
- 7:00 - 18:00, fan venting OFF.

The capacity of venting system is 10.8 ACH.

Q.2.7 Test cases summary

Case	**Set-points** [-]	**Thermal mass** [-]	**Internal heat gains** [W]	**Infiltration** [ACH]	**Glass area** [m^2]	**Orientation** [°]	**Shading device** [m]
600FF	20, 27	L	200	0.5	12	180	no
650FF	27, V	L	200	0.5	12	180	no
900FF	20, 27	H	200	0.5	12	180	no
950FF	27, V	H	200	0.5	12	180	no

Table Q.6: *BESTEST, [Judkoff and Neymark 1995, p.1-4]*

Appendix **R**

Description of test buildings

The present appendix contains a description of the five test buildings along with the establishment of their BSim models, which are considered as statistical basis for the evaluation in chapter 7 of simplified models for compliance with Danish BR2015.

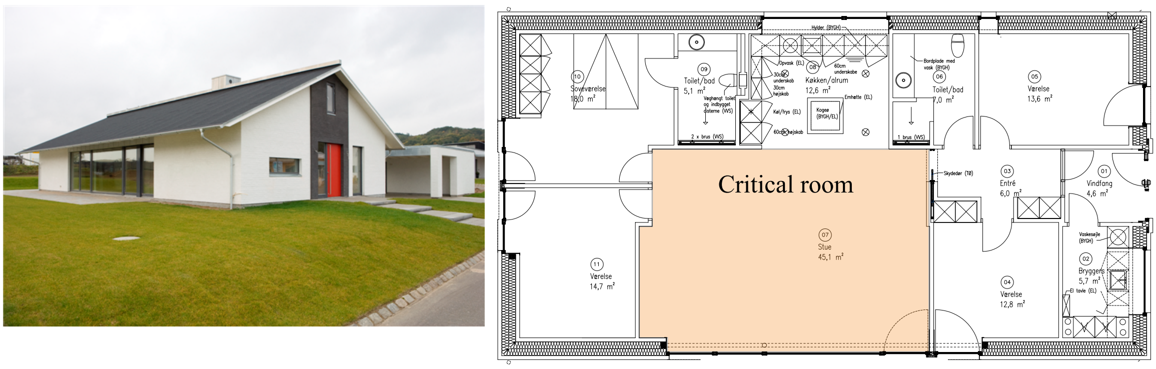
For each test buildings, a BSim model is establish for the critical in order to simulate the thermal indoor environment. The building geometry and materials appears from technical drawings. The indoor temperatures in the adjacent room are assumed equal to the one in the critical room, in order to omit usage of multizone calculation. As the BSim models are applicable for verification of the simplified models intended for compliance with Danish BR2015 requirements regarding thermal comfort, the following conditions are utilised:

- DRY weather data;
- Internal heat gains from occupants and equipment are determined as a constant load of 5 $^{W}/_{m^2}$ throughout the year;
- Infiltration rate is based on results of the performed blowerdoor test;
- Additional air supply by venting and ventilation rates, are based on specifications provided by houses technical reports.

The room air temperature, relative humidity and CO_2 concentration have been measured in the bathroom, kitchen, living room, bedroom and one nursery room at a height of 1.6 m.

R.1 Stenagervænget 12

The single-family house located on Stenagervænget 12 appears as a single-storey building with a heated floor area of 177 m^2. The architectural principles of the house is based on a concept able to fit into residential districts. Although, by using solely brick-walls the building differs from other low-energy building by being the world's first full-brick passive house, [KOMFORTHUSENE 2010]. The building thermal capacity of Stenagervænget 12 is according to Be10 model estimated to be $120\ ^{Wh}/_{^{\circ}C\ m^2}$ of heat floor area as the internal layers of the construction elements consist of brick-walls, wood on the ceiling and floor of wood on concrete. The airtightness of the building has been measured by a blowerdoor test to be 0.59 h^{-1} at a pressure of 50 Pa. [Larsen et al. 2012a, p. 68]



(a) (b)

Figure R.1: *Pictures of Stenagervænget 12 containing facades facing south-east and north-east (a) and plan view indicating the critical room (b), [KOMFORTHUSENE 2010].*

For Stenagervænget 12 the living room is assumed to be the critical room of the building regarding risk of overheating as it contains large windows toward south. The measuring results correspond to this assumption as the highest number of hours with operative temperature exceeding 26°C and 27°C arises in the living room, more specifically 703 hours above 26°C and 93 hours above 27 °C are experienced in the year 2011, [Larsen et al. 2012a, p. 40]

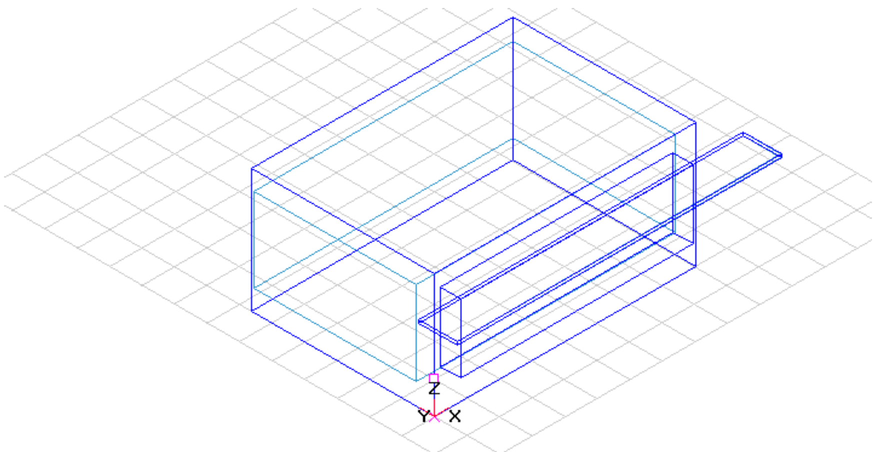


Figure R.2: *Illustration of the BSim model for the critical room in Stenagervænget 12 based on geometry specified in technical drawings.*

This living room has a heated floor area of 45.1 m^2 and a room height of 2.59 m and contains large window area of 15.1 m^2 towards south-east with a purpose to obtained a visual contact to the external conditions as well as comfortable amount of daylight indoor and considered solar energy supply. The window is solely protected from overheating by having the roof which appears as an "overhang", cf. figure R.1(a). The BSim model for Stenagervænget 12 is established as illustrated in figure R.2. A description of the applied systems and their control appear in table R.1.

