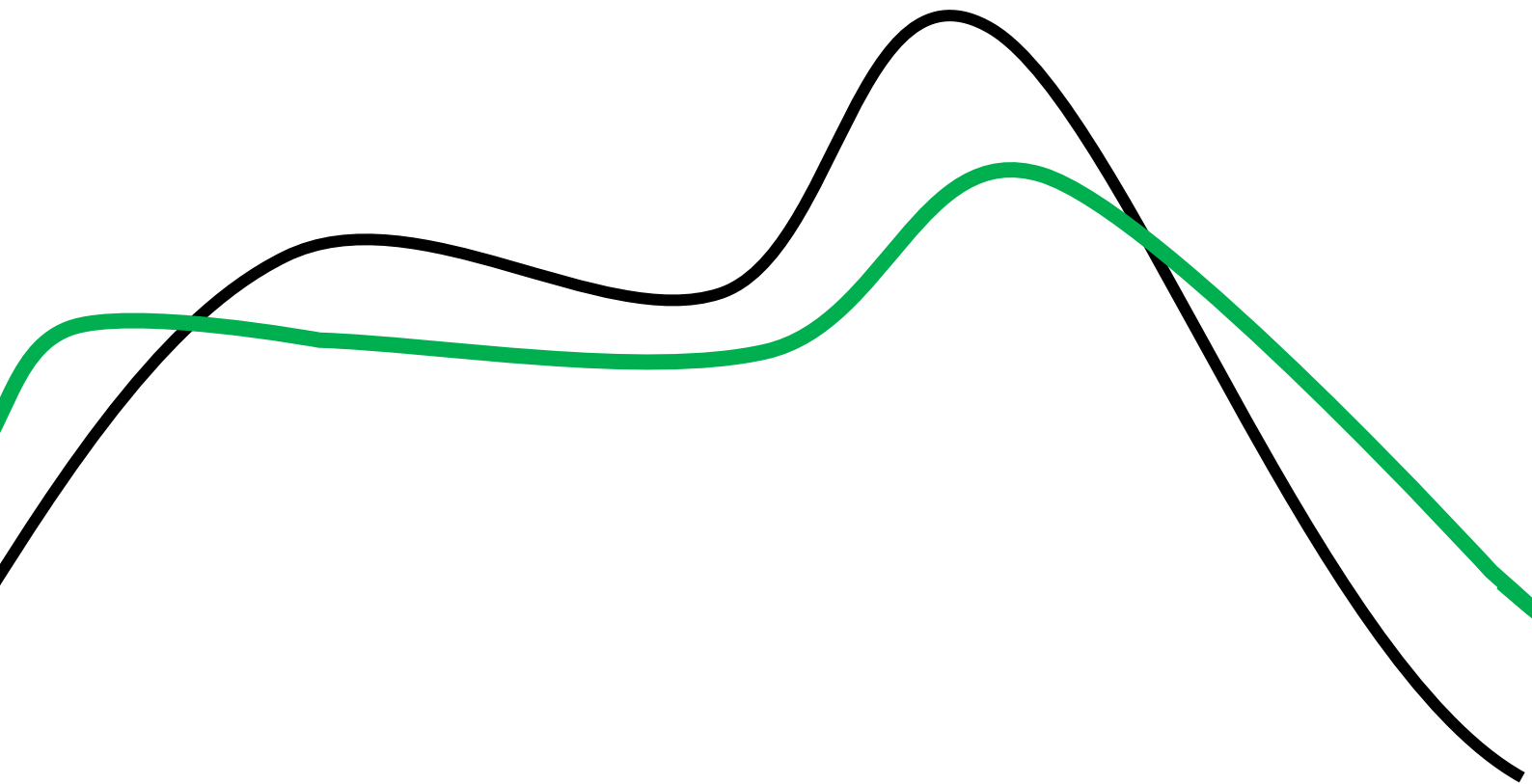


-From energy flexibility to design choice-

A method to produce design and control advice to increase building energy flexibility, based on a case study using open-source computer simulations.

I.Dols 18103480



Research group: Energy in Transition, [B4B project]

-From energy flexibility to design choice-

A method to produce design and control advice to increase building energy flexibility, based on a case study using open-source computer simulations.

I.Dols 18103480

Name (Student Number):
Isa Dols (18103480)

Date: 02-06-2022

Assigned by:
The Hague University research group Energy in Transition

Company supervisor:
Dr.Ir. Baldiri Salcedo Rahola , T.B.SalcedoRahola@hhs.nl

The Hague University of Applied Sciences supervisor:
Dr.Ir. Arie Taal, A.C.Taal@hhs.nl
Ir. Joep de Groot, J.A.degroot@hhs.nl

Research group: Energy in Transition, [B4B project]

Preface

This report was written as part of the Brains4Buildings project an active project within the research group Energy in Transition for the THUAS. The goal of this research is to develop a method to produce design and control advice to increase building energy flexibility based on open-source computer simulation. This will then contribute to balancing the energy grid and therefore contribute to the global energy transition.

This report, which acts as my graduation internship report for The Hague University of Applied Sciences, describes my process towards this goal.

This report has been conducted under supervision of Dr.Ir. T.B. Salcedo Rahola from the research group Energy in Transition(EiT) and Dr.Ir. A.Taal from The Hague University of Applied Sciences.

I would like to thank both supervisors for their guidance and knowledge they have shared with me when I was confronted with challenges. Furthermore I would also like to thank the other 5 students that started together with me at the research group EiT for the nice working atmosphere.

Lastly I would like to thank the IDEAS development team for their assistance while developing a model using the Modelica software, specifically Ir. J. Jansen from the KU Leuven.

03 June 2022 Delft, The Netherlands

Isa Dols

Summary

This report is the result of my internship at the research group Energy in Transition at The Hague University of Applied Sciences. The report shows the process and results from the development of a method to produce design and control advice to increase building energy flexibility based on open-source computer simulations.

The development has been done by answering the following research question: ‘How can a Modelica computer model be used to shape an advice on a buildings *Energy Flexibility* to help control engineers and designers make control and design choices on this subject?’. To answer this main question the following sub-questions are answered in this report:

‘How can energy flexibility in buildings be measured?’, ‘How can the methodology of Modelica software be applied?’ and ‘How can the energy flexibility of a building be interpreted to help make control and design choices of a building on the subject of energy flexibility?’.

These questions were answered by starting with a literature review in chapter 2 *State-of-the-arts of energy flexibility in buildings*. This chapter starts with a problem analysis and analyzes earlier done research on this subject. This is followed by determining the measuring method of energy flexibility, which answers the first sub-question from this research: ‘How can energy flexibility in buildings be measured?’. With the acquired knowledge from the literature review and assignment the list of requirements was established.

In chapter 3 *Methodology*, the lessons learned from the literature review have been applied to shape a methodology that is carried out to perform this research. This methodology has been drafted keeping the main research question of this report in mind: ‘How can a Modelica computer model be used to shape an advice on a buildings *Energy Flexibility* to help control engineers and designers make control and design choices on this subject?’.

In order to verify the suggested methodology from chapter 3, this was tested in chapter 4 *Implementation methodology on a case study*. In this chapter a reference model was created of a case study. This model was created using the Modelica programming language and in this chapter the sub-question: ‘How can the methodology of Modelica software be applied?’ is answered. Furthermore configurations of the reference model were made in order to create the energy flexibility graphs. Finally the different ways of applying and interpreting these flexibility graphs were discussed and thereby helped answer the last sub-question: ‘How can the energy flexibility of a building be interpreted to help make control and design choices of a building on the subject of energy flexibility?’. Lastly the research is concluded in chapter 5 and recommendations are made in chapter 6.

During this research all taken steps have been backed up with reliable resources while developing the methodology. Furthermore the proposed methodology has proven its ability to create flexibility graphs. Lastly the ways of interpreting flexibility graphs have also been analyzed and determined to have an advisory role on design choices when focusing on increasing the energy flexibility of a building. Thereby the result of this report is a methodology that can produce design and control advice to increase building energy flexibility based on open-source computer simulations.

Nomenclature

General

Abbreviation	Name
EiT	Energy in Transition
EU	European Union
HRS	Heat Recovery System
HVAC	Heating Ventilation and Air Conditioning
IBPSA	International Building Performance Simulation Association
KPI	Key Performance Indicator
NZEB	Net Zero Energy Building
RT	Real Time
THUAS	The Hague University of Applied Sciences
TMY	Typical Meteorological Year

Symbols/Definitions

Symbol	Unit	Description
A	m ²	Area
E	kWh	Energy
P	W	Power (E/t)
S	m	distance
T	K or °C	Temperature
t	s	Time
V	m ³	Volume

Table of contents

Preface	3
Summary	4
Nomenclature	5
1. Introduction	8
1.1 Assignment description	8
1.2 Company description	9
1.3 Goals of internship	11
1.4 Reading guide	12
2. State-of-the-art of energy flexibility in buildings	13
2.1 Problem analysis	14
2.2 Annex 67	15
2.3 Reference papers	15
2.4 Measuring methods of energy flexibility	16
2.5 Penalty Signal	18
2.6 Building parameters	20
2.7 List of requirements	21
3. Methodology	23
4. Implementation methodology on a case study	25
4.1 Applicability of Modelica	25
4.1.1 Modelica	25
4.1.2 IBPSA	26
4.2 Case study reference model simulation	27
4.2.1 Case study setup	27
4.2.2 Reference model	30
4.2.3 Verification	32
4.3 Energy flexibility model configurations and outputs	39
4.3.1 Flexible model configurations	40
4.3.2. Flexibility output	43
4.3.3. Interpretation advice	47
4.4 Future applicability	49
5. Conclusion and recommendations	50
References	53
Appendix	55

I.	Reference papers	56
II.	Modelica how-to: Weather data	57
III.	Modelica how-to: Package type	59
IV.	Modelica how-to: Weather file configuring	61
V.	SimpleHouse Modelica Model	62
VI.	Poster	63
VII.	Provisional scientific paper	64
VIII.	Reference model description	71
IX.	Competence justification	76

1. Introduction

To finish the education of Mechanical Engineering at The Hague University of Applied Sciences (THUAS), students follow a final internship of 17 weeks to apply the skills they learned during their education. This is my final report of this internship at the research group Energy in Transition (EiT). My assignment will focus on increasing the energy flexibility in buildings. This introduction firstly describes the assignment, the company and finally the competence and company goals of the internship and finally includes a reader guide of this report.

1.1 Assignment description

The aim of this paper is to propose a method to produce design and control advice to increase building energy flexibility based on open-source computer simulations, preferably using the openModelica software.

In order to perform these simulations, a computer model will be created using the available IBPSA libraries within the openModelica software. This model should measure the energy flexibility of a building, using the methodology proposed in the EBC project Annex 67. They propose the following definition of energy flexibility in a building:

“The Energy Flexibility of a building is the ability to manage its demand and generation according to local climate conditions, user needs and grid requirements. Energy Flexibility of buildings will thus allow for demand side management/load control and thereby demand response based on the requirements of the surrounding grids. (Reyners et al., 2021)”.

The measurable representation of this *Energy Flexibility* proposed by Annex 67 is defined by comparing the energy load of a reference model and the energy load of a flexible model. This comparison makes the *Energy Flexibility* of the building quantifiable. This translated into a graph as shown in Figure 1.1.1:

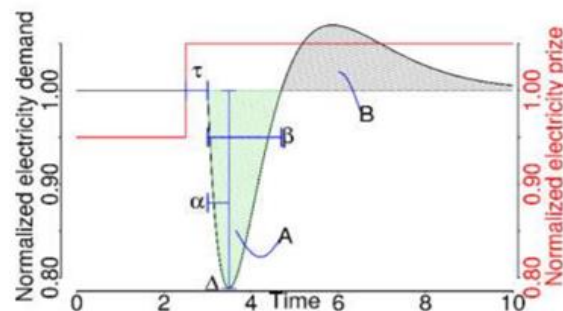


Figure 1.1.1 Response graph on Energy Flexibility(Annex 67, 2019)

τ =time from the penalty signal to action start

β = the duration of the response

α = the duration of the response till highest energy shift

A = the shifted amount of energy after initiation

B = the rebound effect for returning the situation back to the “reference”.

The main research question of this research is:

How can a Modelica computer model be used to shape an advice on a buildings *Energy Flexibility* to help control engineers and designers make control and design choices on this subject?

To answer this question the following sub-questions will be answered in this report:

- How can energy flexibility in buildings be measured?
- How can the methodology of Modelica software be applied?
- How can the energy flexibility of a building be interpreted to help make control and design choices of a building on the subject of energy flexibility?

1.2 Company description

THUAS has a research group Energy in Transition under the supervision of Lector Dr.Ir.Ing. S.Mertens. This research group is set up in 2020 and has around 10 active researchers working on multiple different projects.

The energy transition meaning the transition from fossil energy to sustainable energy is crucial for the future. The full energy supply should therefore be a sustainable energy supply. But supply and demand of sustainable energy often do not match and the balance is necessary. This is one of the main focusses of the research group Energy in Transition.

Goals of research group Energy in Transition (Lectureship, 2020):

- “• Finding directional, innovative, cost-efficient solutions through technical and economic research by the research group's knowledge circle.
- Defining and mapping technical applied research at higher professional education.
 - Collaborate with other research groups that are important for the research of the Energy in Transition research group”

Organization	The research group has one Lector and a team of ten researchers underneath
Financials	Because the research falls under the The Hague University of applied sciences, this professorship is paid through them with the help of subsidies. It is not a profit oriented organization
Employees	11 employees + additional internships
Materials	Intellectual properties on earlier done research, no physical materials.

Table 1.2.1 OFEM Lectureship Energy in Transition

The Lectureship Energy in Transition is working on multiple projects. One of the projects the Lectureship is working on is the B4B project. This project is coordinated by Laure Itard from the TU Delft.

“This multiple year program focuses on developing methods to leverage big data from smart meters, building management systems and the Internet of Things to reduce energy consumption, increase comfort, respond flexibly to user behavior and local energy supply and demand , and to save on the maintenance costs of installations. This will be done through the development of faster and more efficient Machine Learning and Artificial Intelligence models and algorithms. The project focuses on non-residential buildings, such as commercial and institutional buildings (Brains4buildings, 2021). ”

Lectureship Energy in Transition is connected to two of the work packages active in this program, being WP1 and WP2.

“• WP1: development of smart diagnostic systems to reduce energy losses in buildings in an automated way. This can then be used for performance maintenance planning.

• WP2 2: development of smart control models to increase energy flexibility (heating, cooling and electricity) within buildings. Optimization costs, as well as CO2 emissions, comfort and maximum use of local sources are included.” (Brains4buildings, 2021)

The project leader of WP2 is T.B. Salcedo Rahola. He is an Associate Lecturer at the Energy in Transition research group, next to his lectures at the THUAS. He studied Mechanical Engineering at the UPC University in Barcelona, Spain, and obtained his PhD on the use of integrated contracts in energy renovation of social housing at TU Delft.

T.B. Salcedo Rahola will also be my mentor in the duration of this internship. This internship will also work under the WP2 of Brains for Buildings.

Organization	B4B is being guided through the TU Delft and has a setup with a planned duration of 4 years. With the start being at 1 st of May 2021.
Financials	Funding through Dutch Ministry of Economic Affairs & Climate
Employees	8 researchers + additional interns
Materials	Intellectual properties on earlier done research, no physical materials. The idea is to have everything that is created within B4B as open source.

Table 1.2.2 OFEM B4B

1.3 Goals of internship

In this section the competence goals given from the THUAS are discussed, together with the company goals and finally my student goal.

Competence goals

Below the learning objectives from the study guide are displayed:

1. Gain work experience and self-knowledge in a company (no assessment)
2. Apply (+ expand) knowledge & skills from a mechanical engineering context. (review)
3. Professionalization at HBO level (assessment)

During this internship there are 4 main competences that have been developed, this being: analyzing, designing, researching and professionalizing. Because this project can be seen as complex, especially with it being focused on a rather new software and method, there most definitely is the possibility for these competences to develop. (THUAS, 2021)

Competence	Current level	Goal level	Planned activities (see appendix IX for competence justification)
Analyzing	3	3	Analyze the functions and analyzing the correct methodology for this research.
Designing	3	3	Designing a code and attached model and making this fit all the set requirements of the project.
Researching	2	2	Performing a literature review. Researching goals, a new programming language, influences on energy flexibility, validating a computer model, and divining the defining the measurement methodology based on previous research.
Professionalizing	2	2 or 3	Writing a scientific paper and working in a professional environment.

Table 1.2.1 Competences

Company goals

The goal of this report is to propose a method to produce design and control advice to increase building energy flexibility based on open-source computer simulations, preferably using the openModelica software.

I will be the first one working on this project. In prospect it is expected for me to start this project and document this correctly in case of further research. Not only my results but also the taken steps will therefore be well documented.

Deliverables (company):

- A plan of approach with an analysis of what is needed to achieve the desired result within the first two weeks.
- Simulation models.
- Final report in scientific paper format (not more than 8 pages), and additional appendixes

(this can be simulations/ measurements, etc.).

- Progress board to monitor weekly task progress (for example Trello board)
- All documents / simulations are shared online through Microsoft Teams. All organized within folders and subfolders, all files should have a good name, version numbers and date stamps.
- Design a project poster on A1 format, this poster should be able to sell your product.
- Power Point presentation for the end-assessment.

Student goals

My goal is to carry out the assignment to the best of my abilities. By doing so completing my competence levels and getting a learning experience.

1.4 Reading guide

The remainder of this report starts with chapter 2 State-of-the-arts of energy flexibility in buildings. This chapter is based on literature review which starts with a problem analysis, and analyzes earlier done research on this subject. This is followed by determining the measuring method of energy flexibility, which answers the first sub-question from this research: 'How can energy flexibility in buildings be measured?' With the acquired knowledge from the literature review and assignment the list of requirements was established.

In chapter 3 *Methodology*, the lessons learned from the literature review have been applied to shape a methodology that is carried out to perform this research. This methodology has been drafted keeping the main research question of this report in mind: 'How can a Modelica computer model be used to shape an advice on a buildings *Energy Flexibility* to help control engineers and designers make control and design choices on this subject?'.

In order to verify the suggested methodology from chapter 3, this was tested in chapter 4 *Implementation methodology on a case study*. In this chapter a reference model was created of a case study. This model was created using the Modelica programming language and in this chapter the sub-question: 'How can the methodology of Modelica software be applied?', is answered. Furthermore configurations of the reference model were made in order to create the energy flexibility graphs. Finally the different ways of applying and interpreting these flexibility graphs were discussed and thereby helped answer the last sub-question: 'How can the energy flexibility of a building be interpreted to help make control and design choices of a building on the subject of energy flexibility?'. Lastly the research is concluded in chapter 5 and recommendations are made in chapter 6.

2. State-of-the-art of energy flexibility in buildings

This study started with a literature review to determine exactly how-to define energy flexibility and to perform a problem analysis, see section 2.1. In the literature review the methodology of the EBC project Annex 67 will take the lead further explained in section 2.2 *Annex 67*. This was followed by a literature review on the quantification of energy flexibility in buildings by case studies, see section 2.3 *Reference papers*.