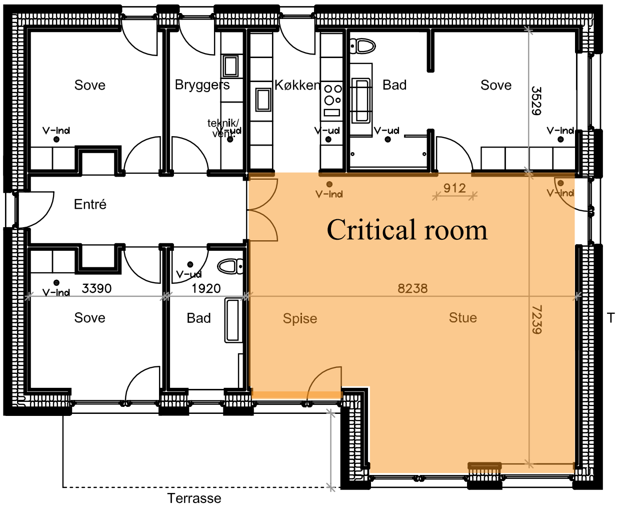
Stenagervænget 12							
Heated floor area: 45.129 m^2				**Schedule**			
System	**Description**			**Control**			**Time**
People load	**Peopleload_S12**			**FullLoad**			**Always**
	Number of people	1	-	100% 1-24			
	Heat gen.	0.068	kW				
	Moist gen.	0.41	kg/h				
	CO2 gen.	11.5	l/h				
Equipment	**Equipment_S12**			**FullLoad**			**Always**
	Heat load	0.158	kW	100% 1-24			
	Part to air	0.5	-				
Infiltration	**Infiltration_S12**			**FullLoad**			**Always**
	Basic airchange	0.09	/h	100% 1-24			
	TmpFactor	0	/h/K				
	TmpPower	0	-				
	WindFactor	0	s/m/h				
Venting	**Venting_S12**			**VentingCtrl**			**Always**
	Basic airchange	1.64	/h	SetPoint	23	°C	
	TmpFactor	-	-	SetP CO2	0	ppm	
	TmpPower	-	-	Factor	1	-	
	WindFactor	-	-				
	Max AirChange	1.64	/h				
	Max Wind	0	m/s				
Ventilation	**Ventilation_S12**			**ZoneTempCtrl**			**Always**
	<u>Input</u>			Part of norm. flow	1	-	
	Supply	0.04	m^3/s	Min Inlet Temp	14	°C	
	Pressure rise	0	Pa	Max Inlet Temp	50	°C	
	Total eff	0.75	-	Heating SetPnt	20	°C	
	Part of air	1	-	Cooling SetPnt	23	°C	
	<u>Output</u>			Air hum.	0	kg/kg	
	Supply	0.04	m^3/s				
	Pressure rise	0	Pa				
	Total eff	0.75	-				
	Part of air	1	-				
	<u>Heating coil</u>						
	Max Power	20	kW				
Heating	**Heating**			**HeatingCtrl**			**HeatingSeason**
	MaxPower	7.5	kW	Factor	1	-	October - May
	Fixed Part	0.05	-	Set Point	20	°C	
	Part To Air	1.0	-	DesignTemp	-12	°C	
				MinPow	0	kW	
				Te min	20	°C	

Table R.1: *Systems implemented in BSim for Stenagervænget 12.*

R.2 Stenagervænget 28

The single-family house located on Stenagervænget 28 appears also as a single-storey building with a heated floor area of 163 m^2. The architectural principles of the house is based on a concept able to fit into any residential district by having a "nordic architecture", [KOMFORTHUSENE 2010]. The building thermal capacity of Stenagervænget 28 is according to Be10 model estimated to be 120 $^{Wh}/_{°C\,m^2}$ of heat floor area as the internal layers of the construction elements consist of light-weight concrete-walls, wood on the ceiling and floor of concrete. The airtightness of the building has been measured by a blowerdoor test to be 0.50 h^{-1} at a pressure of 50 Pa. [Larsen et al. 2012b, p. 64]

(a)



(b)

Figure R.3: *Pictures of Stenagervænget 28 containing facade facing south-east (a) and plan view indicating the critical room (b), [KOMFORTHUSENE 2010].*

For Stenagervænget 28 the living room is assumed to be the critical room of the building regarding risk of overheating as it contains large windows toward south. The measuring results correspond to this assumption as the highest number of hours with operative temperature exceeding 26°C and 27°C arises in the living room, more specifically 1770 hours above 26°C and 381 hours above 27 °C are experienced in the year 2011, [Larsen et al. 2012b, p. 37]

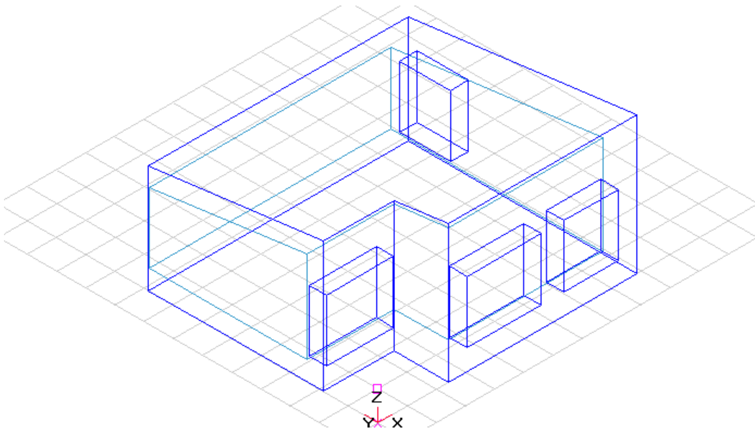


Figure R.4: *Illustration of the BSim model for the critical room in Stenagervænget 28 based on geometry specified in technical drawings.*

This living room has a heated floor area of 65.2 m^2 and an average room height of 2.85 m and contains large window area of 17.8 m^2 towards mainly south-east with a purpose to obtained a visual contact to the external conditions as well as comfortable amount of daylight indoor and considered solar energy supply. The window is not protected from overheating by having neither shading devices nor obstructions causing shadow, cf. figure R.3(a). The BSim model for Stenagervænget 28 is established as illustrated in figure R.4. A description of the applied systems and their control appear in table R.2.