This literature review has been done with the following key search terms:

[energy AND flexibility] OR [energy AND flexibility AND case-study] OR [Annex AND energy AND flexibility] OR [energy AND energy flexibility AND quantification] OR [energy AND flexibility AND design] OR [Energy AND Measuring AND Tool] OR [Flexibility AND Measuring AND Tool]

Furthermore, part of this research is derived from previous report from students at The Hague University of Applied Sciences, working on projects connected to energy flexibility or the case study that is used in this report.

From the literature review the key performance indicators (KPI) were analyzed in section 2.4 together with the penalty signal that initiates the energy flexibility performance in section 2.5 and lastly the building parameters that can influence the energy flexibility in section 2.6.

Finally the list of requirements (LoR) for this research can be found in section 2.7. The LoR has been created to ensure the main aim of the research is kept within sight.

2.1 Problem analysis

In order to get a correct understanding on the subject energy flexibility in buildings, it is of importance to realize why the increase of energy flexibility in buildings is of value. This has been answered in the problem analysis below.

To achieve the Paris Agreement goals (United Nations, 2021) , the use of fossil fuel will need to be reduced at an average rate of 6% per year from 2020 till 2030, as proposed in the Production Gap report (Achakulwisut et al., 2021) . As a consequence there has been an exponential growth of renewable energy production over recent years, especially solar and wind (Hivepower, 2022). The increase of renewable energy causes a disbalance between the energy production and consumption because of the dependence on the natural elements. One way to rebalance the grid is by adjusting the consumption in respects to the production, by having the ability to control the grid energy demand.

Buildings are responsible for 40% of the total energy consumption in the EU (EU, 2021). Therefore, they can play a key role in the grid balance. To be able to adjust the grid energy demand pattern of a building without compromising its user requirements the building should acquire certain energy flexibility (Reynders et al., 2018). The concept of building energy flexibility has been early addressed in the work from Syx et al. (2011), and Nuytten et al. (2013) among others. Later a widely accepted definition has been developed by Annex 67 (2018):

‘The capacity of a building to manage its demand and generation according to local climate conditions, user needs and grid requirements. Energy Flexibility of buildings will thus allow for demand side management/load.’

2.2 Annex 67

In the problem analysis the definition proposed by Annex 67 has been accepted as leading within this research. To verify the reliability on the research done by Annex 67, it is of importance to understand how they are structured as a research group and what the aim of their project is, this is discussed in the section below.

The Annex 67 is one of the projects under the IEA_EBC program. The IEA-EBC program is an international oriented energy research and innovation program, it focusses on building and community fields. It enables large scale R&D projects, in total 26 countries are active in the program. Annex 67 is one of the large scale R&D projects the IEA_EBC program has taken upon itself.

The aim of Annex 67 is set by Søren Østergaard Jensen et al. (2017, p.4) as:

'To increase knowledge on and demonstrate the Energy Flexibility buildings can provide for the energy grids, and to identify critical aspects and possible solutions to manage this Energy Flexibility.'

Currently the Annex 67 has been followed by a new project 'Annex 82'. Annex 82 has the objective to further develop and demonstrate the characterization and labelling methods to be able to verify their integrity. A work meeting of Annex 82 has been attended to get further intel on the current projects connected to Annex. Which helped to indentify reference projects for this research.

Because the research in the Annex 67 project has been widely verified with scientific papers, is therefore seen as reliable.

2.3 Reference papers

While performing the literature review the lessons learned from earlier case studies researching energy flexibility were summarized. By building on this knowledge, this research can add value instead of repeating earlier works.

Firstly what was learned is that there are different energy flexibility measuring methods (Marotta et al., 2021) (Junker et al., 2018), though within all this research similar key performance indicators (KPI's) come forward, this is further explained in section 2.3 *Measuring method*. The characterization on energy flexibility is also discussed such as the factor of the initiator, often referred to as the penalty signal, this is discussed in section 2.5 *Penalty signal*.

Furthermore multiple case studies were done using computer models in order to execute a flexibility measurement. These computer models are used to create comparisons with non-flexible buildings and flexible buildings. The computer model developed in this research can be found in chapter 4 *Simulated model*. The parameters that influenced the energy flexibility came forward during the results of multiple case studies. The high impact that the control system has on the energy flexibility also came forward here (Zhuo et al., 2019), this is further discussed in section 2.6. The full lessons learned can be found in the table from appendix I *Reference papers*.

The reference papers provided several key insights and helped shape the following steps in this research.

2.4 Measuring methods of energy flexibility

Like discussed in section 2.3 there are multiple ways to measure energy flexibility. In this section the method proposed by Annex 67 gets compared to the method by Marotte et al.. This is done to determine the measuring method for the energy flexibility and thereby help answer the first sub-question: How can energy flexibility in buildings be measured?

Annex 67

In the method proposed by Annex 67, a reference model and a flexible model are compared to each other. The models get a penalty signal on which the system of the building will respond. The comparison between the reference model and flexible model, see figure 2.4.1, is what can conduct the graph in figure 2.4.2 below. In graph 2.4.2 the 6 KPI's proposed by Annex 67 can be viewed.

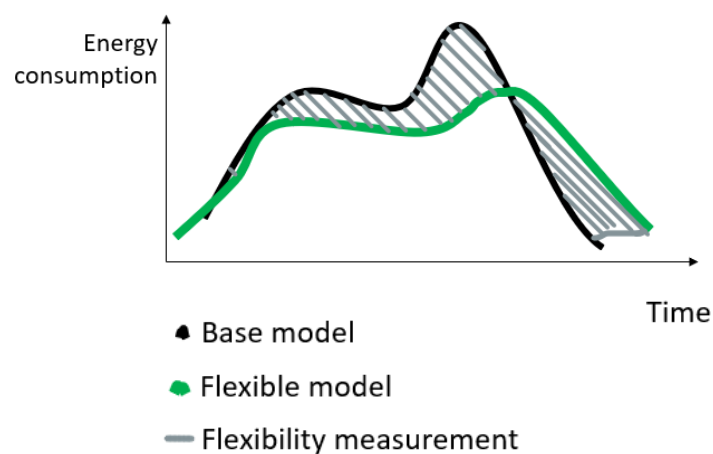


Figure 2.4.1 Energy load comparison

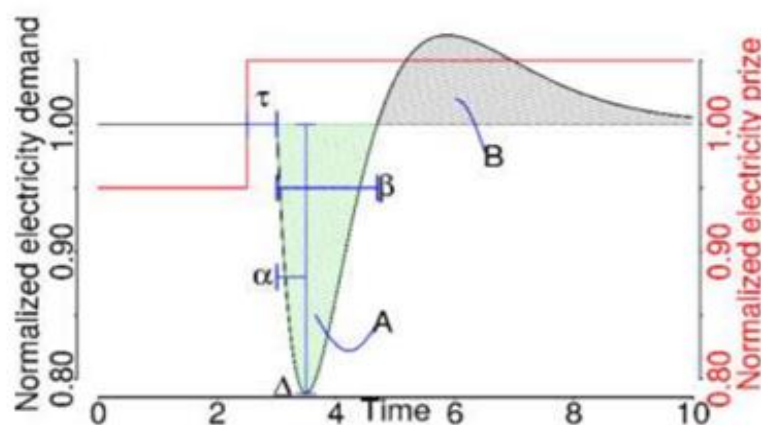


Figure 2.4.2 Response graph on Energy Flexibility(Annex 67, 2019)

KPI	Ab.	Explanation	Unit
Initiation time	τ	The time from the penalty signal to action start.	s
Duration time	β	The duration of the response.	s
Duration peak time	α	The duration of the response till highest energy shift	s
Shifted energy capacity	A	The shifted amount of energy after initiation	(W/m ²).h
Rebound effect	B	the rebound effect for returning the situation back to the “reference”.	(W/m ²).h
Maximum energy change	Δ	The maximum change in demand following the penalty signal.	W/m ²

Table 2.4.1 Response graph on Energy Flexibility(Annex 67, 2019)

Marotta et al., 2021

In the paper of Marotta et al. (2021), the following KPI's are proposed to certify the energy flexibility of a building. They propose the Flexibility Performance Indicator (FPI) as the following:

$$FPI = \frac{1}{4} (p_1 t_{res}^* + p_2 P_{res}^* - p_3 t_{rec}^* + p_4 \eta_{DR})$$

To determine the FBI the following equations are used.

$$P_{res} = \frac{1}{t_{res}} \int_0^{t_{res}} (P_{ref} - P_{flex}) dt$$

$$E_{DR} = \frac{1}{t_{res}} \int_0^{t_{flex}} (P_{ref} - P_{flex}) dt$$

$$\eta_{DR} = \frac{E E_{DR}}{\int_0^{t_{flex}} P_{ref} dt}$$

$$t_{rec}^* = \frac{t_{rec}}{24}$$

$$t_{res}^* = \frac{t_{res}}{24}$$

$$P_{res}^* = P_{res} / P_{rated}$$

Parameter	Explanation	Unit
p_1, p_2, p_3, p_4	Weight factors	n/a
t_{res}	Response time. Number of hours of inactivity of the space heating system in conditions of thermal comfort.	h
t_{rec}	Recovery time. Number of hours required, after a flex. event, to restore the initial thermal comfort state.	h
P_{rated}	Design power of the space heating system.	kW
P_{ref}	Electric power in base case	kW
P_{flex}	Electric power in flexible case	kW

Table 2.4.2 FPI (Moretta et al., 2021)

When comparing the findings of above, there seems to be an overlapping approach. In both methods a reference model/case and flexible model/case are compared. These are compared on the electrical consumption in respect to time.

Therefore these are the main measured parameters in order to be able to conclude something about the energy flexibility of a building.

In the paper of Marotta et al. (2021) the final conducted FPI does contain a sensitivity measurement within the definition because of the weight factors. Though these are not further referenced in the paper nor in other papers, this makes it *not* a widely accepted definition. Therefore this is left outside the scope of this research.

Furthermore a big difference is in the visualization of the outputs, a graph compared to a number. Because the goal is to shape an advice, the graph can provide more information to the engineer or designer. Therefore this is seen as a more suitable visualization for this research.

Therefore the measuring method proposed by Annex 67 is the chosen method for this research, and shapes the answer to the research sub-question: How can energy flexibility in buildings be measured?

2.5 Penalty Signal

The penalty signal is the trigger the control system receives on which the building should respond. Therefore the penalty signal is integrated in the control of the installation. In this section the different motives of the penalty signal are discussed as well as the way this is chosen to be incorporated into this research.

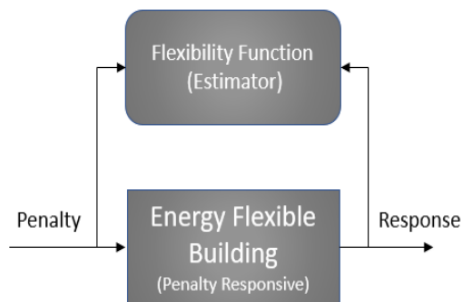


Figure 2.5.1 Penalty signal response (Annex, 2020)

A penalty signal can be initiated because of different causes. This is the case because there are multiple stake holders with different interests in respect to buildings energy flexibility.

The four main stakeholders are the following (Jurgen et al., 2020):

- Occupant
- Building/Manager
- Energy supplier
- Government/municipality

The five most common penalty signal initiators are the following (Jurgen et al., 2020):

- Marginal CO2 intensity
- Average CO2 intensity
- Electricity spot price
- Electricity balancing price
- Network tariffs for electricity and district

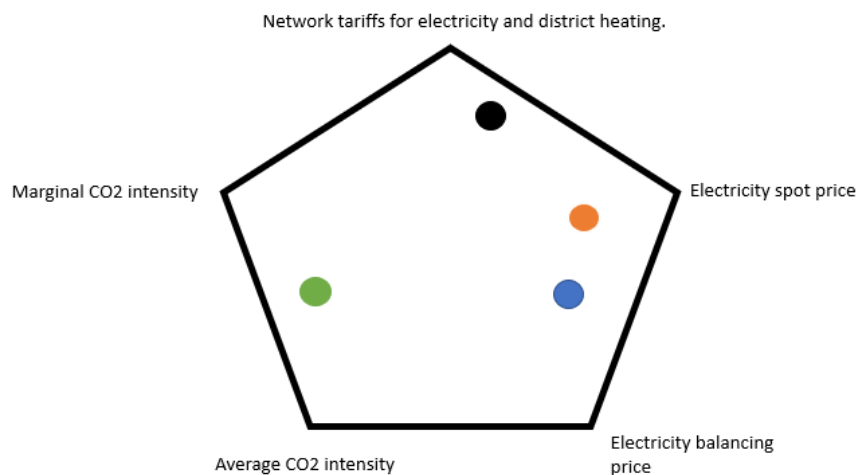


Figure 3.5.2 Stakeholders relative to Penalty signal

- Marginal CO2 intensity
 - This is a main importance for government due to regulation laws (Rijksoverheid, 2021) , though also a factor for occupants when sustainable is an important value for them.
- Average CO2 intensity
 - This is a main importance for government because of regulation laws, though also a factor for occupants when they have a sustainable mindset.
- Electricity spot price
 - This is a main importance for occupancies and managers (Consumentenbond, 2021), because they will be responsible for the payment.
- Electricity balancing price
 - This is of main importance for occupancies and managers, because they will be responsible for the payment.
- Network tariffs for electricity and district heating.
 - This is of main importance for energy supplier and manager to be able to provide constant service.

This research mainly focusses on the reaction a building will have after this penalty signal and less on the penalty signal itself. Therefore the penalty signal will be viewed as a binary initiator in the rest of this report and its configurations are seen as outside the scope.

2.6 Building parameters

The goal of this report is to be able to advice engineers and designers on their design choices to enhance the energy flexibility of a building. In a building there are certain parameters that have an impact on the energy flexibility. These parameters are analyzed to determine which of these needed to be taken in account while analyzing the energy flexibility, this is done in the section below.

The researchers within the Annex 67 project have listed the key parameters in table 2.6.1 and ranked them on their sensitivity. This analysis is performed by doing ANOVA tests on linear regression models. These factors are rankings and not weight factors. The result of this test are in line with earlier done studies (Johra et al., 2019), (Le Dréau Heiselberg, 2016) ,(Masy et al.,2015).

General ranking	Parameter	α (s)	β (s)	A (J)	B (J)	Δ (W)
1	Insulation level	5	7	7	7	7
2	Thermal inertia	3	2	6	6	6
3	Heating /Cooling system	7	3	3	3	5
4	Control strategy / penalty signal	6	4	4	4	4
5	Building type	4	1	5	5	3
6	Outdoor temperature	2	5	2	2	2
7	Solar radiation	1	6	1	1	1

Table 2.6.1. parameter sensitivity (Knotter et al., 2019)

As seen in table 3.2.1.1. the impact of insulation and thermal inertia are of the highest impact. When taking a closer look at the thermal inertia you could split this up in two parameters: System Thermal inertia and envelope thermal inertia. This is of added value because they can be done separate from each other and both are of high impact. Together with the control strategy/penalty signal this will be seen as the focus parameters in this report. The reason this is taken into account instead of the heating/cooling system is because it is in a different category.

Without the system being aware of a penalty it will not be possible to properly measure its energy flexibility as described in section 3.2.1 *Measuring method*. Because of the size of this assignment the other parameters are considered outside the scope of this research.

Main advice parameters
Insulation
Thermal inertia
Control/penalty signal

Table 2.6.2 Main parameters

2.7 List of requirements

A LoR has been created to ensure the main aim of the research is kept within sight. This list of requirements uses the MoSCoW method, this method arranges the requirements on their importance:

M	Must
S	Should
C	Could
W	Would

Table 2.7.1 MoSCoW method

Because the final product is a method and not a tool or object the requirements are mainly focused on how the research is executed and the LoR could be composed with help of the assignment, conversations with my supervisor and literature review. This LoR has been verified within EiT at 03-05-2022.

Nb.	Requirement	Unit	Verification	Resource and date	MoSCoW
1	Computer model				
1.1	The model must be created using open_source software	n/a	The software used should be openly available to users.	Vision B4B - 14-01-2022	M
1.2	The model should be developed in the Modelica language and Omedit enviroment.	n/a.	n/a.	Assignment description - 14-01-2022	S
1.3	The model must include the HVAC system.	n/a.	Computer model	Assignment description - 14-01-2023	M
1.4	The model could include its energy generation system	n/a.	n/a.	Discussion supervisor- 10-02-2022	C
1.5	The model must output its energy consumption in RT.	Watt	n/a.	Annex 67 - 28-02-2022	M

1.6	The model should be verifiable.	n/a.	Available dataset	Discussion supervisor- 20-02-2022	S
1.7	Variables of the model must be able to be created	n/a.	n/a.	Annex 67 - 28-02-2022	M
1.8	The model must include a reaction on a penalty signal	n/a.	n/a.	Annex 67 - 28-02-2022	M
2	Flexibility model				
2.1	The model should give its output in a graph illustration.	n/a.	n/a.	Literature review - 20-04-2022	S
2.2	The shifted amount of energy after initiation must be viewable from flexibility model.	Watt	flexibility graph	Annex 67 - 28-02-2022	M
2.3	The rebound effect of energy after initiation must be viewable from flexibility model.	Watt	flexibility graph	Annex 67 - 28-02-2023	M
2.4	The time from penalty signal to action could be viewable.	seconds	flexibility graph	Annex 67 - 28-02-2024	C
2.5	The duration of response should be viewable.	seconds	flexibility graph	Annex 67 - 28-02-2025	M
2.6	The maximum change in demand following the penalty signal should be viewable.	Watt	flexibility graph	Annex 67 - 28-02-2026	M
2.7	The model should be interpretable for engineers and designers	n/a.	Have output assessed by specialists	Discussion supervisor- 03-05-2022	S
3	Methodology				
3.1	The method developed should be applicable for general buildings.	n/a.	n/a.	Assignment description - 20-02-2022	S
3.2	The method should not be dependable on a specific modeling language	n/a.	n/a.	Assignment description - 20-02-2022	S

Table 2.7.2 LoR

3. Methodology

In this chapter the lessons learned in the literature review have been applied to shape a methodology that is carried out to perform this research. This methodology has been generalized in order to not be depending on a certain building type nor modeling language, as these are the set requirements 3.1 and 3.2 from the LoR. Furthermore the methodology is developed with keeping the main research question in mind:

How can a Modelica computer model be used to shape an advice on a buildings Energy Flexibility to help control engineers and designers make control and design choices on this subject?

1. *Create digital reference-model of building envelope, installation and the environmental conditions.*

Like discussed in the numerous case studies in section 2.3, *Reference papers*, in order to perform an energy flexibility measurement a digital model needs to be created/available. Taking the factors discussed during Chapter 2, *State-of-the-art of energy flexibility in buildings*, this model should include the factors that influence the energy demand of the building. In this research this is done using the component based programming language Modelica and taking a case study of a NZEB, see section 4.2.2, *Reference model*, for the result.

2. *Verify model energy demand output with data*

When taking a look at the LoR, it is seen that the created digital model should be verifiable in requirement 1.6. In this research this is done by comparing the data available of the case study to the created model, see section 4.2.3, *Verification*.

3. *Insert Penalty Signal in control system and set to measuring conditions*

Like discussed in section 2.5, *Penalty signal*, a penalty signal in the control needs to be added in order to trigger a flexible behavior reaction. In this research this signal will be used as a binary input also discussed in section 2.5.

4. *Create flexible model(s):*

- a. Variant: Insulation
- b. Variant: Thermal inertia
- c. Variant: Control/Penalty Signal
- d. Other Variants can also be evaluated if of interest for engineer/designer, though for this research this is considered outside the scope.

In the measuring method proposed in section 2.5, the conclusion was made that in order to perform an energy flexibility measurement two energy loads need to be compared, one coming from a reference model and the other coming from a flexible model. This flexible model is similar to the reference model though one variable has been changed in order to test its influence on the energy flexibility of the building. The variables changed in this research were discussed in section 2.6 *Parameters*, and incorporated in the flexible model seen in section 4.3.1 *Flexible model*.

5. *Extract RT energy demand from reference model and flexible model*

Like discussed in section 2.5 *Measuring method*, the energy load from the reference model and flexible model need to be compared, in order to do this the real time (RT) energy load demand needs to be extracted after running the simulations. For this research this is discussed in section 4.2.3 *Flexibility output*.

6. *Create reference line from flexible-model energy load and delta-line from flexible-model energy demand to compute graph.*

In order to determine the KPI's discussed in section 2.4 *Measuring method*, the comparison between the loads will be plotted in a graph. See section 4.3.3 *Flexibility output*, for the result in this research.

7. Repeat step 4, 5 and 6 to create different flexible models and their outputs.

To be able to compare the influences of different parameters and their influence on energy flexibility of a building, different flexible models must be created. In this research this has been done by analyzing three cases, see section 4.3.1 *Flexible simulation setup*.

8. Compare graphs, determine impact advice for designers/engineers.

In order to properly answer the main research question the focus needs be on the advice to the designer. The flexibility output that is configured therefore needs to be structured in a way to add value to the designing process of a building. In this research this has been discussed in section 4.3.3 *Interpretation advice*.

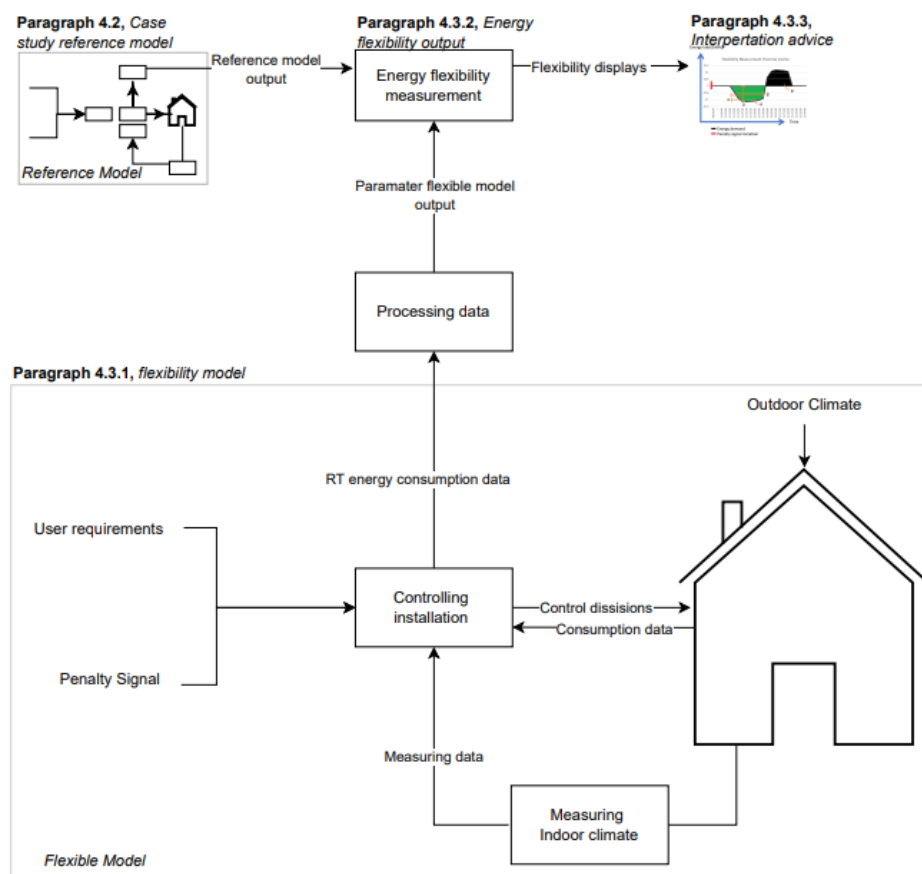


Figure 3.1. Simplified block diagram, Methodology of producing energy flexibility advice

All steps discussed together shape the methodology for this research. These steps are executed in the following chapters to validate this methodology and answer the main research question of this report.

4. Implementation methodology on a case study

Like discussed in step one of the methodology, to evaluate the energy flexibility of the building a digital reference model had to be created to generate the load curve of different building configurations. This reference model has been created using the OpenModelica environment with the Modelica language, in order to fulfill the application requirements 1.1 and 1.2 from the LoR. Modelica is a multi-domain modeling language for component oriented modeling. The applicability of this programming language is discussed in section 4.1 *Applicability of Modelica*. The created reference model is based on a case study of a Net Zero Energy Building (NZEB) from Zoetermeer, this can be found in section 4.2 *Case study reference model*. This section has been divided in three parts: the case study, the reference model and the verification of the reference model. From the reference model multiple configurations were made to create flexible models in section 4.3.1 *Flexible model configurations*. This has been followed by comparing the energy load of the reference model and flexible models to create flexibility graphs in section 4.3.2 *Flexibility output*. In order to use the output of this comparison the interpretation possibilities of the flexibility graphs are discussed in section 4.3.3 *Interpretation Advice*, and finally the future applicability of this method is discussed in section 4.4 *Future applicability*.

4.1 Applicability of Modelica

Like mentioned in requirement 1.1 and 1.2 from the LoR, the reference model should be created using the Modelica language in an open-source environment. In this section the use of Modelica is explained together with its libraries and its applicability for this research.

4.1.1 Modelica

Modelica is a multi-domain modeling language for component oriented modeling. Because of the component oriented aspect it is also easy to adjust a single component in the model, in case of different requirements. It also allows the usage of libraries, in this model the IBPSA library has been used with the focus on the IDEAS library. The IBPSA library is mainly used for building and community energy and control systems (Vöth et al., 2020), this is further discussed in the next section 4.1.2 *IBPSA*.

Modelica transforms the model into an ordinary differential equation (ODE) representation to perform the simulation using numerical integration methods. These methods are called solvers inside the program, and when running a simulation the type of solver can be chosen. The solver used in this research is the DASSL solver, this is also the default solver in OMedit.

The usage of Modelica results in a visual model that can be adjusted within each component and by the type of component. This allows variants of the model to be easily created, which was of importance when starting this research. Furthermore the OpenModelica is an open source application which can encourage further research and allows it to publish all documents openly within this research. Therefore the use of this environment and language are seen as suited for this research.

Because of challenges while working with Modelica, there are multiple how-to guides made during this research in order for a next student to work more efficiently through learning its language and environment. These guides can be found in appendix II, III and IV, *Modelica how-to's*, of this report.

4.1.2 IBPSA

This library has been used creating the reference model because the IBPSA library provides the possibility for efficient usage within the openModelica environment, the usage of this library is addressed in this section.

The IBPSA library is an open-source library with pre coded models for the implementation of building and community energy and control systems. The IBPSA library is an initiative coming from the IBPSA Project 1, they are developing open-source software for building energy and control systems (IBPSA, 2022). Part of their work also extended in an older Annex project, “Annex 60”. This Annex project focused on open-source computational tools for building/community oriented energy systems (IEA, 2018).

The IBPSA library is being used as the core of the following four libraries:

- *AixLib*, from RWTH Aachen University, Germany (Aixlib, 2017)
- *Buildings*, from LBNL, Berkeley, CA, USA, (Berkeley University, 2022)
- *BuildingSystems*, from UdK Berlin, Germany, (Nytsch-Geusen.C, 2021)
- *IDEAS* from KU Leuven, Belgium (KU Leuven, 2022)

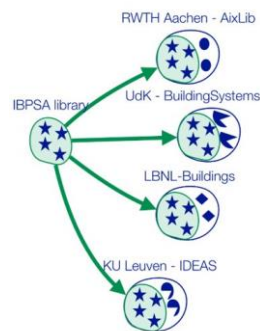


Figure 5.1.2.a (IEA, 2018)

These libraries are all programmed in the Modelica language but are not all developed in OMedit, they are mainly developed in commercial environments like Dymola. This causes errors while working with the libraries in OMedit. First I looked into the libraries, and later one I looked for the contact with the people of KU leuven therefore the IDEAS library has been used as the main library in this research. While working on this research this library has been adjusted multiple times after being in contact with the developers through github. For now this is still a time consuming part of programming with Modelica and the IBPSA libraries, though it is expected to become more user friendly in further development. Furthermore the libraries are one of the key arguments of working with Modelica therefore this is used in this research. Therefore the Modelica software and the IBPSA libraries are applicable for this research.

4.2 Case study reference model simulation

As earlier described in the LoR the reference model must be verifiable, this has been done by using a case study with available performance data. This section has been divided in three parts, explanation about the case study in section 4.2.1, the actual reference model in section 4.2.2 and finally the reference models verification is performed in section 4.2.3.

4.2.1 Case study setup

For the case study the NZEB housing in Zoetermeer were used. These houses were chosen because of the available data. The installations are installed and monitored by Factory Zero, the research group Energy in Transition has an ongoing relation with FZ. Therefore this is a suitable case study. In this section the location and specifications are described in order to base the reference model on this case study.



Figure 5.2.1 Street view Case study (Google maps, 2022)



Figure 5.2.2 Case study (Architectuur punt, 2020)

Although the data from 2019 of this case study is available, the buildings parameters like R_c values, materials and measurements are not. After trying through several ways to get this data, it was not possible to get hands on these. This is due to complaints about the homes' climate, which has been the subject of multiple news media. Therefore, neither the housing corporation nor the project developer wanted to associate themselves with the project. These parameters have been approximated with the information that is publicly available and with the help of Factory zero.

Envelope

The envelope of the house will be a big influence on the energy flexibility of the building, due to parameters as insulation and thermal mass which are depending on the envelope. These parameters are referred to as important parameters that can influence the energy flexibility in section 2.6, *Parameters*.

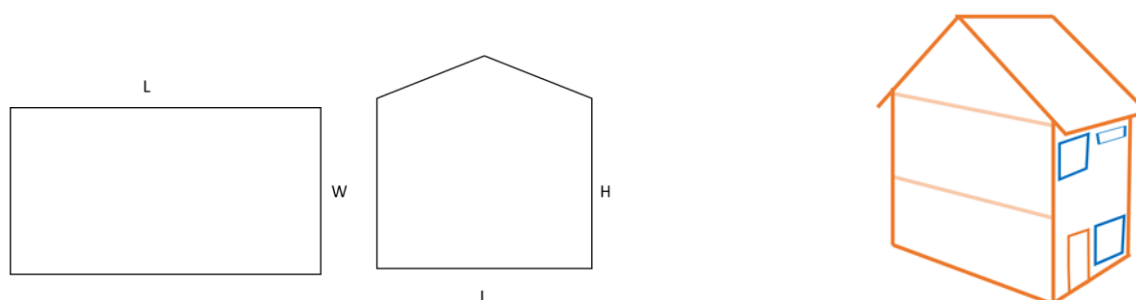


Figure 5.2.1.a Lay out overview

Abr.	Parameter	Measurement	Unit	Source
L	Length	10	[m]	Floor plan
W	Width	6	[m]	Floor plan
H	Height one floor	2,6	[m]	(NEN, 2022)
V	Volume(LxWx2H)	301	[m ³]	Factory Zero
S	Exact living area	115.80	[m ²]	Factory Zero

Table 4.2.1.a Measurements lay out case study

Type	U-Value	Unit	Source
Triple glass (Hr+++)	(0.5-0.9)	W/m ² K.	Residents pamphlet

Table 4.2.1.b Specifications windows case study

Type	U-Value	Unit	Source
Outer wall- brick (+layer of plaster) [5 cm]	45	W/m ² K.	https://papagreen.org/tools/isolatiewaarden-in-lambda-rden-u-van-250-materialen/
Insulation -sheepwool [18-35 cm]	(0.8)	W/m ² K.	https://www.duurzaamthuis.nl/verbouwen/passiefhuis
Inner wall plaster [2 cm]	16	W/m ² K.	https://papagreen.org/tools/isolatiewaarden-in-lambda-rden-u-van-250-materialen/

Table 4.2.1.c specifications walls case study

Installation

Like discussed in requirement 1.3 from the Lor, the reference model will need to include a HVAC system, therefore the installations specifications are discussed below.

The installation systems used for the houses are in a box on the outside of the houses, see figure 4.2.1.c *Installations case study*. The heat delivery is done by a radiant floor together with air and the mechanical ventilation has a Heat Recovery System (HRS). The distribution system uses waterpipes for the heating and vents for air. Finally the heat production is done with an air-water-heatpump and the electrical production is done with solar panels on top of the roof. For the full installation details see the full research *Factory_Zero January* of Cagnan et al. (2020).



Figure 4.2.1.b Case study (Architectuur punt, 2020)

1. Outside heat pump
2. Inside heat pump
3. Motherboard heat pump
4. Heat recovery system
5. Inverter
6. Intelligence box (*Intelligentie kast*)
7. Buffer tank

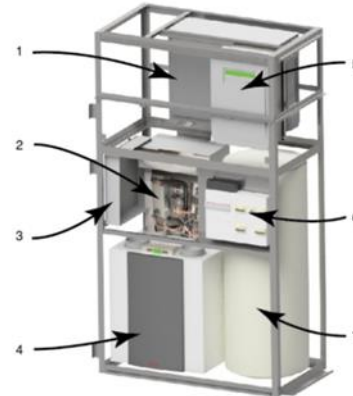


Figure 5.2.1.c Installations case study (Cagan et al., 2020)

The general specifications about the location, envelope and installation are known of this case study. Because these are the main aspects that will influence the energy load demand of the building (Tian et al., 2016), the available information on the case study is seen as a valid ground to make the reference model.

4.2.2 Reference model

This section describes the computer model that has been created from this case study referred to in this paper as the reference model. For a more detailed description of the model please see Appendix VII *Reference model description*.

This model needed to include the HVAC system, requirement 1.3 from LoR. Furthermore the LoR also required for easy parameter changes could be made in order to later create the variable models, requirement 1.7. Lastly the reference model needs to be verifiable and therefore the specification given in section , *Case study setup*, should be implemented into the reference model in its best ability.

Underneath in figure 4.2.2.a the outcome of the reference model can be seen in a schematic view. This model is derived from the Simplehouse model in the IDEAS library, this model is created by Micheal Wetter (appendix VI *SimpleHouse Modelica model*) and is a resistor capacitor (RC) based model . From this example the control and heating/cooling system have been adjusted, furthermore all the parameters have been set on the approximated values from the case study from section 4.2.1 , *Case study setup*.

In the schematic overview below the RC model is divided in four sub systems: Weather, Wall, Heating and Ventilation. Each of these systems will be shortly described below.

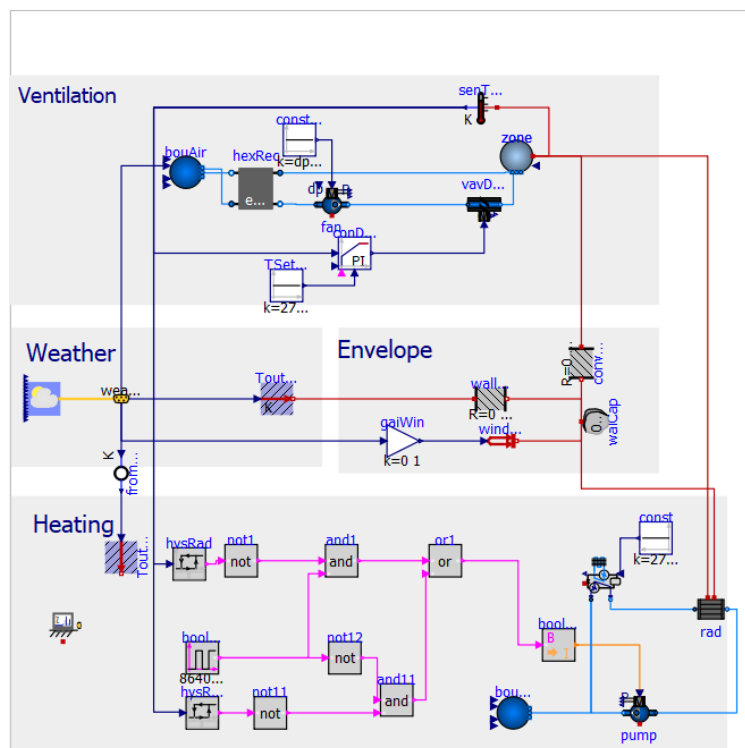


Figure 4.2.2.a Schematic overview reference model

Weather

Like mentioned in section 4.2.1 *Case study setup*, the available measuring data is from 2019 and the case study is located in Zoetermeer. In order to simulate the weather conditions of this year and location the weather data from Rotterdam in 2019 has been imported to the reference model. This being the closest weather station from the case study with the correct data from the KNMI.

In order to import the weather data from the KNMI, the data needed to be set into a specific format, this was done by processing the data using Excel and converting the file type, for the exact steps see appendix IV, *How-to Modelica weather file configuring*. This weather data imports the horizontal solar radiation and outside temperature.

Envelope

The envelope is a simple 2 resistor 1 capacitor model, within this model the R_c value of the case-study are imported together with the measurements and estimated thermal mass of the walls from a typical NZEB type of house (Passive House Institute, n/a). Furthermore the windows are also added in the envelope and to consider the influence of the solar radiation.

Heating

The water-air heat pump has a heating capacity of 5000 kWh, equal to the case study (Cagan et al., 2020). The heat pump is connected to a radiator to simulate the floor heating from the case study. Furthermore it is also attached to a thermostat, when looking at the case study's user behavior, it was noticed that the temperature of the houses does not switch during the night. This is likely the case because of the good insulation of the houses. The thermostat is still added in the reference model because it allows the model to simulate the reaction to a penalty signal, see requirement 1.8 from the LoR.

Ventilation

Just like the case study, the model includes a HRS in the ventilation system.

When taking a look at the LoR, the model is developed using the opensource Modelica software and thereby meets requirement 1.1 and 1.2. Adding to that the use of Modelica and its component based aspect makes the model easily changeable and thereby provides variable models to be easily created, meeting requirement 1.7. The model also includes its HVAC system and therefore meets requirement 1.3. Furthermore the possibility of triggering the reaction to a penalty signal is included meeting requirement 1.8. In order to meet the requirement that the reference model will need to be verifiable the data of the case study can be used because of the high similarities between the case study and model, this can be read in the next section.

4.2.3 Verification

Like discussed in the previous section 4.2.2 *Reference Model*, the model has been created with the goal of being a computer model of the case study. This is done by making a RC model that has a high similarity to the setup of the case study: Installations, weather inputs, measurements etc.. Though in order to use the reference model for the flexibility measurement this Modelica reference model firstly needs to be verified as sufficiently comparable to the case study.