Stenagervænget 28								
Heated floor area: 65.210 m^2				**Schedule**				
System	**Description**			**Control**			**Time**	
People load	**Peopleload_S28**			**FullLoad**			**Always**	
	Number of people	1	-	100% 1-24				
	Heat gen.	0.098	kW					
	Moist gen.	0.059	kg/h					
	CO2 gen.	16.63	l/h					
Equipment	**Equipment_S28**			**FullLoad**			**Always**	
	Heat load	0.228	kW	100% 1-24				
	Part to air	0.5	-					
Infiltration	**Infiltration_S28**			**FullLoad**			**Always**	
	Basic airchange	0.11	/h	100% 1-24				
	TmpFactor	0	/h/K					
	TmpPower	0	-					
	WindFactor	0	s/m/h					
Venting	**Venting_S28**			**VentingCtrl**			**Always**	
	Basic airchange	1.26	/h	SetPoint	23	°C		
	TmpFactor	-	-	SetP CO2	0	ppm		
	TmpPower	-	-	Factor	1	-		
	WindFactor	-	-					
	Max AirChange	1.26	/h					
	Max Wind	0	m/s					
Ventilation	**Ventilation_S28**			**ZoneTempCtrl**			**Always**	
	Input			Part of norm. flow	1	-		
	Supply	0.04	m^3/s	Min Inlet Temp	14	°C		
	Pressure rise	0	Pa	Max Inlet Temp	50	°C		
	Total eff	0.80	-	Heating SetPnt	20	°C		
	Part of air	1	-	Cooling SetPnt	23	°C		
	Output			Air hum.	0	kg/kg		
	Supply	0.04	m^3/s					
	Pressure rise	0	Pa					
	Total eff	0.80	-					
	Part of air	1	-					
	Heating coil							
	Max Power	20	kW					
Heating	**Heating**			**HeatingCtrl**			**HeatingSeason**	
	MaxPower	7.5	kW	Factor	1	-	October - May	
	Fixed Part	0.05	-	Set Point	20	°C		
	Part To Air	1.0	-	DesignTemp	-12	°C		
				MinPow	0	kW		
				Te min	20	°C		

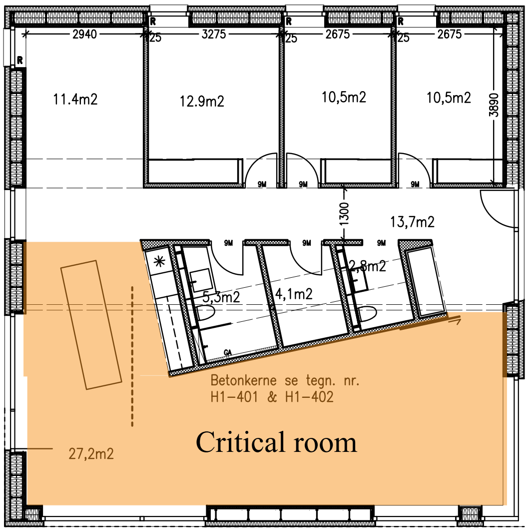
Table R.2: *Systems implemented in BSim for Stenagervænget 28.*

R.3 Stenagervænget 37

The single-family house located on Stenagervænget 37 appears also as a single-storey building with a heated floor area of 169 m^2. The architectural principles of the house is based on a concept able to fit into any residential district by having a "Simple and humanistic design", [KOMFORTHUSENE

2010]. The building thermal capacity of Stenagervænget 37 is according to Be10 model estimated to be 100 $^{Wh}/_{^{\circ}C\,m^2}$ of heat floor area as the internal layers of the construction elements consist of plasterboard-walls, wood on the ceiling and floor of concrete. The airtightness of the building has been measured by a blowerdoor test to be 0.4 h^{-1} at pressure of 50 Pa. [Larsen et al. 2012c, p. 66]

(a)



(b)

Figure R.5: *Pictures of Stenagervænget 37 containing facade facing south and east (a) and plan view indicating the critical room (b), [KOMFORTHUSENE 2010].*

For Stenagervænget 37 the kitchen/living room is assumed to be the critical room of the building regarding risk of overheating as it contains large windows toward south. The measuring results correspond to this assumption as the highest number of hours with operative temperature exceeding 26°C and 27°C arises in the kitchen/living room, more specifically 2355 hours above 26°C and 1533 hours above 27 °C are experienced in the year 2010, [Larsen et al. 2012c, p. 39]

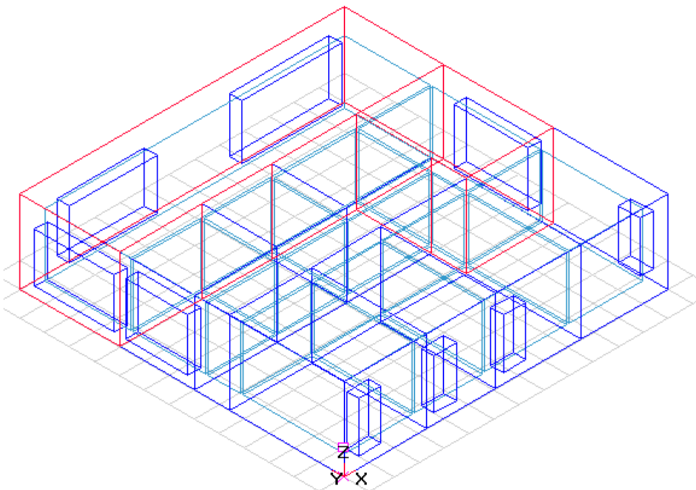


Figure R.6: *Illustration of the BSim model for Stenagervænget 37. Red lines indicate location of critical room.*

This kitchen/living room has a heated floor area of 67.4 m^2 and a room height of 2.50 m and contains large window area of 28.8 m^2 towards mainly south, but also east and west, with a purpose to obtained a visual contact to the external conditions as well as comfortable amount of daylight indoor and considered solar energy supply. The window is not protected from overheating by having an overhang, cf. figure R.5(a). The BSim model for Stenagervænget 37 is established as illustrated in figure R.6. A description of the applied systems and their control appear in table R.3.

Stenagervænget 37							
Heated floor area: 67.400 m^2				**Schedule**			
System	**Description**			**Control**			**Time**
People load	**Peopleload_S37**			**FullLoad**			**Always**
	Number of people	1	-	100% 1-24			
	Heat gen.	0.101	kW				
	Moist gen.	0.060	kg/h				
	CO2 gen.	17.19	l/h				
Equipment	**Equipment_S37**			**FullLoad**			**Always**
	Heat load	0.236	kW	100% 1-24			
	Part to air	0.5	-				
Infiltration	**Infiltration_S37**			**FullLoad**			**Always**
	Basic airchange	0.08	/h	100% 1-24			
	TmpFactor	0	/h/K				
	TmpPower	0	-				
	WindFactor	0	s/m/h				
Venting	**Venting_S37**			**VentingCtrl**			**Always**
	Basic airchange	1.61	/h	SetPoint	23	°C	
	TmpFactor	-	-	SetP CO2	0	ppm	
	TmpPower	-	-	Factor	1	-	
	WindFactor	-	-				
	Max AirChange	1.61	/h				
	Max Wind	0	m/s				
Ventilation	**Ventilation_S37**			**ZoneTempCtrl**			**Always**
	Input			Part of norm. flow	1	-	
	Supply	0.04	m^3/s	Min Inlet Temp	14	°C	
	Pressure rise	0	Pa	Max Inlet Temp	50	°C	
	Total eff	0.75	-	Heating SetPnt	20	°C	
	Part of air	1	-	Cooling SetPnt	23	°C	
	Output			Air hum.	0	kg/kg	
	Supply	0.04	m^3/s				
	Pressure rise	0	Pa				
	Total eff	0.75	-				
	Part of air	1	-				
	Heating coil						
	Max Power	20	kW				
Heating	**Heating**			**HeatingCtrl**			**HeatingSeason**
	MaxPower	7.5	kW	Factor	1	-	October - May
	Fixed Part	0.05	-	Set Point	20	°C	
	Part To Air	1.0	-	DesignTemp	-12	°C	
				MinPow	0	kW	
				Te min	20	°C	