The verification of the model is challenging because of the differences between the Modelica model and the case study. For example a difference of the model compared to the case study is that the model has been simulated as a free standing house, compared to the row houses in the case study. This is expected to result in more energy usage, because the delta T will be higher for the sides of the building. Furthermore the model does not take internal gains into account nor the user behavior considering open windows and water usage, therefore the model and data are not expected to be exactly the same.

In order to determine if the model can be used as an example for the type of case study a couple of output comparisons were made. These are done for the following aspects:

- Outside conditions
The data of Factory zero that is used is coming from the year 2019, in order to make a valid comparison the same weather conditions needed to be implemented in the model, especially to see the same graph behavior.
- Indoor climate temperature
By analyzing the indoor climate of the model compared to the data the behavior of the full building can be analyzed.
- Installations
The model's system contains a ventilation unit and a heat pump these two components shape the main installation. Because the heat pump is expected to take on the largest energy consumption in the system and fluctuate the most as well. For this reason, the heat pump was analyzed thorough for the verification.

Outdoor conditions

In the model only the solar radiation and temperature of 2019 are taken into account. This is still seen as viable because these are the two variables that have the most influence on the thermal energy use of a house (Morgan & de Dear, 2003), in reality there are more weather influences on the building, like: wind, rain, frost and snow.

Underneath the outside temperature data from the model and the measured data from the case study are illustrated in graph 4.2.3.a.

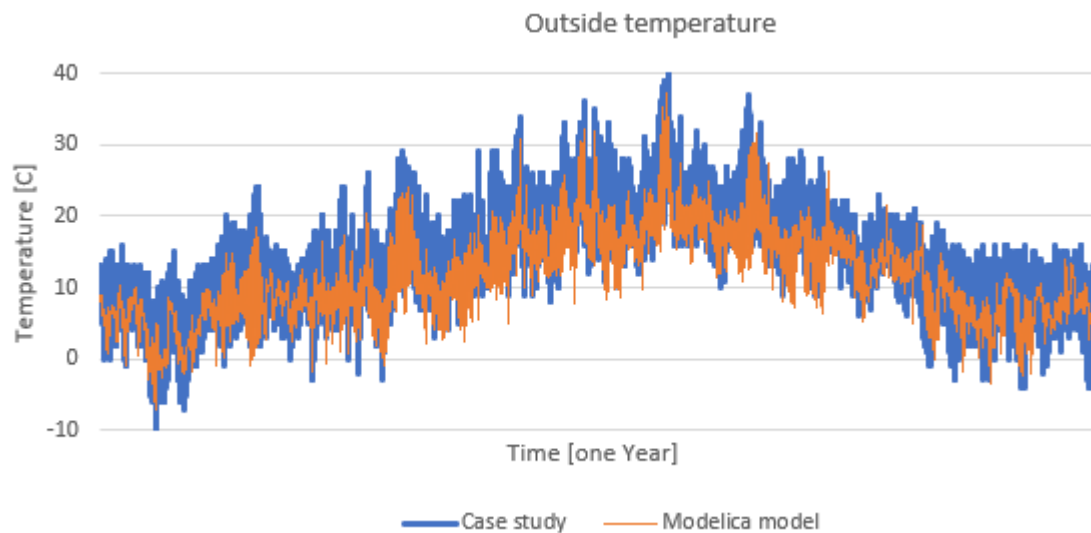


Figure 4.2.3.a. Outside temperature comparison

When looking at the temperature trend with a critical eye, we see that the Modelica model seems to be slightly below the temperature of the case study. This could have to do with where the measurement was taken. The outside temperature of the case study is measured at the HVAC unit that is placed outside the house, but in the middle of a neighborhood. While the data used in the reference model is taken from the records of the nearest KNMI station. Furthermore the difference of the sensor being located in the middle of the city which is generally warmer than its outskirts where the KNMI station is placed will also be of influence. Lastly the accuracy of the sensor near the HVAC system is not known, neither if the measurement could get some influence from the functioning of the equipment close to the sensor. Though since the line in which the temperature continues is certainly similar it is accepted for the model. However, it is expected that the energy consumption in the model will be slightly higher because of this difference.

Indoor climate temperature 2019

In total the data of 120 case-study houses was available. To analyze the indoor climate of the Modelica model this has been compared to the behavior of three of the case-study houses. These houses have been selected on their average energy consumption from Cagan et al. (2020). These are houses 007,055, and 071. It is important to note that these are not house numbers, but are randomized tags assigned to the houses due to privacy.

Case-study data

House 007

Desired temperature : 20-22 [C]

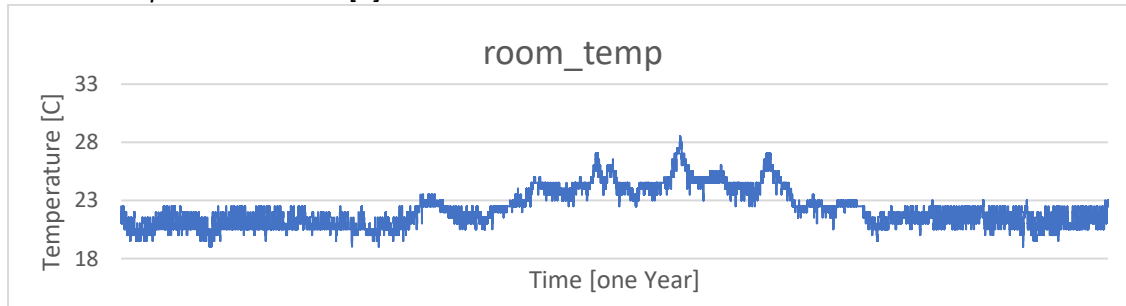


Figure 4.2.3.b Indoor climate house 007

House 055

Desired temperature : 21.5-22 [C]

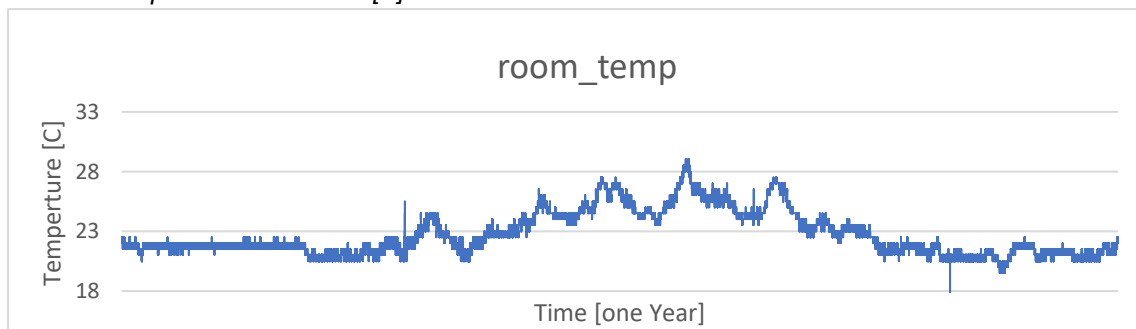


Figure 4.2.3.c Indoor climate house 055

House 071

Desired temperature : 19.5-20.5 [C]

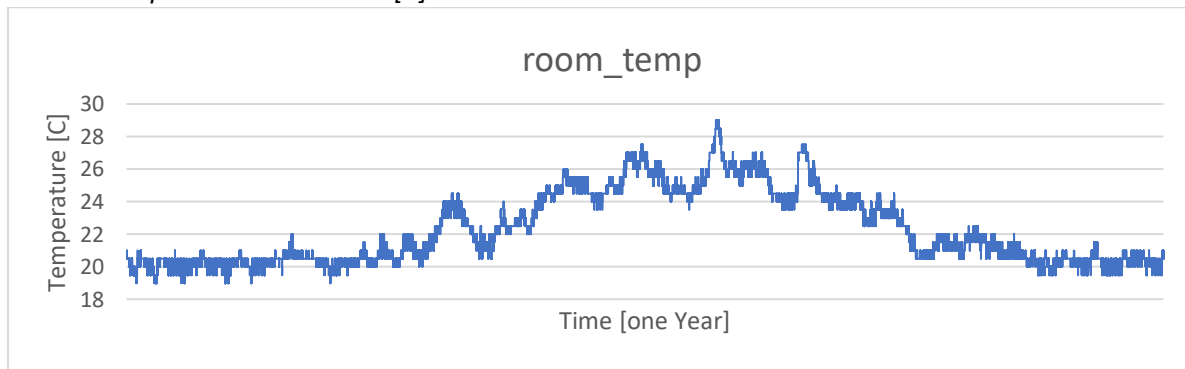


Figure 4.2.3.d Indoor climate house 071

Modelica model data

Desired temperature 20-22 [C]

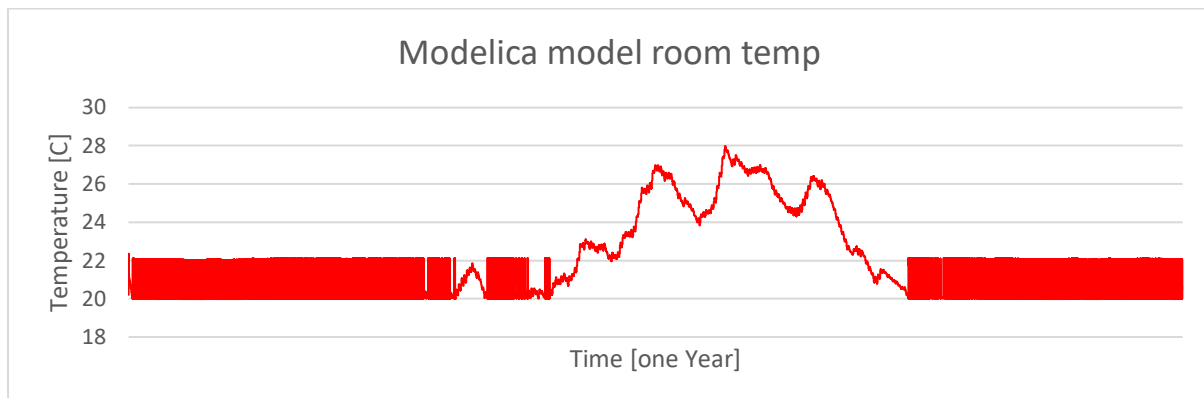


Figure 4.2.3.e Indoor climate house Reference model

Comparison indoor temperature

When looking at the overall line of the indoor temperature we see that in the three houses the temperature in the spring and summer exceeds the set temperatures in the houses because there is no cooling system. In the Modelica reference model we see a similar pattern, though this period seems to be slightly slimmer in the case study houses. This could have to do with the model being a free standing house, or because the model has no internal heat gains.

Furthermore the three houses and Modelica model have their maximum temperature around 28 degrees Celsius. Slight differences could be caused by user behavior like opening a window or the internal gains of appliances and occupants.

Heat pump behavior

In total the data of 120 case-study houses was available. To analyze the Heat pump behavior of the Modelica model this has been compared to the behavior of number 007 of the case-study houses. This house has been chosen for two main reasons. Because of its energy consumption and because the desired user's temperature between 20-22 degrees Celsius (Cagan et al.,2020). Furthermore the consumption of the heat pump has only been analyzed for heating and not for water usage.

Case-study data-Yearly

House 007

Yearly consumption heat pump due to heating 1190 kWh/year

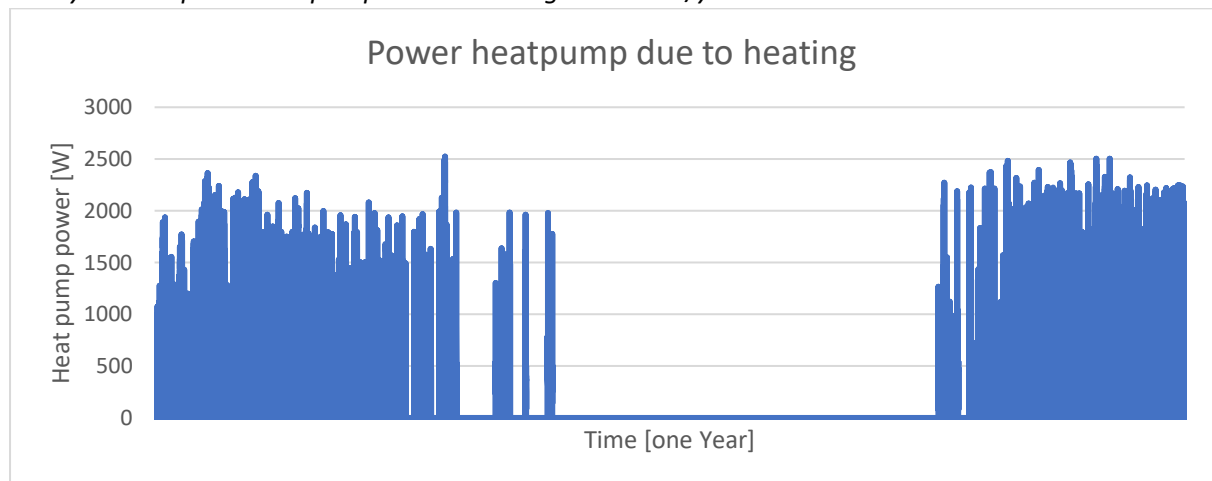


Figure 4.2.3.f Yearly heat pump consumption house 007 case study

Modelica model data-Yearly

Yearly consumption heat pump due to heating 1506 kWh/year

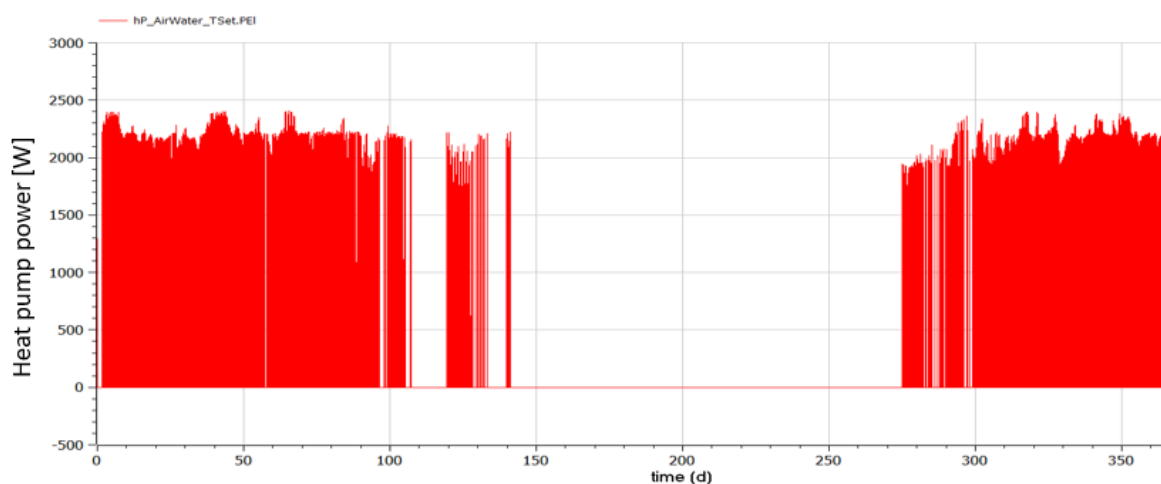


Figure 4.2.3.g Yearly heat pump consumption Reference model

Case-study data-Daily

Next to the yearly consumption there was also looked at the daily heat-pump behavior. The day that was analyzed was the 31 of January due to this being a day where the CO₂ levels of the house where low to moderate, this was chosen to limit the influence of the internal gains.

House 007

Energy consumption from 15th may. till heat pump due to heating 6.17 [kWh]

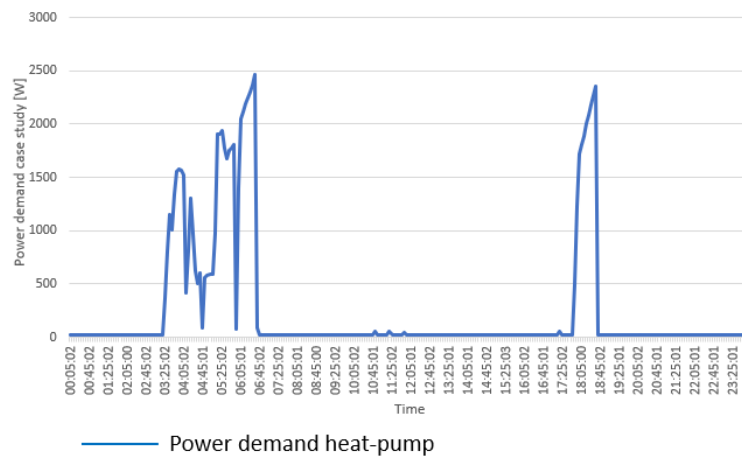


Figure 4.2.3 h Daily heat pump energy consumption 007

Modelica model data-Daily

Energy consumption 15th may heat pump due to heating 5.32[kWh]

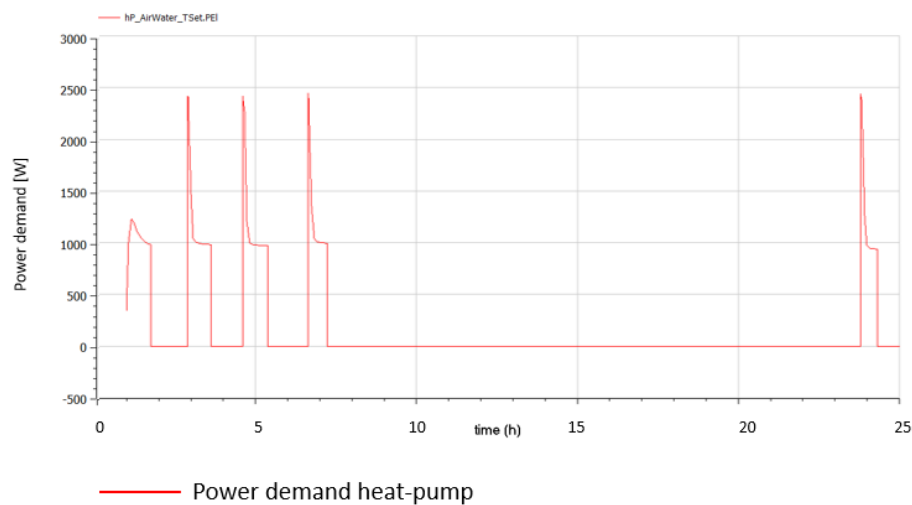


Figure 4.2.3 l Daily heat pump energy consumption reference model

Comparison Heat pump behavior

The yearly consumption of the Modelica model differs ($1506/1190 = 1.266$) 27% from the case study house, although this is a substantial difference, the behavior pattern of the Modelica model compared to the case study do align. The difference could be explained by the row house case study versus the free standing Modelica model, internal gains difference, weather data, orientation of the house or the user behavior. When comparing the heat pump behavior in a cold period this difference is minimized to ($5.32/6.17 = 0.83$) 14% or 0.85 kWh, this is less energy than one on and off cycle of the heat pump. This is why this deviation is considered acceptable.

Discussion Verification

When looking at the case study houses you can see the temperature during the summer in both outputs are at its peak around the 28 degrees Celsius. Furthermore the overall Indoor temperature graphs also follow the same trend. When we look at the heat pump we also see that the graphs follow the same trend. Though the model also shows differences from the data such as the yearly heat pump energy usage. This aligns with the hypotheses in the introduction considering the row house versus a free standing house, though the indoor gains could give the same argumentation the other way around.

The computer model has the same energy use trend as the measured case study. The differences can be explained by the computer model configuration (free standing house instead of row house) and the lack of internal heat gains. Therefore the model is well suited to test the changes on energy use of different alternative set-ups as is intended in this study.

4.3 Energy flexibility model configurations and outputs

As has been stated in chapter 3 *Methodology*, a computer model of a case study should be created to generate the load curve of different building configurations in order to evaluate the energy flexibility of a building. These building configurations were created by adjusting variables within the Reference model. These variable are chosen because they influence the parameters discussed in section 2.6 *Parameters*.

To quickly summarize section 2.6: When analyzing these parameters from the sensitivity chart from the research of Junker et al. (2019), three parameters were derived as being most relevant for this case study. Therefore these three parameters are analyzed: insulation, thermal inertia and the control. This has resulted in three flexible models, each with one variable adjustment from the Reference model.

Parameter	Adjustment variable from Reference model
Insulation	Rc_value
Thermal inertia	Wall thickness (brick)
Control	Pre heating

Table 4.3.1 Parameters

Like also stated in chapter 3 *Methodology*, the energy loads of the Reference model will need to be compared to the load of the flexible model. Using this comparison the flexibility measuring KPI's described in section 2.4 *Measuring methods of energy flexibility*, can be conducted.

To quickly summarize section 2.4: For these flexibility measuring KPI's please see figure 4.3.1 KPI's. Mentionable is that the initiation time is not taken into consideration following this research due to it not being implemented into the reference model. Because the flexibility graph is still on the neutral line during the initiation time this is expected to not have major influence on the results.

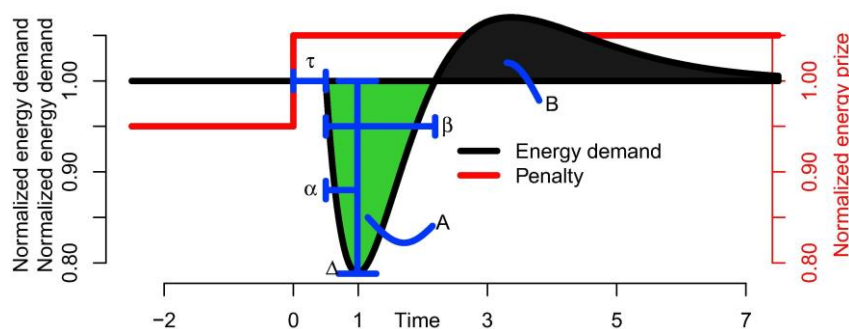


Figure 4.3.1 KPI's (Junker et al., 2018)

KPI	Ab.	Explanation	Unit
Initiation time	τ	The time from the penalty signal to action start.	s
Duration time	β	The duration of the response.	s
Duration peak time	α	The duration of the response till highest energy shift	s
Shifted energy capacity	A	The shifted amount of energy after initiation	kWh
Rebound effect	B	the rebound effect for returning the situation back to the "reference".	kWh
Maximum energy change	Δ	The maximum change in demand following the penalty signal.	W

Table 14.3.2 KPI's explanation

4.3.1 Flexible model configurations

In this section the setup of the flexible model simulation is discussed. Depending on which parameter has been tested the setup of the simulation can slightly vary. This has to do with requirement 1.5 from the LoR, because the RT energy load needs to be exported after the simulation and the simulation length might differ because of different reactions to the penalty signal.

Insulation

Changed parameter

In order to analyze the influence of insulation, the R_{c_value} of the reference model was changed from 5 to 7 [$m^2 \cdot K/W$].

Weather conditions

For the weather conditions a worst case scenario has been applied for the simulation setup. This was a day where the outside weather was -10 degrees Celsius and there was no sun that day. This particular day was chosen because it will be the scenario the design will be most challenging concerning its energy load.

Penalty signal

The penalty signal is implemented in the model by lowering the thermostat in the beginning of the simulation. The system will lower its energy consumption until the user requirement is no longer met and the system will regenerate.

Timeframe

In total a period of 14 hours was looked at to simulate a morning from 08:00 AM till 22:00 PM. This is done to enable the rebound effect of the flexible model in respect to the reference model.

Hypothesis

Because the insulation property makes the transmission of heat to the outside more difficult, it is expected that the better-insulated model will retain its heat better and therefore to give a long response to the penalty signal. Furthermore, the extra insulation is not expected to cause a higher rebound effect on the energy load than the initial shifted energy load. When taking a look at the temperature comparison below in figure 4.3.1.a of the reference model (red line) and flexible model (blue line) we already see this hypothesis partly confirmed. The flexible model cools slower than the reference model. Further analysis of the flexibility will be described in section 4.3.2 *Flexibility output*.

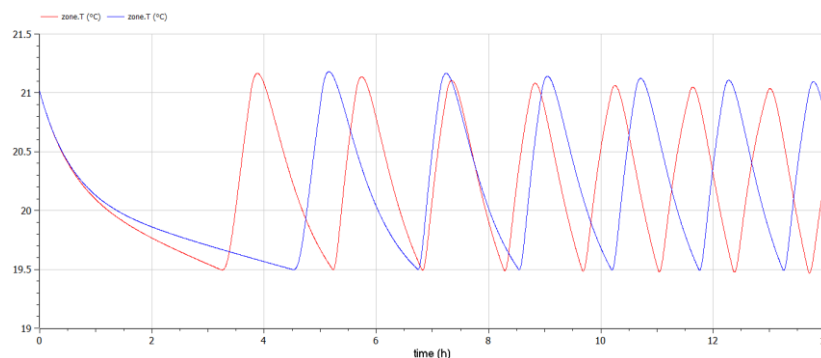


Table 4.3.1.a Temperature comparison reference- and flexible model Insulations

Thermal inertia – building envelope

Changed parameter

In order to analyze the influence of the thermal inertia, the mass of the walls was increased by increasing the thickness of the brick layer from 50 mm to 100 mm walls.

Weather conditions

For the weather conditions a worst case scenario has been applied for the simulation setup. This was a day where the outside weather was – 10 degrees Celsius and there was no sun that day. This particular day was chosen because it will be the scenario the design will be most challenging concerning its energy load.

Penalty signal

The penalty signal is implemented in the model by lowering the thermostat in the beginning of the simulation. The system will lower its energy consumption until the user requirement is no longer met and the system will regenerate.

Timeframe

In total a period of 14 hours was looked at to simulate a morning from 08:00 AM till 22:00 PM. This is done to enable the rebound effect of the flexible model in respect to the reference model.

Hypothesis

The additional thermal mass is expected to influence the response on the penalty signal because it will take longer for all this mass to cool down compared to the reference model. However, it is also expected that it will cost more energy to reheat this mass again, this is expected to be reflected in the rebound effect. When taking a look at the temperature comparison below in figure 4.3.1.b of the reference model (red line) and flexible model (blue line) we already see this hypothesis partly confirmed. The flexible model cools slower than the reference model. Further analysis of the flexibility will be described in section 4.3.2 *Flexibility output*.

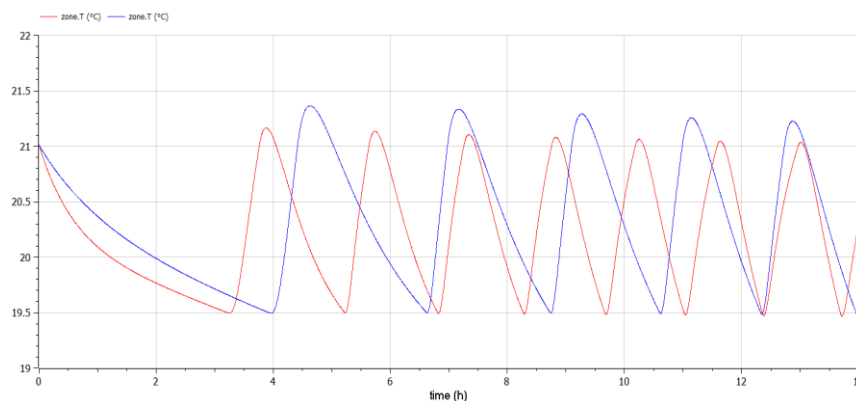


Table 4.3.1.b Temperature comparison reference- and flexible model Thermal Inertia

Control

Changed parameter

In order to analyze the influence of the control, a pre-heating signal was simulated. In this model the room was pre-heated during the night.

Weather conditions

For the weather conditions a worst case scenario has been applied for the simulation setup. This was a day where the outside weather was – 10 degrees Celsius and there was no sun that day. This particular day was chosen because it will be the scenario the design will be most challenging concerning its energy load.

Penalty signal

The penalty signal is implemented in the model by lowering the thermostat after 8.5 hours of the simulation. The system will lower its energy consumption until the user requirement is no longer met and the system will regenerate.

Timeframe

In total a period of 22 hours was looked at to simulate a morning from 00:00 AM till 22:00 PM. This is done to enable the rebound effect of the flexible model in respect to the reference model.

Hypotheses

Pre-heating the house is expected to influence the response on the penalty signal due to the higher thermal value, therefore the flexible model should take longer to cool down compared to the reference model. When taking a look at the temperature comparison below in figure 4.3.1.c of the reference model (red line) and flexible model (blue line) we already see this hypothesis partly confirmed. The flexible model cools slower than the reference model. Further analysis of the flexibility will be described in section 4.3.2 *Flexibility output*.

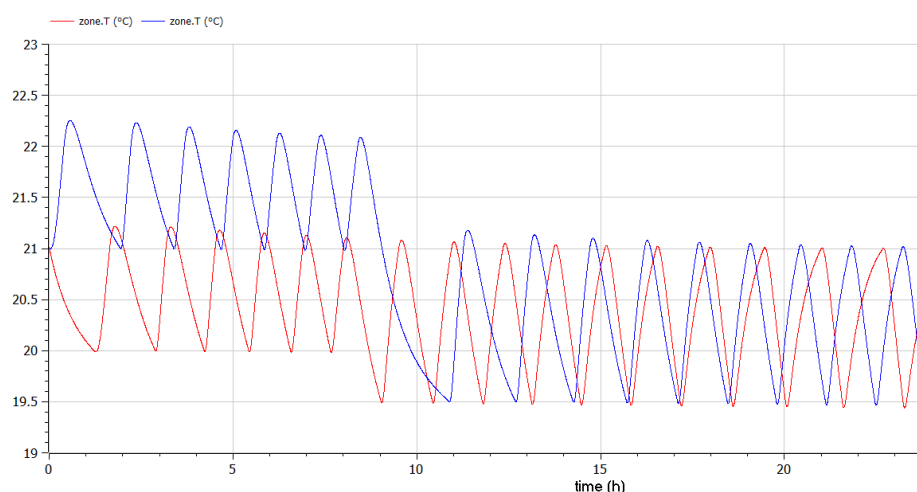


Table 4.3.1.c Temperature comparison reference- and flexible model Control

4.3.2. Flexibility output

From the reference model and variable "flexible" models the energy load data needed to be processed. The energy load produced with the different computer models has been exported to Excel to produce the comparison graphs. From this data the time and quantity of energy load could be displayed, to then create the comparison graphs. See figure 4.3.2.a *Data analysis* below.

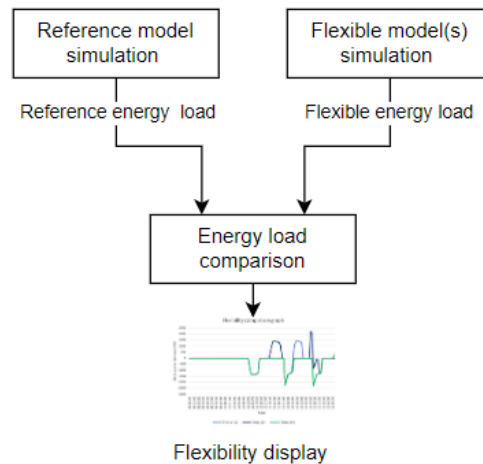


Figure 4.3.2.a. Data analysis

Data processing

1. The data of the energy load was exported from reference model and flexible model as a CSV file, this is done per 10 seconds to get accurate measuring points. Because the heat pump is fluctuating in demand, this energy load is most represented in the data.
2. This format could be opened in Excel as one list, which had to be reduced, cleaned and transformed in order to create lists of time-bound lists of the energy load.
3. Create delta flexibility line by subtracting the reference model energy load from the flexible model energy load.
4. Determine the flexibility KPI's to execute the energy flexibility measurement discussed in chapter 2.4 *Measuring methods of energy flexibility*.

This process is visualized below in figure 4.3.2.b. *Data processing*.

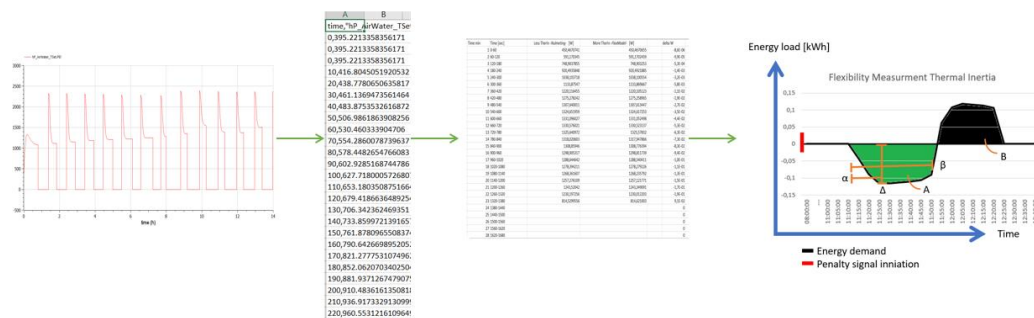


Figure 4.3.2.b. Data processing

Insulation

Firstly the energy load of the reference model and flexible model were plotted, see figure 4.3.2.a *Energy load insulation*. It is seen that at 11:05 the reference model will need to start its system again, compared to the flexible model that starts at 12:20. When subtracting the reference power demand from the flexible power demand this difference is even clearer. By zooming in on the period between the first initialization and the end of the rebound effect in the flexibility measurement (outlined in yellow), figure 4.3.2.a. *Flexibility graph insulation*, can be conducted. This period is chosen because it is seen that after 13:10 the power usage is again in its normalized pattern.

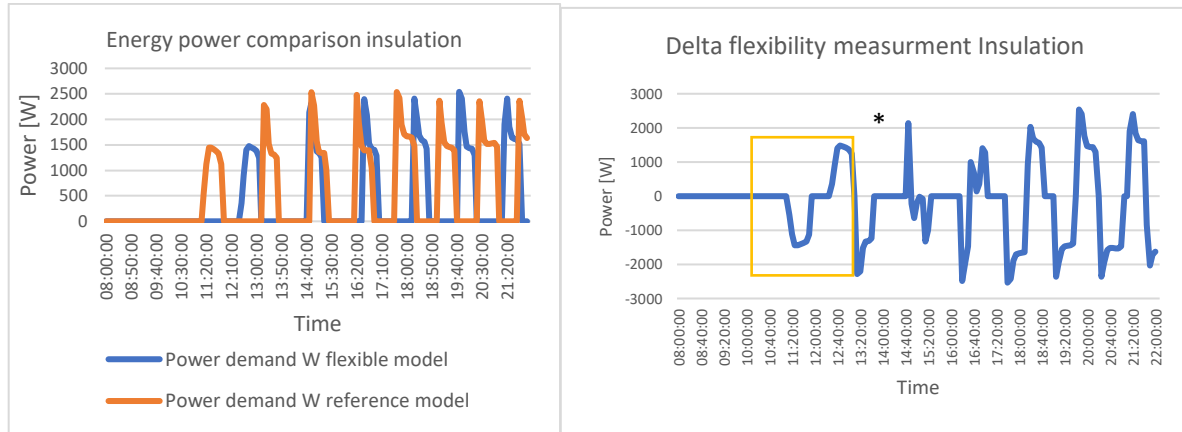


Figure 4.3.2.a Energy load insulation

When adding the energy load of the delta flexibility measurement until 11:55 the total amount of decrease could be determined (A). To determine the rebound effect the energy load after 12:20 until 13:10 was added (B).

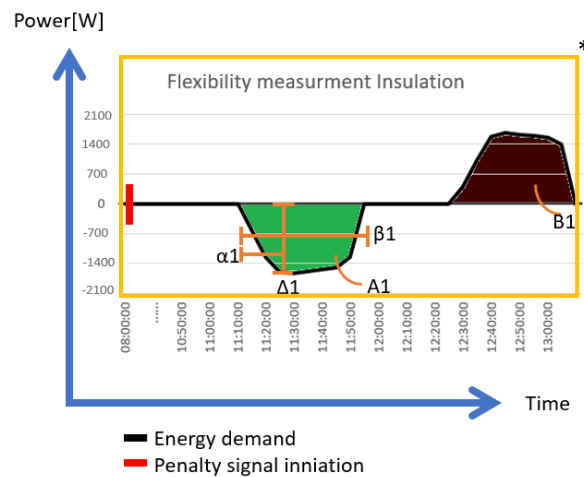


Figure 4.3.2.d Flexibility graph Insulation

KPI	Ab.	Value	Unit
Duration time	β	3000	s
Duration peak time	α	1200	s
Shifted energy load	A	-0.78	kWh
Rebound effect	B	0.77	kWh
Maximum energy change	Δ	-1488	W

Table 4.3.2.a Flexibility Insulation

Thermal Inertia

Firstly the energy load of the reference model and flexible model were plotted, see figure 4.3.2.c. *Energy load thermal inertia*. It is seen that at 11:10 the reference model will need to start its system again, compared to the flexible model that starts at 11:55. When subtracting the reference power demand from the flexible power demand this difference is even more clear. By zooming in on the period between the first initialization and the end of the rebound effect in the flexibility measurement (outlined in yellow), figure 4.3.2.c. *Flexibility graph thermal inertia*, can be conducted. This period is chosen because it is seen that after 12:25 the power usage is again in its normalized pattern.

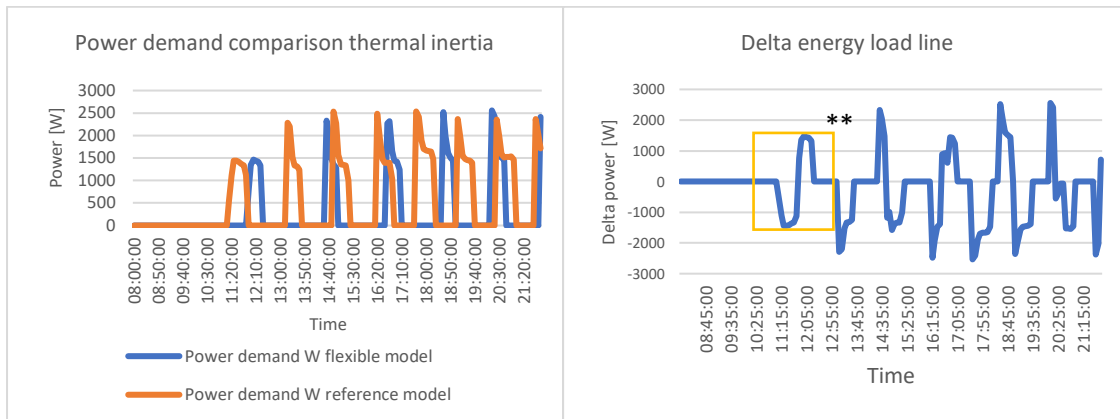


Figure. 4.3.2.c Energy load Thermal Inertia

When adding the energy load of the delta flexibility measurement until 11:50 the total amount of decrease could be determined (A). To determine the rebound effect the energy load after 11:50 until 12:25 was added (B).