Table R.3: *Systems implemented in BSim for Stenagervænget 37.*

R.4 Stenagervænget 39

The single-family house located on Stenagervænget 39 appears also as a single-storey building with a heated floor area of 179.3 m^2. The architectural principles of the house is based on a relaxing concept, [KOMFORTHUSENE 2010]. The building thermal capacity of Stenagervænget 39 is according to Be10 model estimated to be 80 $^{Wh}/_{°C\,m^2}$ of heat floor area as the internal layers of the construction elements consist of wood-walls, wood on the ceiling and floor of wood on concrete. The airtightness of the building has been measured by a blowerdoor test to be 0.40 h^{-1} at a pressure of 50 Pa. [Larsen et al. 2012d, p. 61]

(a)

Figure R.7: *Pictures of Stenagervænget 39 containing facade facing south (a) and plan view indicating the critical room (b), [KOMFORTHUSENE 2010].*

For Stenagervænget 39 the kitchen/living room is assumed to be the critical room of the building regarding risk of overheating as it contains large windows toward south. The measuring results correspond to this assumption as the highest number of hours with operative temperature exceeding 26°C and 27°C arises in the kitchen/living room, more specifically 100 hours above 26°C and 28 hours above 27 °C are experienced in the year 2011, [Larsen et al. 2012d, p. 37]

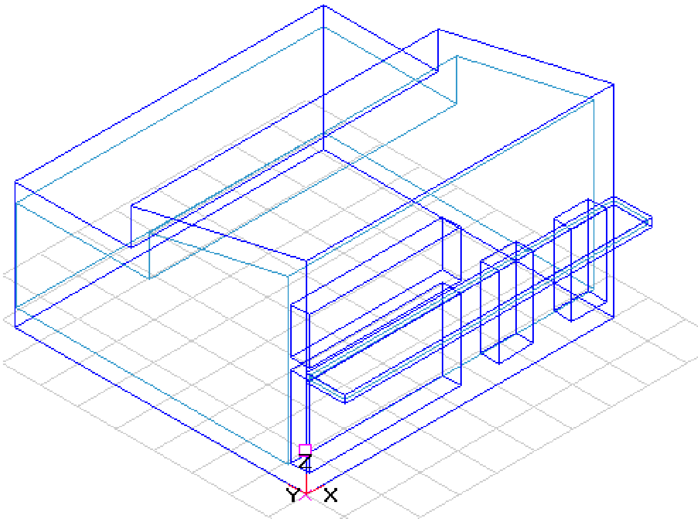


Figure R.8: *Illustration of the BSim model for the critical room in Stenagervænget 39 based on geometry specified in technical drawings.*

This kitchen/living room has a heated floor area of 62.0 m^2 and an average room height of 3.15 m and contains large window area of 17.2 m^2 towards south, with a purpose to obtained a visual contact to the external conditions as well as comfortable amount of daylight indoor and considered solar energy supply. The window is not protected from overheating by having an overhang, cf. figure R.7(a). The BSim model for Stenagervænget 39 is established as illustrated in figure R.8. A description of the applied systems and their control appear in table R.4.

Stenagervænget 39							
Heated floor area: 62.020 m^2				**Schedule**			
System	**Description**			**Control**			**Time**
People load	**Peopleload_S39**			**FullLoad**			**Always**
	Number of people	1	-	100% 1-24			
	Heat gen.	0.093	kW				
	Moist gen.	0.056	kg/h				
	CO2 gen.	15.82	l/h				
Equipment	**Equipment_S39**			**FullLoad**			**Always**
	Heat load	0.217	kW	100% 1-24			
	Part to air	0.5	-				
Infiltration	**Infiltration_S37**			**FullLoad**			**Always**
	Basic airchange	0.09	/h	100% 1-24			
	TmpFactor	0	/h/K				
	TmpPower	0	-				
	WindFactor	0	s/m/h				
Venting	**Venting_S39**			**VentingCtrl**			**Always**
	Basic airchange	1.02	/h	SetPoint	23	°C	
	TmpFactor	-	-	SetP CO2	0	ppm	
	TmpPower	-	-	Factor	1	-	
	WindFactor	-	-				
	Max AirChange	1.02	/h				
	Max Wind	0	m/s				
Ventilation	**Ventilation_S39**			**ZoneTempCtrl**			**Always**
	Input			Part of norm. flow	1	-	
	Supply	0.04	m^3/s	Min Inlet Temp	14	°C	
	Pressure rise	0	Pa	Max Inlet Temp	50	°C	
	Total eff	0.75	-	Heating SetPnt	20	°C	
	Part of air	1	-	Cooling SetPnt	23	°C	
	Output			Air hum.	0	kg/kg	
	Supply	0.04	m^3/s				
	Pressure rise	0	Pa				
	Total eff	0.75	-				
	Part of air	1	-				
	Heating coil						
	Max Power	20	kW				
Heating	**Heating**			**HeatingCtrl**			**HeatingSeason**
	MaxPower	7.5	kW	Factor	1	-	October - May
	Fixed Part	0.05	-	Set Point	20	°C	
	Part To Air	1.0	-	DesignTemp	-12	°C	
				MinPow	0	kW	
				Te min	20	°C	

Table R.4: *Systems implemented in BSim for Stenagervænget 39.*

R.5 Eurodan huse

The lowenergy built with a heated floor area of 196 m^2 by Eurodan Huse A/S appears as an optimised solution of a typical house which comply with the Danish Building Regulations 2015, [Jørgen Rose 2011, p. 32].

The building thermal capacity is according to Be10 model estimated to be 80 $^{\text{Wh}}/_{^{\circ}\text{C m}^2}$ of heat floor area as the internal layers of the construction elements consist of brick-walls, wood on the ceiling and floor of tiles on concrete. The airtightness of the building has been measured by a blowerdoor test to be 0.40 h^{-1} at a pressure of 50 Pa. [Jørgen Rose 2011, p. 23]

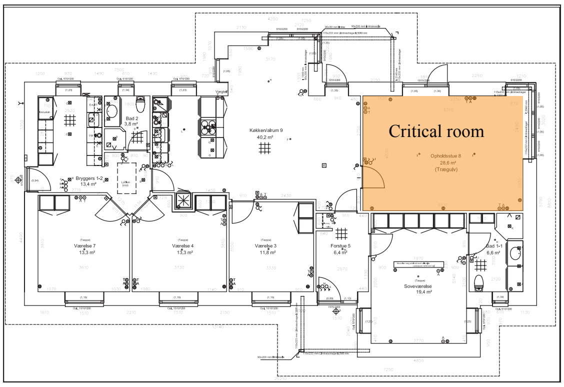


Figure R.9: *Pictures of Eurodan huse containing facade facing south and east (a) and plan view indicating the critical room (b), [Jørgen Rose 2011].*

For Eurodan huse the living room is assumed to be the critical room of the building regarding risk of overheating as it contains windows toward south. The BSim model for Eurodan huse is established as illustrated in figure R.10. A description of the applied systems and their control appear in table R.5.

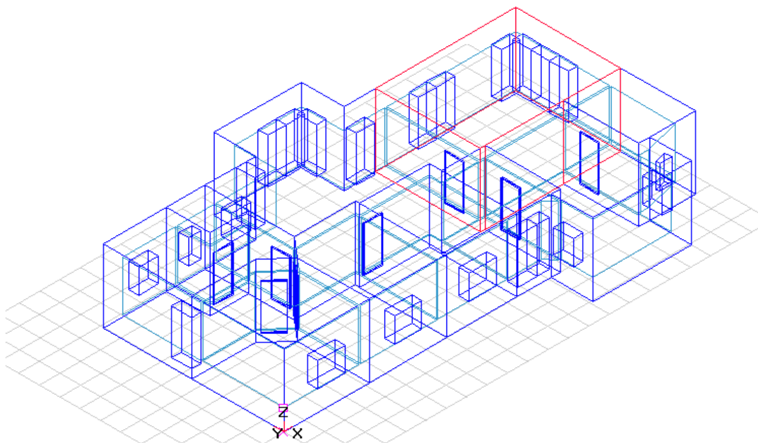


Figure R.10: *Illustration of the BSim model for Eurodan huse. Red lines indicate location of critical room.*

This living room has a heated floor area of 35.2 m^2 and a room height of 2.47 m and contains large window area of 12.0 m^2 towards south and west. The window is not protected from overheating by having an only left side fins comprising the part of the remaining building, cf. figure **??**.

Eurodan huse							
Heated floor area: 35.208 m^2				**Schedule**			
System	**Description**			**Control**			**Time**
People load	**Peopleload_living**			**FullLoad**			**Always**
	Number of people	1	-	100% 1-24			
	Heat gen.	0.053	kW				
	Moist gen.	0.032	kg/h				
	CO2 gen.	8.98	l/h				
Equipment	**Equipment_living**			**FullLoad**			**Always**
	Heat load	0.123	kW	100% 1-24			
	Part to air	0.5	-				
Infiltration	**Infiltration_living**			**FullLoad**			**Always**
	Basic airchange	0.03	/h	100% 1-24			
	TmpFactor	0	/h/K				
	TmpPower	0	-				
	WindFactor	0	s/m/h				
Venting	**Venting_S37**			**VentingCtrl**			**Always**
	Basic airchange	8.00	/h	SetPoint	23	°C	
	TmpFactor	-	-	SetP CO2	0	ppm	
	TmpPower	-	-	Factor	1	-	
	WindFactor	-	-				
	Max AirChange	8.00	/h				
	Max Wind	0	m/s				
Heating	**Heating**			**HeatingCtrl**			**HeatingSeason**
	MaxPower	7.5	kW	Factor	1	-	October - May
	Fixed Part	0.05	-	Set Point	20	°C	
	Part To Air	0.6	-	DesignTemp	-12	°C	
				MinPow	0	kW	
				Te min	20	°C	

Table R.5: *Systems implemented in BSim for Eurodan huse.*

Appendix **S**

Uncertainty analysis

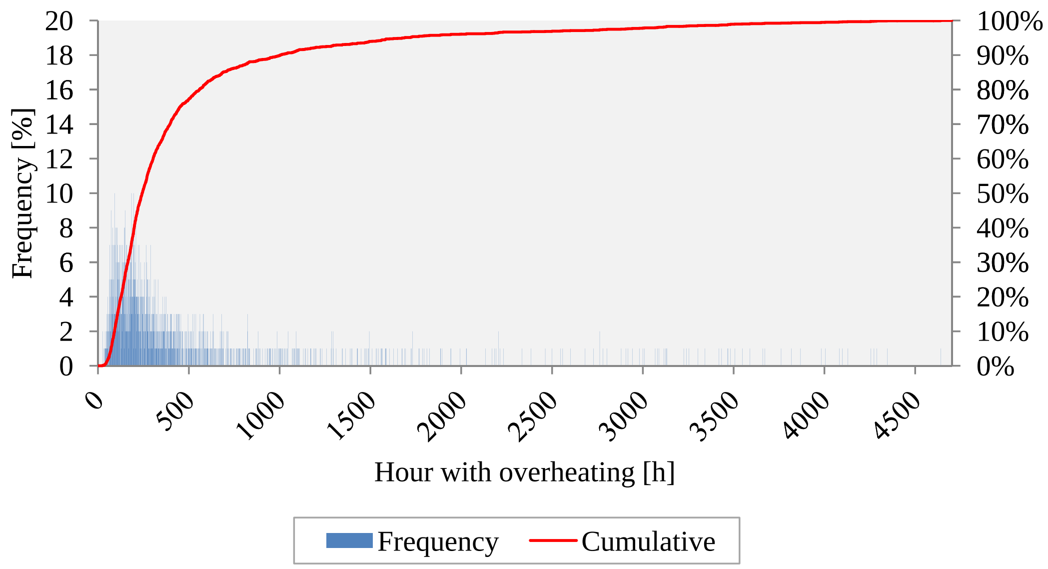
This chapter describes the uncertainty analysis performed for the comfort house Stenagervænget 28 with the purpose to estimate the probability of stochastic output compliance with Danish Building Regulations when deterministic output is compliant. The description of uncertainty analysis incorporates description of input parameters distribution and results.

The dwelling used for the analysis represents a comfort house and is described in appendix R.2. Prior to the uncertainty analysis, an improvement of the thermal indoor environment was carried out by usage passive initiatives, i.e. implementation of integrated solar shading devices comprises a shading factor of 0.4 and increased natural ventilation rates of 2.0 $^{l}/_{s\,m^2}$ of heated floor area, which along with mechanical ventilation rates comprises an air exchange of 2.61 $^{l}/_{s\,m^2}$ of heated floor area if necessary. The purpose of this optimisation was to improve the thermal performance in the building to such an extent that it fulfills the building regulation requirements regarding risk of overheating. The modified stochastic input by means of probability distributions of the ten most important parameters for SBi simplified model are listed in S.1.