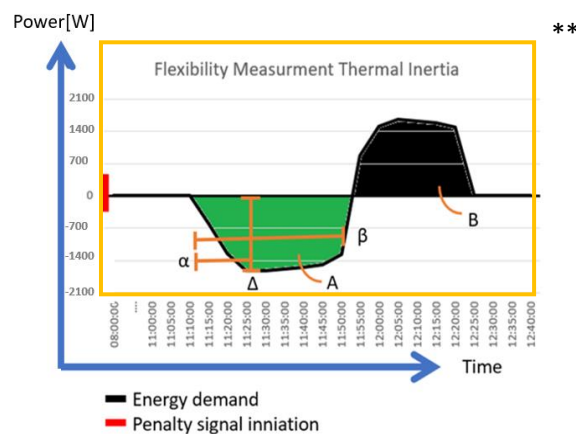


Figure. 4.3.2.d Flexibility graph Thermal Inertia

KPI	Ab.	Value	Unit
Duration time	β	2700	s
Duration peak time	α	1200	s
Shifted energy load	A	-0.77	kWh
Rebound effect	B	0.63	kWh
Maximum energy change	Δ	-1488	W

Table 4.3.2.b Flexibility Thermal Inertia

Control

Firstly, the power demand of the reference model and flexible model were plotted, see figure 4.3.2.e *Energy load control*. Like stated in chapter 4.2.3 *Flexibility model simulation*, the penalty signal is implemented at 08:00. In figure 4.3.2.e *Energy load control*, the delta flexibility line, it is seen that the reference model is active at 08:00 creating a negative line, though the flexible model only gets activated around 09:45. By zooming in on the period between the first initialization and the end of the rebound effect in the flexibility measurement (outlined in yellow), figure 4.3.2.b. *Flexibility graph control*, can be conducted. This period is chosen because it is seen that after 10:30 the power usage is again in its normalized pattern.

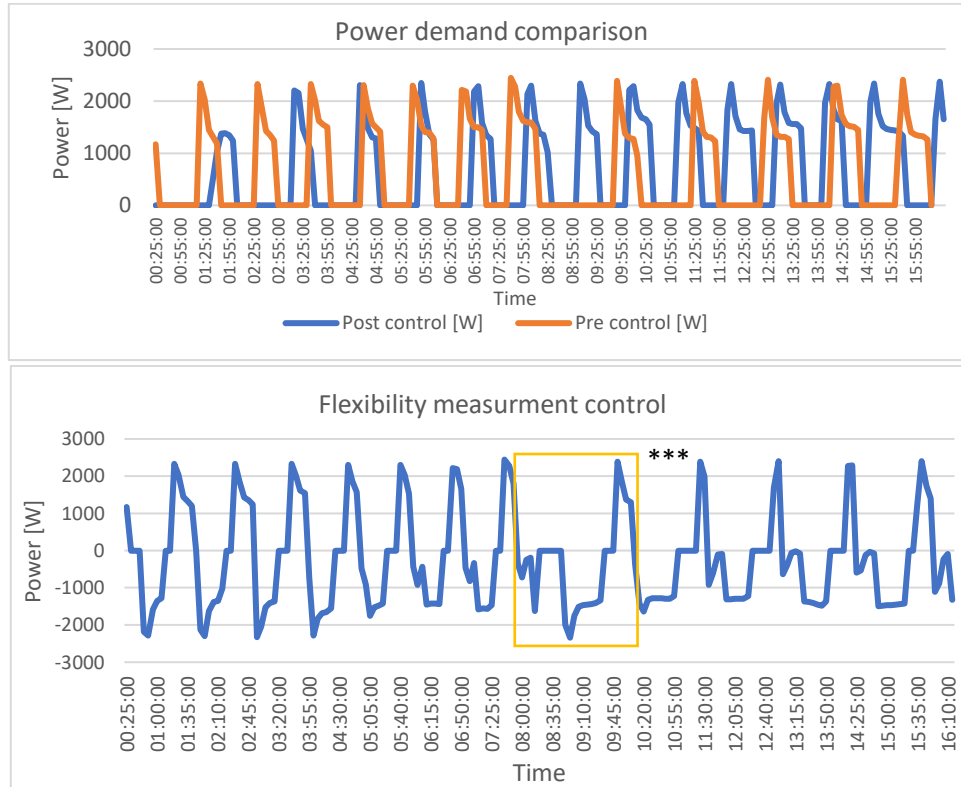


Figure 4.3.2.e Energy load Control

When adding the energy load of the delta flexibility measurement from 08:00 until 09:45, the total amount of decrease could be determined (A). To determine the rebound effect, the energy load to preheat the house was also evaluated. Thus for the rebound effect the delta energy load from 00:00 till 08:00 was added on top of the value from 9:45 until 10:30, to obtain the B value below.

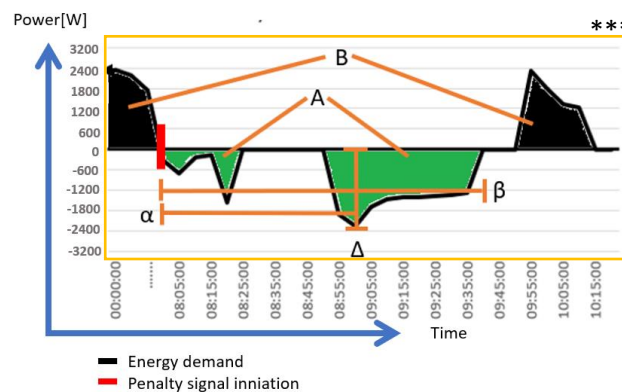


Figure 4.3.2.f Flexibility graph Control

KPI	Ab.	Value	Unit
Duration time	β	6300	s
Duration peak time	α	3600	s
Shifted energy load	A	-1.8	kWh
Rebound effect	B	6.5	kWh
Maximum energy change	Δ	-2420 W	W

Table 4.3.2.c Flexibility Thermal Inertia

4.3.3. Interpretation advice

In order to add value to the designer's choices, the way the output of section 4.3.2. is interpreted/used is of big influence. In this stage the output of the model is applicable for three types of uses that can help a designer make a design decision to increase a building's energy flexibility. These are further described in this section.

- Single variable graph
- Multiple variable graph
- Adjusted variable value graph

Single variable graph

In the last section (4.3.2. *Flexibility output*) one parameter change is repeatedly analyzed on which the change in flexibility is visualized in a graph as figure 4.3.3.a *Single variable graph*, below. This method can be used to verify a variable change, such as the influence of a material. Does this change effect the energy flexibility and if so, do we want to change the material in the design?

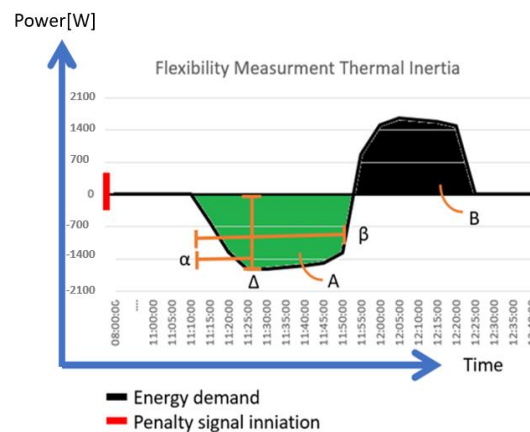


Figure 4.3.3.a Single variable graph

Multiple variable graph

It is also possible to compare the three variables from before, so the designer can view where the biggest impact will be considering in the design choices, if one wants to increase the energy flexibility of the building. By comparing the graphs together with the requirements of the building the biggest impact can be determined concerning the energy flexibility, see figure 4.3.3.b *Multiple variable graphs*.

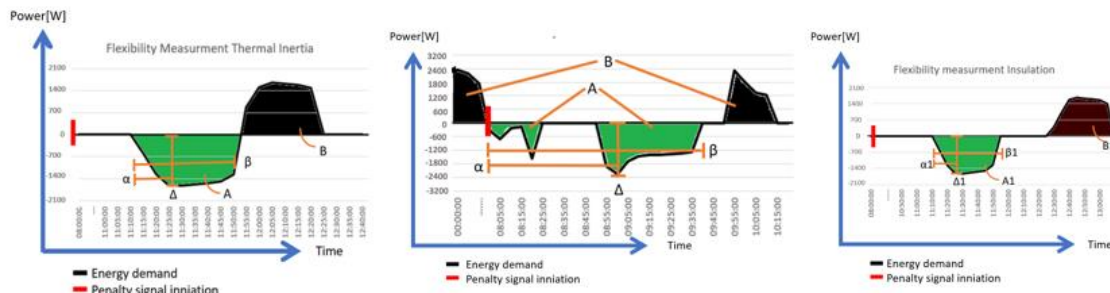


Figure 4.3.3.b Multiple variable graphs

Adjusted variable value graph

In order to see how a certain variable evolves while changing its value, multiple values of this one variable can be compared. In the graph of figure 4.3.3.c *Adjusted variable value graph*, one can see that the thickness does not influence the peak time (α) though it does in the duration time (β), therefore this can be considered in order to chosen the thickness of a certain material in the wall or floor.

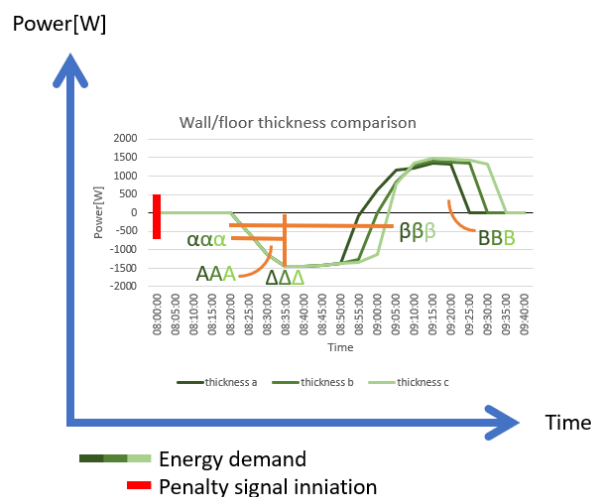


Figure 4.3.3.c Adjusted variable value graph

Together these interpretation possibilities answer the last-sub question in this report: 'How can the energy flexibility of a building be interpreted to help make control and design choices of a building on the subject of energy flexibility?'.

4.4 Future applicability

In order to conduct flexibility graphs like discussed in the previous sections, there firstly needs to be a tool or option to select a reference model comparable to the case the designer is working on. ideally this reference model can be chosen in the situation of a renovation or new construction.

To create a computer model per case will likely too be costly and time consuming for a tool that is ideally used in the R&D phase of the design process. Therefore standardized reference models with adjustable parameters could provide a solution. Ideally this reference model can be adjusted in a user-friendly way, likely by choosing an option from a menu. The energy flexibility graph could be specified as an infographic. These standardized models will be specified by the type of building and its used function, such as: NZEB residential home, eighties office building, fifties residential house, etc.. From this standardized model the measurements can then be changed and possibly other parameters of the building, to better compare to the designer's case. Using this as the reference model now gives the designer the ability to select different parameters and analyze their influence on the energy flexibility.

Ideally this reference model can be conducted by using a user friendly format, likely by choosing an option from a menu. The energy flexibility graph could be shown as an infographic, see figure 4.4.1 *Infographic example*. In this example the thickness of a wall can be adjusted using a slider which then gives the values of the flexibility KPI's.

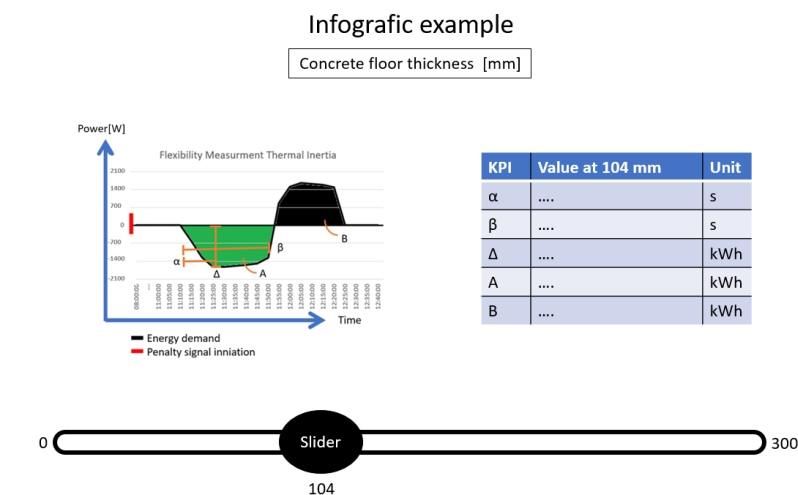


Figure 4.3.4.a Infographic example

Materials could be analyzed using this tool, such as the option between a wooden floorbase or concrete floorbase. The trend of building with wood is in full swing (Antonnen, 2015), this because of its advantage of storing CO₂ in the material. The usage of wood can have more effects on the behavior of the building because wood is much lighter than a material such as concrete, this might affect the energy flexibility due to the difference in density. This hypothesis could be analyzed using this method, and thereby be used as an advisory tool while designing to increase energy flexibility in a building. Furthermore in the future a way of certification surrounding the flexibility measurement could be added similar to BREEAM or MGP, both providing sustainability certifications for buildings.

When reflecting back on the main research question : ‘How can a Modelica computer model be used to shape an advice on a buildings *Energy Flexibility* to help control engineers and designers make control and design choices on this subject?’ the flexibility graphs have been sufficiently created using the method proposed in this report. Furthermore its ways of being interpreted have also been analyzed and determined to have an advisory role on design chosen when focusing on increasing the energy flexibility of a building.

5. Conclusion and recommendations

This chapter reflects on the research questions that were discussed in chapter 1 *Introduction*. The main research question of this research being: ‘How can a Modelica computer model be used to shape an advice on a buildings *Energy Flexibility* to help control engineers and designers make control and design choices on this subject?’. Furthermore there will also be reflected on the competence and company goals mentioned in chapter 1 *Introduction*.

In the first chapter *State-of-the-art Energy flexibility in buildings*, of this report a literature review was performed. In this chapter the problem is analyzed and brought into perspective. Furthermore the reference papers from the literature review provided several key insights and answered the first research sub-question: ‘How can energy flexibility in buildings be measured?’. After the literature review the LoR could be acquired which was used to verify the progress within this research. The lessons learned together with the LoR from the literature review helped to shape chapter 3 *Methodology*. This chapter suggested a methodology that could be followed in order to answer the main research question.

In order to verify the suggested methodology, it was tested in chapter 4 *Implementation methodology on a case study*. In this chapter a reference model was created of a case study. This model was created using the Modelica programming language and in this chapter the sub-question: ‘How can the methodology of Modelica software be applied?’ was answered. Furthermore three variable configurations of the reference model were made in order to create the energy flexibility graphs. Finally the different ways of applying and interpreting these flexibility graphs were discussed and thereby answered the last sub-question: ‘How can the energy flexibility of a building be interpreted to help make control and design choices of a building on the subject of energy flexibility?’.

All taken steps have been backed up with reliable references during the development of the methodology. Furthermore the method was used for configurations of the reference model in order to create the energy flexibility graphs. Lastly its ways of being interpreted have also been analyzed and determined to have an advisory role on design choices when focusing on increasing the energy flexibility of a building. Thereby this methodology answers the main research question from this report.

A relevant aspect that should be looked into in further research is the initiation time, due to this not being added into the reference model. It is unclear if the initiation time will be a constant or dependable variable on the other systems. It also should be noted that the case study used to create the reference model only covered one type of building. For recommendation different types of buildings could be analyzed using the same method suggested in this report, in order to do a sensitivity analysis on how applicable the methodology is per case type. This will strengthen the verification of the methodology.

From this recommendation follow the suggestions from section 4.4 *Future applications*, for standardized reference models that could be conducted by using a user friendly format, likely by choosing an option from a menu. A follow-up research is recommended to explore the possibility of having a tool related to a sustainability certification method similar to BREEAM or MGP. By doing so the value of a standardized flexibility measuring tool can be further justified.

Company goal conclusion

The goal of the company was for this research to propose a method to produce design and control advice to increase building energy flexibility based on open-source computer simulations, preverbally using Modelica software. Like assessed in the conclusion above this goal has been met. Next to this main goal the deliveries the company expected are concluded below.

Deliverable set by research group EiT	Result
Adjusted Plan of approach (week 2)	Because of the requirements from THUAS the PoA already had a first draft. Before week 2 a revised version was discussed with my supervisor from the company and therefore this deliverable was met.
Simulation models	This research has been executed by creating digital simulation models of a case study. All simulation models were shared and explained in the Teams environment. Therefore this deliverable has been met.
Scientific paper	The scientific paper written for this assignment can be found in appendix VII. This paper has not yet been finished due to the size of the project, mainly the steep learning curve from the Modelica language played a big part in this delay. Because the majority of the paper is already written and will be finished by me together with Dr.Ir. Salcedo Rahola, the deliverable is expected to be finished at the end of June.
Progress board monitoring ability	During the internship there was made use of a Trello board using the heads: planned, doing, finished and archived. Therefore this deliverable has been met.
Organized documentation in Teams	All useful documents have been placed and ordered in the B4B Teams group. Therefore this deliverable has been met.
A1 poster to sell the project	The poster created can be found in appendix VI. This has been discussed with my company supervisor Dr.Ir. Salcedo Rahola.
Powerpoint end assessment	A presentation was given to the B4B WP2 group. The final presentation will be done on the 20 th of June, and therefore will be delivered at the end of this internship.

Table 5.1 Company goal conclusions

Competence goal conclusion

This research has been found as complex due to its many components and its information flow being relatively young. Furthermore the usage of Modelica required a high amount of independence, due to no other colleges working in this environment and little available learning tools. Overall the competences goals discussed have been met, for the full competence analyzes please see appendix IX.

Competence	Current level	Goal level	Examples of activities done to achieve the competence goals
Analyzing	3	3	I performed a problem analysis and defined the measurement methodology based on previous research. Furthermore a verification of the reference model was done by analyzing the available data in respect to the reference model.
Designing	3	3	Designing a code and attached model that fits the set requirements of the project, using Modelica.
Researching	2	2	A thorough literature review was performed.
Professionalizing	2	2 or 3	Writing a scientific paper, furthermore taking an overall professional attitude while making contacts, like with KU Leuven in order to have supporting contacts while developing the Modelica model.