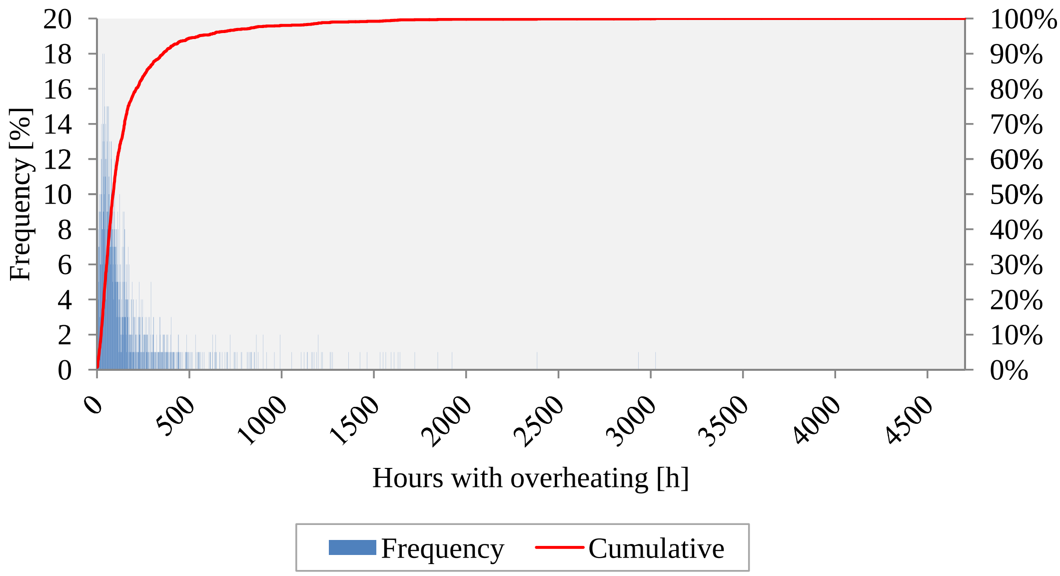
No.	**Factor**	**Unit**	**Type**	**Mean value** μ	**Standard deviation** σ	**Variation coefficient** δ	**Expected interval** *min max*
15	Thermal capacity	$[^{Wh}/_{^\circ C\,m^2}]$	U	-	-	-	80 - 120
21	Solar energy transmittance	$[-]$	N	0.60	0.015	2.5%	0.57 - 0.63
22	Shading factor	$[-]$	N	0.40	0.05	12.5%	0.30 - 0.50
23	Internal heat gains	$[^{W}/_{m^2}]$	N	4.88	1.49	30.5%	1.9 - 7.85
25	Ventilation set-point temperature	$[^\circ C]$	L	0.89*	0.45	-	22 - 27
26	Proportional band	$[^\circ C]$	U	-	-	-	0 - 2
27	Basic ventilation rate	$[^{l}/_{s\,m^2}]$	N	0.3	0.12	33.3%	0.07 - 0.53
28	Daytime ventilation rate	$[^{l}/_{s\,m^2}]$	N	2.61	1.04	39.6%	0.50 - 4.30
29	Evening ventilation rate	$[^{l}/_{s\,m^2}]$	N	2.61	1.04	39.6%	0.50 - 4.30
30	Night ventilation rate	$[^{l}/_{s\,m^2}]$	N	2.61	1.04	39.6%	0.50 - 4.30

Table S.1: *Probability distributions of occupants related input parameters. Following distribution types are used: N - normal, L - log-normal, U - uniform. *Displaced with respect to X axis by 21.01°C.*

The entire output expressed as frequency and cumulative distribution of hours with operative temperatures exceeding 26°C and 27°C are illustrated in figure S.1. From the figures, it is evident that the probability of exceeding both the expected and required number of hour with excessive operative temperatures are quick high.



(a)



(b)

Figure S.1: *Result of uncertainty analysis regarding hours with overheating valid for Stenagervænget 28 with improved thermal indoor environment. The results are expressed as frequency and cumulative distribution of hours with operative temperatures exceeding 26°C(a) and 27°C(b)*

Bibliography

Aggerholm, 2013. S. Aggerholm. *Personal communication*, 2013.

ASHRAE, 2009. ASHRAE. *Handbook - Fundamentals*. ISBN: 978-1-933742-55-7, SI edition. 2009.

Atanasiu, 2011. B. Atanasiu. *Principles for nearly Zero-Energy Buildings*. Buildings Performance Institute Europe (BPIE), 2011.

Bergsøe, 1994. N. Bergsøe. *SBi-Report 236: Ventilation conditions in recent naturally ventilation, detached houses*, Statens Byggeforskningsinstitut, SBi, 1994.

Box, Hunter, and Hunter, 1978. G. E. P. Box, W. G. Hunter, and J. S. Hunter. *Statistics for Experimenters*. ISBN: 0-471-09315-7. John Wiley & Sons, Inc., 1978.

Brohus, 2012-2013. H. Brohus. *Personal communication*, 2012-2013.

Brohus, P. Heiselberg, and Sørensen, 2010. H. Brohus, A. Simonsen P. Heiselberg, and K.C. Sørensen. *Influence of Occupants' Behaviour on the Energy Consumption of Domestic Buildings*. 2010.

By og Byg Anvisning 202, 2002. By og Byg Anvisning 202. *Naturlig ventilation i erhvervsbygninger*. 1st edition. Karl Terpager Andersen, Per Heiselberg and Søren Aggerholm, 2002. ISBN: 87-563-1128-1.

Clarke, 2001. J. A. Clarke. *Energy simulation in building design*. ISBN: 0 7506 5082 6, 2st edition. 2001.

D. Wangsøe, 2004. D. Wangsøe. *Solenergibyggeri*, 2004.

Danish Energy Agency, 2010. Danish Energy Agency. *Danish building regulations 2010*, 2010. URL `http://www.ebst.dk/bygningsreglementet.dk`. Date of download: 2012.04.24.

Dansk Byggeri, 2007. Dansk Byggeri. *Hvor går grænsen?*, 2007. URL `http://www.tolerancer.dk/`. Date of download: 2013.03.21.

Danvak ApS, 1987. Danvak ApS. *Varme- og Klimateknik - Grundbog*. 1. udgave. P.J Schmidt Grafisk, Vojens, 1987.

Dijk and Spiekman, 2004. D.v. Dijk and M. Spiekman. *Energy Performance of Buildings. Outline for Harmonised EP Procedures. Final report*, 2004.

DS 418, 2011. DS 418. *Calculation of heat loss from buildings*, 2011.

DTU, **2006**. DTU. *Load calculations*, 2006. Lecture note for course 41721 Ventilation and Climatic Systems.

Ekstrom, **2005**. P.A. Ekstrom. *Eikos. A Simulation Toolbox for Sensitivity Analysis*, 2005.