Table 5.2 Competence goals

References

- Annex 67. (2018). *What is Annex 67?* EBC Annex 67. Retrieved 30 May 2022, from <https://www.annex67.org/about-annex-67/>
- Annex 82. (2022). *EBC Annex 82*. Retrieved 30 May 2022, from <https://annex82.iea-ebc.org/about>
- Antonnen, N. (2015). *REVIEW OF WOOD-BASED CONSTRUCTION AND ARCHITECTURE - TECHNOLOGY, STATUS AND TRENDS*. <https://www.dasos.fi/wp-content/uploads/2019/10/Dasos-report-Wood-based-Construction-and-Architecture-2015.pdf>
- ArchitectuurPunt Zoetermeer. (2020, August 19). *Nul Op de Meter renovatie Palenstein - nominatie Gemma Smid Architectuurprijs 2020*. Retrieved 3 May 2022, from <https://www.architectuurpuntzoetermeer.nl/nul-op-de-meter-palenstein-nominatie-gemma-smid-architectuurprijs-2020/>
- Berkeley Lab. (2022). *Modelica Buildings library*. Modelica Buildings Library. Retrieved 3 May 2022, from <https://simulationresearch.lbl.gov/modelica/>
- Brains4buildings. (2021, May). *Brains for Buildings*. Retrieved from Brains for Buildings: <https://brains4buildings.org/>
- Denholm, Paul, en Maureen Hand. 'Grid Flexibility and Storage Required to Achieve Very High Penetration of Variable Renewable Electricity'. *Energy Policy* 39, nr. 3 (maart 2011): 1817–30. <https://doi.org/10.1016/j.enpol.2011.01.019>.
- DGW. (2018, December). *Nul op de Meter*. Retrieved 14 February 2022, from <https://www.dgw.nl/nul-op-de-meter>
- Dyck-Madsen, Søren. 'Visions for Application of Energy Flexible Buildings in Denmark Or', z.d., 21.
- IBPSA. (2022). *GitHub - ibpsa/modelica-ibpsa: Modelica library for building and district energy systems developed within IBPSA Project 1*. GitHub. Retrieved 3 May 2022, from <https://github.com/ibpsa/modelica-ibpsa>
- IEA EBC. (2018). *IEA EBC Annex 60*. Retrieved 29 May 2022, from <https://www.iea-annex60.org/>
- IEA EBC. (n.d.). *International Energy Agency's Energy in Buildings and Communities Programme // IEA EBC*. EBC. Retrieved 30 May 2022, from <https://www.iea-ebc.org/>
- Ise, Fraunhofer. 'Examples of Energy Flexibility in Buildings', z.d., 7.
- Jensen, Søren Østergaard. 'Energy Flexible Buildings', z.d., 16.
- Jensen, Søren Østergaard, Anna Marszal-Pomianowska, Roberto Lollini, Wilmer Pasut, Armin Knotzer, Peter Engelmann, Anne Stafford, en Glenn Reynders. 'IEA EBC Annex 67 Energy Flexible Buildings'. *Energy and Buildings* 155 (november 2017): 25–34. <https://doi.org/10.1016/j.enbuild.2017.08.044>.
- Jensen, S. Ø. (2016, May). *Energy Flexible Buildings*. IBC Annex 67. https://www.annex67.org/media/1057/ebc_annex_67_annex_text.pdf
- Jensen, S. S., Marszal-Pomianowska, A., Lollini, R., Pasut, W., Knotzer, A., Engelmann, P., Stafford, A., & Reynders, G. (2017). IEA EBC Annex 67 Energy Flexible Buildings. *Energy and Buildings*, 155, 25–34. <https://doi.org/10.1016/j.enbuild.2017.08.044>
- Jorissen, Filip. 'Toolchain for Optimal Control and Design of Energy Systems in Buildings', z.d., 344.
- Junker, Rune Grønborg, Armin Ghasem Azar, Rui Amaral Lopes, Karen Byskov Lindberg, Glenn Reynders, Rishi Relan, en Henrik Madsen. 'Characterizing the Energy Flexibility of Buildings and Districts'. *Applied Energy* 225 (september 2018): 175–82. <https://doi.org/10.1016/j.apenergy.2018.05.037>.
- KU Leuven. (2022). *GitHub - open-ideas/IDEAS: Modelica library allowing simultaneous transient simulation of thermal and electrical systems at both building and feeder level*. GitHub. Retrieved 3 May 2022, from <https://github.com/open-ideas/IDEAS>
- Laughman, Christopher R., Scott A. Bortoff, en Hongtao Qiao. 'Modeling and Coordinated Control of an Air-Source Heat Pump and Hydronic Radiant Heating System', 77–85, 2019. <https://doi.org/10.3384/ecp1814877>.
- Lectureship, L. E. (2020). *Lectureship Energy in Transition*. Retrieved from The Hague university of applied sciences: <https://www.dehaagsehogeschool.nl/onderzoek/lectoraten/details/energy-in-transition#over-het-lectoraat>
- Li, Han, Zhe Wang, Tianzhen Hong, en Mary Ann Piette. 'Energy Flexibility of Residential Buildings: A Systematic Review of Characterization and Quantification Methods and

- Applications'. *Advances in Applied Energy* 3 (augustus 2021): 100054.
<https://doi.org/10.1016/j.adapen.2021.100054>.
- Ma, Zheng, en Jim Parker. 'Stakeholders' Perspectives on Energy Flexible Buildings', 2019, 10.
- Marotta, Ilaria, Francesco Guarino, Maurizio Cellura, en Sonia Longo. 'Investigation of Design Strategies and Quantification of Energy Flexibility in Buildings: A Case-Study in Southern Italy'. *Journal of Building Engineering* 41 (september 2021): 102392.
<https://doi.org/10.1016/j.jobbe.2021.102392>.
- Marszal-Pomianowska, Anna Joanna, Energy in Buildings and Communities Programme, en Teknologisk Institut Annex 67 Energy Flexible Buildings Technology Collaboration Programme. *Characterization of Energy Flexibility in Buildings*. Taastrup: Danish Technological Institute, 2019.
- Modelica (n.d.), openModelica, IBPSA. Retrieved 25 April 2022, from
<https://build.openmodelica.org/Documentation/IBPSA.html>
- Morgan, C., & de Dear, R. (2003). Weather, clothing and thermal adaptation to indoor climate. *Climate Research*, 24, 267–284. <https://doi.org/10.3354/cr024267>
- NEN. (2022). *Bouwregelgeving*. Retrieved 3 May 2022, from
<https://www.nen.nl/bouw/bouwregelgeving>
- Nytsch-Geusen, C. (2021). *BuildingSystems*. Buildingsystems. Retrieved 3 May 2022, from
<https://modelica-buildingsystems.de/>
- Passive House Institute Dr. Wolfgang Feist. (n.d.). *Component Database Clickable House*. Retrieved 10 April 2022, from <https://database.passivehouse.com/en/components/>
- Passiefbouwen. (n.d.). *Passiefhuis standaard is oplossing voor klimaatdoelstellingen*. Retrieved 1 April 2022, from <https://passiefbouwen.nl/publicaties/passiefhuis-standaard-is-oplossing-klimaatdoelstellingen>
- Reynders, Glenn, Rui Amaral Lopes, Anna Marszal-Pomianowska, Daniel Aelenei, João Martins, en Dirk Saelens. 'Energy Flexible Buildings: An Evaluation of Definitions and Quantification Methodologies Applied to Thermal Storage'. *Energy and Buildings* 166 (mei 2018): 372–90.
<https://doi.org/10.1016/j.enbuild.2018.02.040>.
- Reynders, Glenn, Jan Diriken, en Dirk Saelens. 'Generic Characterization Method for Energy Flexibility: Applied to Structural Thermal Storage in Residential Buildings'. *Applied Energy* 198 (juli 2017): 192–202. <https://doi.org/10.1016/j.apenergy.2017.04.061>.
- Ruusu, Reino, Sunliang Cao, Benjamin Manrique Delgado, en Ala Hasan. 'Direct Quantification of Multiple-Source Energy Flexibility in a Residential Building Using a New Model Predictive High-Level Controller'. *Energy Conversion and Management* 180 (januari 2019): 1109–28.
<https://doi.org/10.1016/j.enconman.2018.11.026>
- RWTH (2021). *GitHub - RWTH-EBC/AixLib: A Modelica model library for building performance simulations*. GitHub. Retrieved 3 May 2022, from <https://github.com/RWTH-EBC/AixLib>
- Sidqi, Yousra, Pierre Ferrez, Dominique Gabioud, en Pierre Roduit. 'Flexibility Quantification in Households: A Swiss Case Study'. *Energy Informatics* 3, nr. S1 (oktober 2020): 23.
<https://doi.org/10.1186/s42162-020-00126-4>.
- THUAS. (2021). *Studiewijzer afstuderen 2021-2022*. Delft: THUAS.
- Vigna, Ilaria, Roberta Pernetti, Wilmer Pasut, en Roberto Lollini. 'Literature Review on Energy Flexibility Definitions and Indicators for Building Clusters', z.d., 28.
- Vöth, Stefan, en Maria Vasilyeva. 'Potential of Modelica for the Creation of Digital Twins'. In *Advances in Raw Material Industries for Sustainable Development Goals*, onder redactie van Vladimir Litvinenko, 1ste dr., 386–89. CRC Press, 2020.
<https://doi.org/10.1201/9781003164395-48>.
- Wetter, Michael. 'Modelica Library for Building Heating, Ventilation and Air-Conditioning Systems', 393–402, 2009. <https://doi.org/10.3384/ecp09430042>.
- Wetter, Michael, Wangda Zuo, en Thierry Stephane Nouidui. 'Modeling of Heat Transfer in Rooms in the Modelica "Buildings" Library', 1 november 2011. <https://doi.org/10.2172/1168737>.
- Zhou, Yuekuan, en Sunliang Cao. 'Energy Flexibility Investigation of Advanced Grid-Responsive Energy Control Strategies with the Static Battery and Electric Vehicles: A Case Study of a High-Rise Office Building in Hong Kong'. *Energy Conversion and Management* 199 (november 2019): 111888. <https://doi.org/10.1016/j.enconman.2019.111888>.

Appendix

The following documents can be found in this appendix:

- I. Reference papers
- II. Modelica how-to: Weather data
- III. Modelica how-to: Package type
- IV. Modelica how-to: Weather file configuration
- V. SimpleHouse Modelica Model
- VI. Poster
- VII. Provisional scientific paper
- VIII. Reference model description
- IX. Competence justification

I. Reference papers

Investigation of Design Strategies and Quantification of Energy Flexibility in Buildings: A Case-Study in Southern Italy'	
Source	(Marotta et al., 2021)
Content	This paper focusses on enhancing the energy flexibility of a building through Rule-Based Control algorithms, it applies its method on a case study in the South of Italy.
Lessons learned	<ul style="list-style-type: none"> • Different measuring method of flexibility then Annex 67 proposed. • Importance of storage devices when increasing a buildings energy flexibility. • The importance and complexity the influence of innovative devices and materials have in respect to each other.
Flexibility Quantification in Households: A Swiss Case Study	
Source	(Sidqe et al., 2020)
Content	This paper analysis the quantification of the flexibility of heating appliances throughout the year, it approaches this with a clustered case study of 200 households.
Lessons learned	<ul style="list-style-type: none"> • The big potential of space heating (especially in winter) • Possibility of shifting energy consumption without altering occupant comfort.
Energy Flexibility Investigation of Advanced Grid-Responsive Energy Control Strategies with the Static Battery and Electric Vehicles: A Case Study of a High-Rise Office Building in Hong Kong.	
Source	(Zhou et al., 2019)
Explanation	This study developed a component-based model was developed, to demonstrate the quantifiable energy flexibility of a high-rise office building in Hong Kong.
Lessons learned	<ul style="list-style-type: none"> • Flexibility indicator for hybrid-grid connection • Control has a big impact on the flexibility of a building
Characterizing the Energy Flexibility of Buildings and Districts	
Source	(Junker et al., 2018)
Explanation	Although this paper does not contain a case study it is the paper connected to the research of annex 67, which is the base of this research. It discusses the importance and factors that are applicable to energy flexibility in buildings.
Lessons learned	<ul style="list-style-type: none"> • The three main characterizing aspect concerning energy flexibility in buildings: <ul style="list-style-type: none"> I. Capacity (the amount of energy able to shift per time unit) II. Time (initiation of action and its duration) III. Cost (potential saving and possible penalty signal initiator) • The key performance indicator of energy flexibility • The buildings energy parameters including sensitivity analysis.

Table I. Reference model

II. Modelica how-to: Weather data

In this how-to it is described how you can import weather data from desired geo location into IDEAS library OMedit

Adding new weather data

To add new weather data, proceed as follows:

1. Download the weather data file with the `epw` extension from <http://energyplus.net/weather>.
2. Add the file to `IDEAS/Resources/weather data` (or to any directory for which you have write permission).
3. On a console window, type
4. `cd IDEAS/Resources/weather data`
5. `java -jar ../bin/ConvertWeather data.jar inputFile.epw`
if `inputFile` contains space in the name:
`java -jar ../bin/ConvertWeather data.jar "inputFile .epw"`
This will generate the weather data file `inputFile.mos`, which can be read by the model [IDEAS.BoundaryConditions.Weather data.ReaderTMY3](#).

Step by Step:

1. Download java 11

Download java 11 major 55 (minimal needed to read Jar file)

Download java 11 from: <https://www.oracle.com/java/technologies/downloads/>

Java will not work immediately after downloading, due to the variable missing in the windows environment, to add this variable see the install video below.

Install video: <https://www.youtube.com/watch?v=1ZbHHLobT8A>

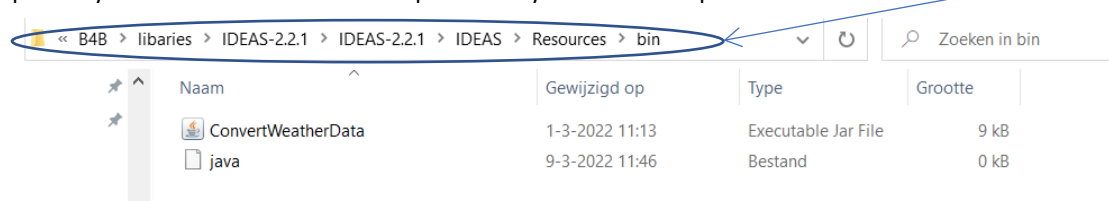
2. Download weather epw file

Download the weather file of you desired location as a `epw` file (make sure unzipped!) this can be done from [EnergyPlus](#)

3. Add the file to IDEAS/Resources/weather data (or to any directory for which you have write permission).

4. Open console

Go to the location of weather data in your fileviewer (where you just put the `epw` file) and type `cmd` in the pathway beam and the console will open already in the correct path.



5. Execute conversion

Type the following in the console: `java -jar ../bin/ConvertWeather data.jar inputFile.epw`

If inputFile contains space in the name:

```
java -jar ../bin/ConvertWeather data.jar "inputFile.epw"
```

Meaning: activate java, activate jar opening function, location jar-executing- file, document to convert.

The Jar file contains the conversion from EPW=>MOS

The MOS file should be converted and can be viewed in the weather data map.

III. Modelica how-to: Package type

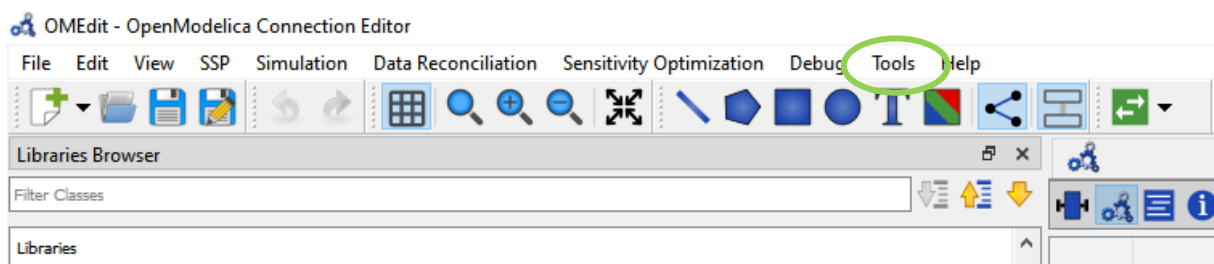
Sometimes a library is made using a certain Modelica package. When downloading OMedit it automatically uploads the latest package. In some cases it is not a problem for OMedit but in other cases it is. This document describes how you can change the package type.

In this case you can either use a conversion script or change the library in OMedit.

This document describes how you change the library in OMedit. Example from version 4.0.0 to 3.2.3.

Step 1:

Click on Tools left above in OMedit

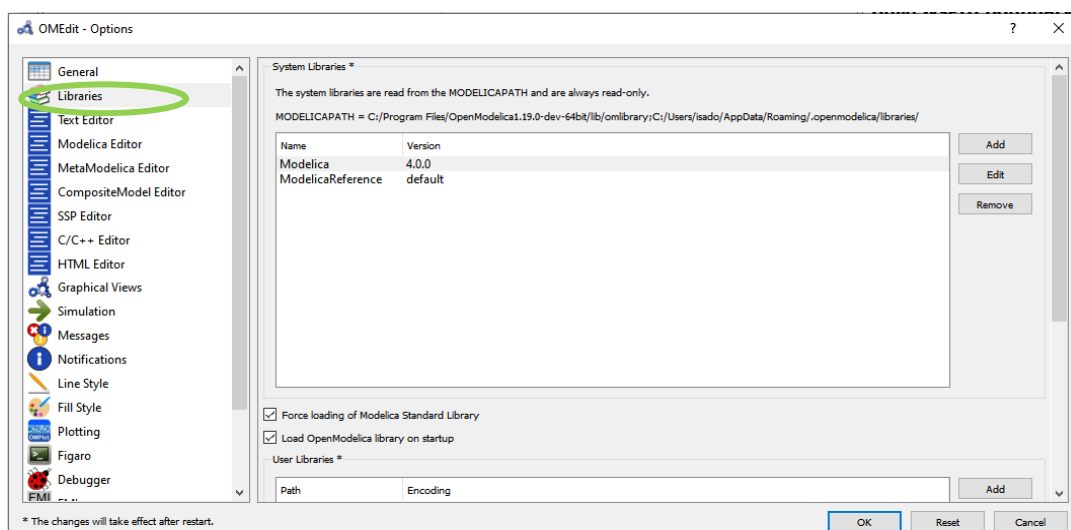


Step 2:

Click on options

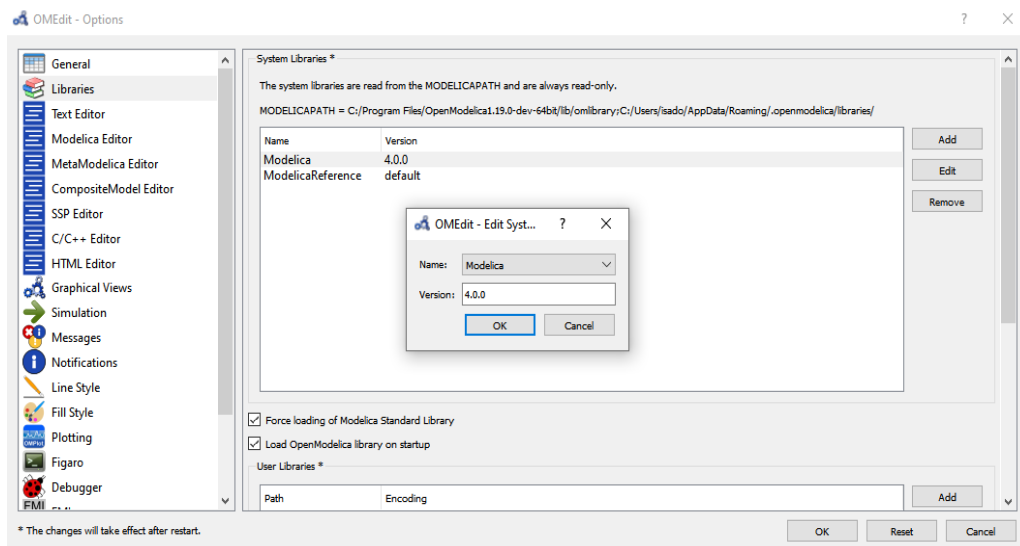
Step 3:

Click on Libraries



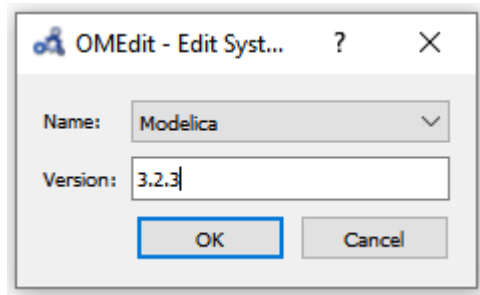
Step 4:

Click on 4.0.0 underneath Version



Step 5:

Change to 3.2.3



Step 6:

Click OK and again OK

Step 7:

Restart OMedit

Modelica package should be changed

IV. Modelica how-to: Weather file configuring

In this document the approach to importing real weather-station data is explained.