EN 1279-1, **2006**. EN 1279-1. *Glass in building - Insulating glass units - Part 1: Generalities, dimensional tolerances and rules for the system description*, 2006.

EN 15251, **2007**. EN 15251. *Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics*, 2007.

EN ISO 13786, **2007**. EN ISO 13786. *Thermal performance of building components - Dynamic thermal characteristics - Calculation methods*, 2007.

EN ISO 13790, **2008**. EN ISO 13790. *Energy performance of buildings - Calculation of energy use for space heating and cooling*, 2008.

EN ISO 14863, **2005**. EN ISO 14863. *Thermal bridges in building construction - Linear thermal transmittance - simplified methods and default values*, 2005.

EN ISO 6946, **2007**. EN ISO 6946. *Building components and building elements - Thermal resistance and thermal transmittance - Calculation methods*, 2007.

Erhverv- og byggestyrelsen, **2011**. Erhverv- og byggestyrelsen. *Baggrundsnotat for bygningsklasse 2020*, 2011.

EU Energy Policy, **2012**. EU Energy Policy. *Energy Performance of Buildings Directive (EPBD)*, 2012. URL `http://www.inforse.org/europe/eu_build-di.htm`. Last check: 2012.10.21.

European Commision, **2005**. European Commision. *The new SME definition*. Enterprise and Industry Publications, 2005.

Gram-Hanssen, **2005**. K. Gram-Hanssen. *Husholdningers elforbrug - hvem bruger hvor meget, til hvad or hvorfor*, Statens Byggeforskningsinstitut, SBi, 2005.

M. Spiekman H. van Dijk and P. de Wilde, *2005*. M. Spiekman H. van Dijk and P. de Wilde. A monthly method for calculating energy performance in the context of European building regulations. Montreal, Canada, 2005. Ninth International IBPSA Conference.

Hamby, **1994**. D. M. Hamby. *A review of techniques for parameter sensitivity analysis of environmental models*. Environmental Monitoring and Assessment, 32, 135–154, 1994.

P. Heiselberg and H. Brohus. P. Heiselberg and H. Brohus. Sensitivity Analysis Applied in Design of Low Energy Office Building. AIVC.

Heiselberg, **2008a**. Per Heiselberg. *Microclimate of Buildings*. Integrated design of Buildings, 1. edition. Aalborg University, 2008.

Heiselberg, **2008b**. Per Heiselberg. *Passive and Natural Cooling*, 2008. Department of Civil Engineering, AAU, Denmark.

Heiselberg, 2006. Per Heiselberg. *Passive Solar Heating*. Integrated design of Buildings, 1. edition. Aalborg University, 2006.

Hyldgård, Funch, and Steen-Thøde, 2001. Carl Erik Hyldgård, E.J. Funch, and M. Steen-Thøde. *Grundlæggende Klimateknik og Bygningsfysik*. ISBN: 1395-8232-U9714, 3. oplag. Aalborg Universitet Institut for Byggeri og Anlæg, 2001.

IES, 2012. Ltd. IES. *IES VE - building performance simulation tool*, 2012.

Jensen, Nørgaard, Daniels, and Justesen, 2011. R.L. Jensen, J. Nørgaard, O. Daniels, and R.O. Justesen. *Person- og forbrugsprofiler. Bygningsintegreret energiforsyning*, Aalborg Universitet, 2011.

Jørgen Rose, 2011. Jørgen Rose. *Jørgen Rose Udvikling af typehuse i lavenergiklasse 1 - DTU Byg*, 2011.

Judkoff and Neymark, 1995. R. Judkoff and J. Neymark. *International Energy Agency Building Energy Simulation Test (BESTEST) and Diagnostic Method*, 1995.

J. Karlsson. Windows Optical Performance and Energy Efficiency. PhD thesis, 2001.

Keiding, Gunnarsen, Rosdahl, Machon, Møller, and Valbjørn, 2003. L. Keiding, L. Gunnarsen, N. Rosdahl, M. Machon, R. Møller, and O. Valbjørn. *Miljøfaktorer i danskernes hverdag med særlig fokus på boligmiljø. Resultater fra undersøgelse af danskernes sundhed og sygelighed i 2000*, Statens Institut for Folkesundhed, 2003.

Knudsen, 2010. H.N. Knudsen. *Presentation - Beboeres tilfredshed og oplevelser i lavenergiboliger*, 2010.

KOMFORTHUSENE, 2010. KOMFORTHUSENE. *De 10 KOMFORT HUSE i Skibet ved vejle*, 2010. URL `http://www.komforthusene.dk/de+10+huse`. Date of download: 2013.05.31.

Kristensen and Jensen, 2011. L. Kristensen and O. M. Jensen. *Erfaringsopfølgning på lavenergibyggeri klasse 1 og 2*, 2011.

J. Kurnitski, July 2012a. J. Kurnitski. Healthy buildings conference summary - indoor climate in low energy buildings. Brisbane, Australia, July 2012a. REHVA. URL `http://www.rehva.eu/en/622.extra-article-indoor-climate-in-low-energy-buildings-main-topic-in-healthy-buildings-conferenc` Date of download: 2012.10.05.

Kurnitski, 2012b. J. Kurnitski. *EPBD implementation in Finland*, 2012. URL `http://files.kotisivukone.com/finvac.kotisivukone.com/tiedostot/kurnitski.pdf`. Date of download: 2012.10.18.

Lamond, 2011. W. Lamond. *Investigation of Summer Overheating of the Passive House Design in the Scottish Climate*, University of Strathclyde Engineering, 2011.

Landing, 2011. T. Landing. *4D verdensmester i Energieffektivitet*, 2011.

Larsen, 2013. O. Kalyanova Larsen. *Personal communication*, 2013.

Larsen, **2011a**. T. S. Larsen. *Overheating and insufficient heating problems in low energy houses up to now call for improvements in future*, 2011a.

Larsen, **2011b**. T. S. Larsen. *Vurdering af indeklimaet i hidtidigt lavenergibyggeri*. DCE Contract Report No. 100. Aalborg University, 2011.

Larsen, Jensen, and Daniels, **2012a**. T. S. Larsen, R. L. Jensen, and O. Daniels. *Målinger og analyse af indeklima og energiforbrug i komforthusene - Stenagervænget 12*. ISSN: 1901-726X, DCE Technical Report No. 127. Aalborg University, 2012.

Larsen, Jensen, and Daniels, **2012b**. T. S. Larsen, R. L. Jensen, and O. Daniels. *Målinger og analyse af indeklima og energiforbrug i komforthusene - Stenagervænget 28*. ISSN: 1901-726X, DCE Technical Report No. 128. Aalborg University, 2012.

Larsen, Jensen, and Daniels, **2012c**. T. S. Larsen, R. L. Jensen, and O. Daniels. *Målinger og analyse af indeklima og energiforbrug i komforthusene - Stenagervænget 37*. ISSN: 1901-726X, DCE Technical Report No. 129. Aalborg University, 2012.

Larsen, Jensen, and Daniels, **2012d**. T. S. Larsen, R. L. Jensen, and O. Daniels. *Målinger og analyse af indeklima og energiforbrug i komforthusene - Stenagervænget 39*. ISSN: 1901-726X, DCE Technical Report No. 130. Aalborg University, 2012.

Larsen, Jensen, and Daniels, **2012e**. T. S. Larsen, R. L. Jensen, and O. Daniels. *The Comfort Houses - Measurements and analysis of the indoor environment and energy consumption in 8 passive houses 2008-2011*. ISSN: 1901-726X, DCE Technical Report No. 145. Aalborg University, 2012.

LBNL, **2011**. LBNL. *WINDOW 6 - publicly available computer program for calculating total window thermal performance indices*, 2011. Version: 6.3.62.0.

Lomas and Eppel, **1992**. K.J. Lomas and H. Eppel. *Sensitivity analysis techniques for building thermal simulation programs*. Energy and Buildings, 19, 21–44, 1992.

Ma and Wang, **2012**. P. Ma and L.-S. Wang. *Effective heat capacity of exterior Planar Thermal Mass (ePTM) subject to periodic heating and cooling*. Energy and Buildings, 47, 394–401, 2012.

Markedsdata, **2013**. NN Markedsdata. *NN Markedsdata*, 2013. URL `http://erhverv.nnmarkedsdata.dk/`. Date of download: 2013.01.23.

Mortensen, **2012-2013**. L. H. Mortensen. *Personal communication*, 2012-2013.

Mortensen, **2012**. L. H. Mortensen. *DANVAK presentation - Forenklet beregning af sommertemperaturer*, 2012.

P. Narowski, M. Mijakowski, A. Panek, J. Ruciñska, and J. Sowa, *2010*. P. Narowski, M. Mijakowski, A. Panek, J. Ruciñska, and J. Sowa. CESB10. Proposal of simplified calculation 6R1C method of buldings energy performance adopted to Polish conditions. Prague, Czech Republic, 2010.

Nielsen and Svendsen, **2003**. T. R. Nielsen and S. Svendsen. *Harmonisering af grundlaget for beregning af energitilskud fra vinduer*. ISSN: 1393-402x, 1. edition. By & Byg and BYG.DTU, Technical University of Danish, 2003.

Nielsen, Duer, and Svendsen, **2000**. T. R. Nielsen, K. Duer, and S. Svendsen. *Energy performance of glazings and windows*. Solar Energy, 69, 137–143, 2000.

Nielsen, Svendsen, Duer, Schultz, Mogensen, and Laustsen, **2003**. T. R. Nielsen, S. Svendsen, K. Duer, J. M. Schultz, M. M. Mogensen, and J. B. Laustsen. *Ruder og vinduers energimæssige egenskaber. Kompendium 1: Grundlæggende energimæssige egenskaber*. ISSN: 1396-4046, 6. edition. BYG.DTU, Technical University of Danish, 2003.

NOËL, **2004**. J. NOËL. *CoDyBA BESTEST Qualification*, 2004.

Oxford University Press, **2012a**. Oxford University Press. *Oxford English Dictionary*, 2012. URL `http://oxforddictionaries.com/us/definition/american_english/robust`. Date of download: 2013.06.06.

Oxford University Press, **2012b**. Oxford University Press. *Oxford English Dictionary*, 2012. URL `http://oxforddictionaries.com/us/definition/american_english/accuracy`. Date of download: 2013.06.06.

Saltelli, Chan, and Scott, **2000**. A. Saltelli, K. Chan, and E. M. Scott. *Sensitivity Analysis*. ISBN: 0-471-99892-3. John Wiley and Sons Ltd, 2000.

Saltelli, Tarantola, Campolongo, and Ratto, **2004**. A. Saltelli, S. Tarantola, F. Campolongo, and M. Ratto. *Sensitivity analysis in practice - a guide to assessing scientific models*. ISBN: 0-470-87093-1. John Wiley and Sons Ltd, 2004.

SBi, **2009**. SBi. *Klimadata*, 2009. URL `http://www.sbi.dk/indeklima/simulering/bsim-building-simulation/kun-for-brugere/kun-for-brugere-af-bsim/copy_of_klimadata/klimadata`. Date of download: 2013.02.20.

SBi, **2011**. SBi. *Be10 - building energy calculation tool*, 2011. Version: 6.11.10.

SBi, **2004a**. SBi. *BSim - an integrated PC tool for analysing buildings and installations*, 2004. Version: 6.

SBi, **2004b**. SBi. *BSim help file*, 2004.

SBi, **2013***. SBi. *Simplified hourly model to calculate summer temperatures in dwellings*, 2013*. Version: 7.12.8.12 - Not released yet.

SBi-anvisning 196, **2000**. SBi-anvisning 196. *Indeklimahåndbogen*. 2nd edition. O. Valbjørn and S. Laustsen and J. Høwisch and O. Nielsen and P. A. Nielsen, 2000.

SBi-anvisning 213, **2008**. SBi-anvisning 213. *SBi-anvisning 213*. Søren Aggerholm og Karl Grau, Version. Statens Byggeforskningsinstitut, 2008.

The Danish Ministry of Climate and Energy, **2011**. The Danish Ministry of Climate and Energy. *Energy Strategy 2050*. Litotryk København A/S, 2011.

Thomsen, Wittchen, and EuroACE, **2008**. K. E. Thomsen, K. B. Wittchen, and EuroACE. *European national strategies to move towards very low energy buildings*. Danish Building Research Institute (SBi), 2008.

Thullner, **2010**. K. Thullner. *Low-energy buildings in Europe - standards, criteria and consequences*, Lund Technical University, 2010.

tegl. tænk i tegl. *Europæiske stenformater*. URL `http://www.taenkitegl.dk/specielle-sider/viden/fakta-om-tegl.html`. Date of download: 2013.04.17.

Williams, **2004**. R. Williams. *Sociology Graduate Statistics I. Normal distribution*, 2004. Department of Sociology, University of Notre Dame, USA.

Wittchen, Hansen, Radisch, and Treldal, **2011**. K. B. Wittchen, E. J. P. Hansen, N. H. Radisch, and J. Treldal. *Energioptimering af kontorbyggeri*. 1st edition. Statens Byggeforskningsinstitut, 2011. ISBN: 978-87-563-1523-4.

Wittchen, **2004**. K.B. Wittchen. *Vurdering af potentialet for varmebesparelser i eksisterende boliger*, Statens Byggeforskningsinstitut, SBi, 2004.