Firstly see the “Modelica how-to importing weather data” file to understand how a TMY.EPW file is converted to the needed TMY.MOS file.

The TMY [Typical Meteorological Year] are available in EPW format, the weather data of weather stations are often displayed in text-files.

- Check which connections are made inside your simulation considering TMY Reader.
- Determent which columns of a MOS file apply to the connections in the simulation.
- Change these columns with the data from your weather-station using Excel.

Points of attention!

- Comma`s are not allowed in the MOS fils
- Timesteps in 3600 seconds.
- There needs to be data in columns that are not used
- The header in the file needs to comply with the amount of Rows and lines in the Header:

This header is constructed as follows:

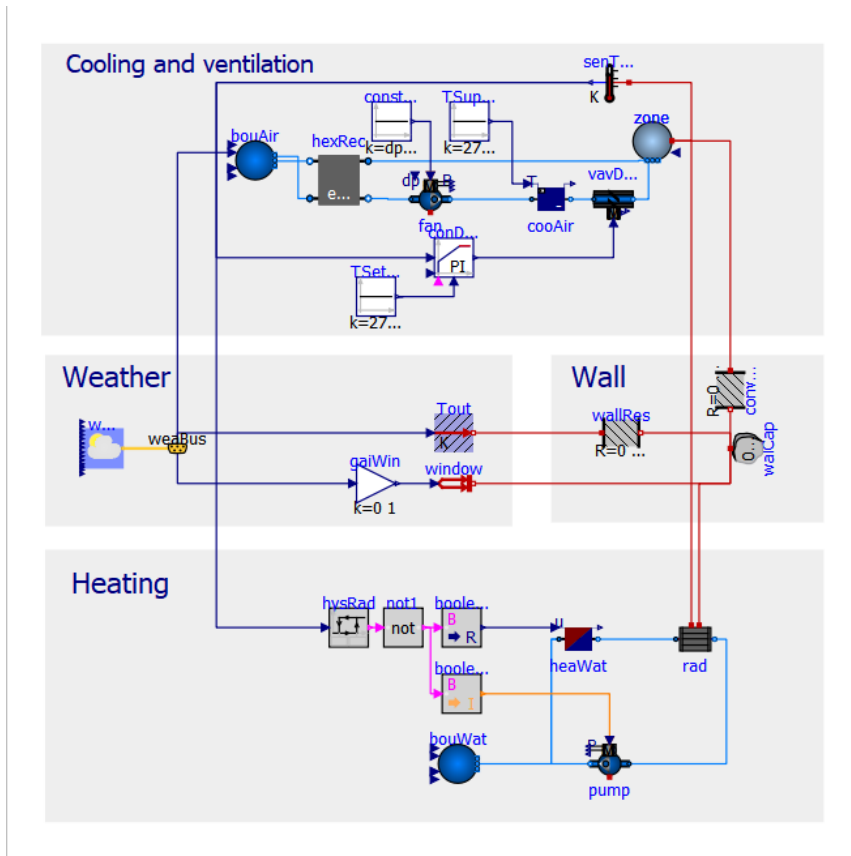
```
""""  
#1  
double tab1(Rows,Collums)  
""""
```

Your TMY.MOS file should be changed

V. SimpleHouse Modelica Model

SOURCE: IDEAS library>Fluid>Example>SimpleHouse

This model contains a simple model of a house with a heating system, ventilation and weather boundary conditions. It serves as a demonstration case of how the IDEAS library can be used.



- May 8, 2017, by Michael Wetter:
Updated heater model.
This is for [IDEAS, #763](#).
- November 10, 2016, by Michael Wetter:
Connected supply air temperature to outdoor air temperature, added cooling to supply air, changed capacity of heating system, switched heating pump off when heater is off, and added proportional controller for the air damper.
This is for [#584](#).
- September 9, 2016, by Michael Wetter:
Corrected error in window model, as the solar heat gain was not multiplied with the window area. Dymola 2017 reported this error due to mismatching units of W/m^2 and W .
- June 23, 2016, by Michael Wetter:
Changed graphical annotation.
- March 11, 2016, by Michael Wetter:
Corrected wrong limits for `hysAir` so that $u_{Low} < u_{High}$. This is for [#429](#).
- January 22, 2016, by Michael Wetter:
Corrected type declaration of pressure difference. This is for [#404](#).
- September 19, 2015, by Filip Jorissen:
First implementation.

-From energy flexibility to design choice-

A method to produce design and control advice to increase building energy flexibility, based on open-source computer simulations, using a case study.

1. Why should we want energy flexible buildings?

The increase of renewable energy causes a disbalance between the energy production and consumption because of the dependence on the natural elements. Buildings are responsible for 40% of the total energy consumption in the EU[1]. Therefore, buildings can play a key role in the grid balance when they can adjust their energy demand pattern.

Brains4Buildings (B4B)

Brains4Buildings is a four year project that is coordinated by the TU Delft. This research was an assignment under Workpackage 2 (WP2) within B4B. WP2 addresses the development of smart control models to increase energy flexibility (heat, cold and electricity) within buildings [2].

3. How can energy flexibility be measured

In the energy flexibility measuring method proposed by Annex 67, a reference energy load and a energy load with flexible operation are compared to each other. From this comparison the Key Performance Indicators can be determined as visualized below. The implementation of such a comparison can be viewed in fig.2 flexibility display, on the right.

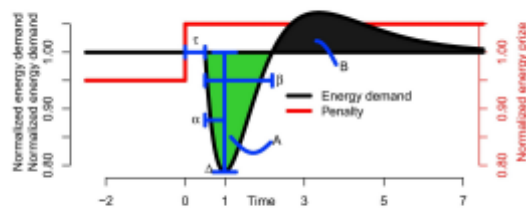


Fig. 3. Flexibility KPI's [2]

γ (Time): The delay from adjusting the energy price and seeing an effect on the energy demand. 0.5 in the example.
α (Power): The maximum change in demand following the penalty change. 0.2 in the example.
β (Time): The time it takes from the start in change in demand until it reaches the lowest level. 0.6 in the example.
A (Energy): The total time of decreased energy demand. 2 in the example.
B (Energy): The total amount of increased energy demand. (Annex 67, 2020)

5. Results

A method has been developed that can give advice to designers in order to increase the energy flexibility of a building through its design. This method has been verified by executing the developed methodology on a case-study.

In the future this method can be applied to create standardized reference models with adjustable parameters for energy load comparisons, the standardized models will allow for a fast and cost effective implementation in the R&D phase of designing a building. Thereby allowing to increasing the energy flexibility in buildings!

[1] EU, (2021)
[2] Brains4Buildings, (2022)
[3] Annex 67, (2021)



Fig. 1. Public domain

2. What is energy flexibility?

The capacity of a building to manage its demand and generation according to local climate conditions, user needs and grid requirements. Energy Flexibility of buildings will thus allow for demand side management/load[3].

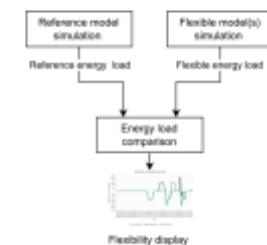


Fig. 2. Flexibility measurement

4. How was the energy load determined in this project

To determine the energy load of a building, a computer model of a Net Zero Energy Building case-study was created to generate the load curve of different building configurations. This computer model has been created using the OpenModelica environment with the Modelica language. Modelica is a component based programming language, and part of this research was focussed on analyzing its applicability.

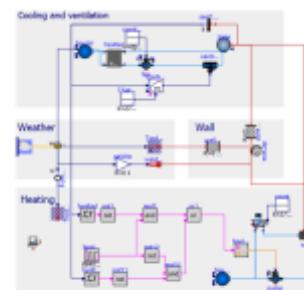


Fig. 4. Modelica model derived from Tachetel's example (BPTA library)

let's change
YOU. US. THE WORLD.



THE HAGUE
UNIVERSITY OF
APPLIED SCIENCES

VII. Provisional scientific paper

The goal is to get this paper published in the special issue from Elsevier: *Enhancing energy flexibility and climate resilience of urban energy systems*. The paper is expected to be finished by the end of June 2022, and the final paper will be handed in on the 30th of September to Elsevier.

-From energy flexibility to design choice-

A method to produce design and control advice to increase building energy flexibility, based on open-source computer simulations, using a case study

1. Introduction

To achieve the Paris Agreement goals [1], the use of fossil fuel will need to be reduced at an average rate of 6% per year from 2020 till 2030, as proposed in the Production Gap report [2]. As a consequence over the last recent years, there has been an exponential growth of renewable energy production, specially solar and wind [3-4]. The increase of renewable energy causes a disbalance between the energy production and consumption because of the dependence on the natural elements. One way to rebalance the grid is by adjusting the consumption in respects to the production, by having the ability to control the grid energy demand.

Buildings are responsible for 40% of the total energy consumption in the EU [5]. Therefore, it can play a key role in the grid balance. To be able to adjust the grid energy demand pattern of a building without compromising its user requirements the building should acquire certain energy flexibility [6-7]. The concept of building energy flexibility has been early addressed in the work from Syx et al, and Nuytten [7-8] among others. Later a widely accepted definition has been developed by Annex 67 [10]:

“The capacity of a building to manage its demand and generation according to local climate conditions, user needs and grid requirements. Energy Flexibility of buildings will thus allow for demand side management/load control and thereby demand response based on the requirements of the surrounding grids.”

Annex 67 has also developed a standardized method to measure energy flexibility [13]. The measurement takes into account three main properties mentioned in literature to characterize energy flexibility [11-13]:

- I. Capacity (the amount of energy able to shift per time unit)
- II. Time (initiation of action and its duration)
- III. Cost (potential saving and possible penalty signal initiator)

Added to the efforts to define a method to characterize the building energy flexibility several papers have been published addressing the influence of different building elements on the energy flexibility capacity of a building, for example:

Reynders et al [13] have looked at the impact of the energy storage capacity of a building. This is one of the variables that can be of substantial influence on buildings energy flexibility [13]. Furthermore, Marrott et al. [14] carried out a case study in Italy in which apart from the quantification of energy flexibility it also focusses on the design strategies and the importance energy flexibility can have in the building design process.

The aim of this paper is to propose a method to produce design and control advice to increase building energy flexibility based on open-source computer simulations.

This paper is structured as the following: In section 2 the methodology that can be used to create an energy flexibility advice is discussed together with how this could be implemented in a case study. This is followed with the results in section 3, which discusses the outputs this method can create and how this can be interpreted by a designer. In section 4 the conclusion and discussion are debated together with the outline for future work.

2. Methodology

The method to create an energy flexibility advice proposed in this paper has been developed based on a literature review, computer modeling, data analyzes and expert conversations.

Key performance Indicators (KPI's)

In the energy flexibility measuring method proposed by Annex 67 [6], a reference load and a load with flexible operation are compared to each other. The load with flexible operation is the building load as response to a specific penalty signal. Figure X.1 exemplifies a comparison between a reference load and a load with flexible operation. Figure X.2 summarize the 6 KPI's proposed by Annex 67 to characterize the comparison between the load curves.

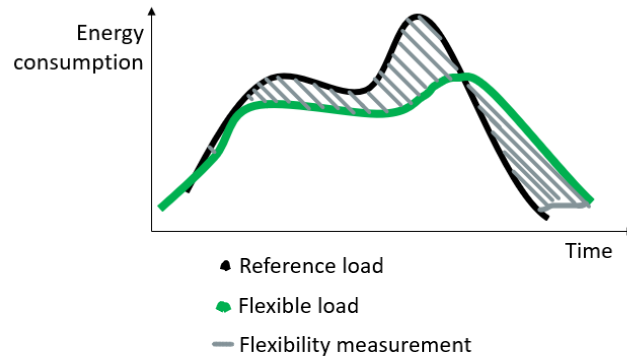


Fig. 1. Comparison energy load, to determine energy flexibility

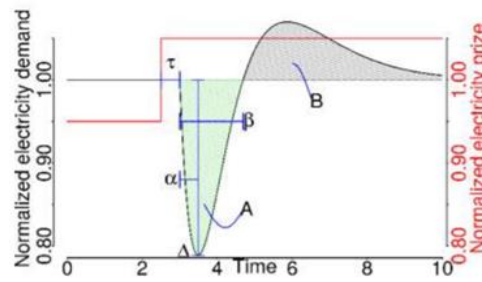


Fig. 2. Flexibility characterization [11]

Table 1

Flexibility characterization KPI's [11]

KPI	Ab.	Explanation	Unit
Initiation time	τ	The time from the penalty signal to action start.	s
Duration time	β	The duration of the response .	s
Duration peak time	α	The duration of the response till highest energy shift	s
Shifted energy capacity	A	The shifted amount of energy after initiation	(W/m ²).h
Rebound effect	B	the rebound effect for returning the situation back to the "reference".	(W/m ²).h
Maximum energy change	Δ	The maximum change in demand following the penalty signal.	W/m ²

Marotta et al [14], have also proposed a Flexibility Performance Indicator (FPI) that summarizes the six indicators on a single indicator. As the goal of this research is to provide useful information to take design choices the possibility to take into account such indicator has been dismissed as there will be lost of insightful information.

Computer Model

To evaluate the energy flexibility of the building a computer model of the case study has been created to generate the load curve of different building configurations. This computer model has been created using the OpenModelica environment with the Modelica language. Modelica is multi-domain modeling language for component oriented modeling. Because of the component oriented aspect it is also easy to adjust a single component in the model, in case of different requirements. It also allows the usage of libraries, in this model the IBPSA library has been used. The IBPSA library is mainly used for building and community energy and control systems [15-16].

The usage of Modelica results in a visual model that can be adjusted within each component and by the type of component. This allows variants of the model to be easy created, which was of importance when starting this research. Furthermore the OMedit is an open source application which can encourage further research and allows all documents to be published openly within this research.

Case Study

The case study that was used to create this model is a Net Zero Energy Building (NZEB) house in Zoetermeer, this is an energy sufficient row house located in the west of The Netherlands [17].

The computer model that has been created, is based on the simple house example created by Michael Wetter from the IBPSA library. This model is adjusted to meet the envelope and installations of the case study [18]. The output of this model has been verified by comparing its outputs to the data available from the case study.

this model will from now on be referred to as the reference model.

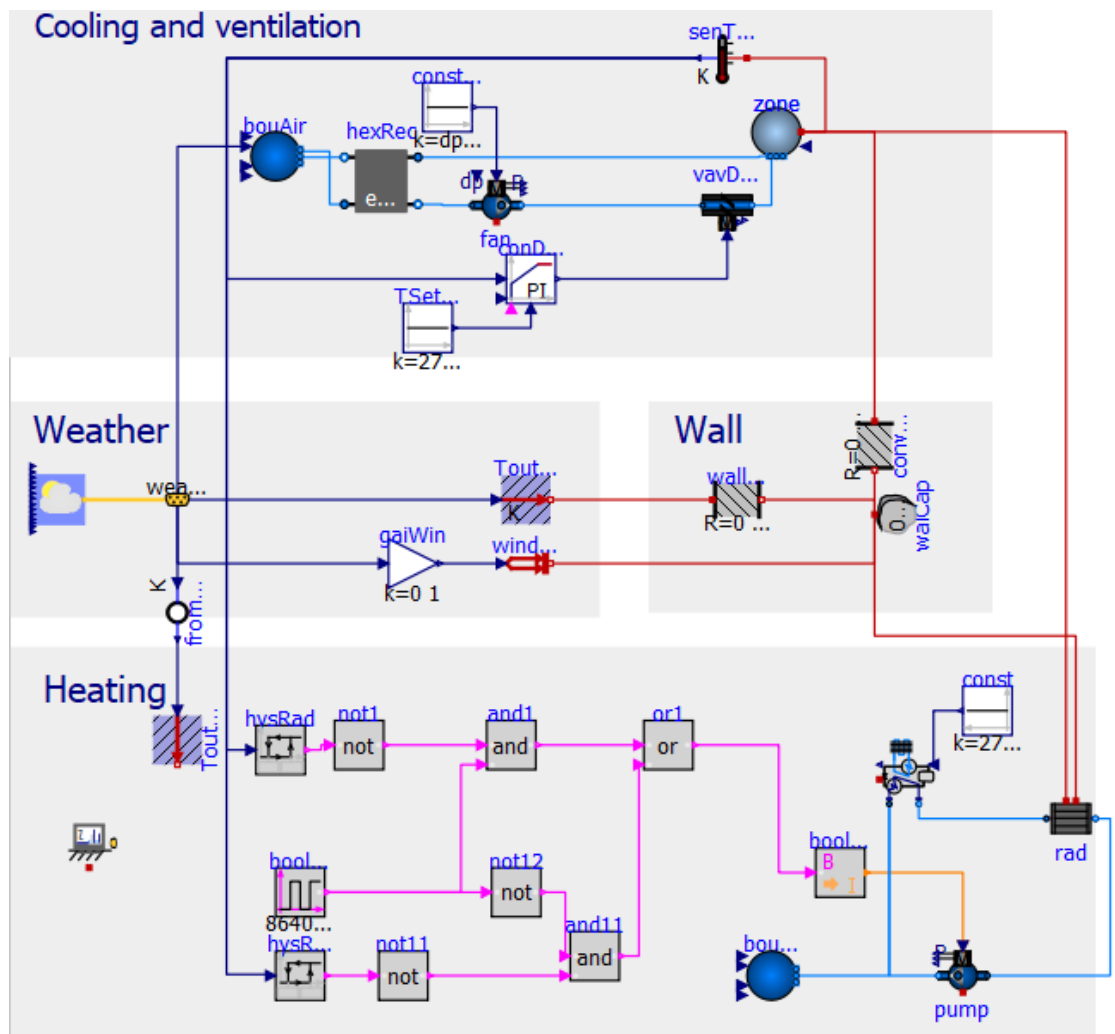


Fig. 3. Reference model adjusted version from IBPSA example Simplemodel Michael Wetter

Parameters

Like stated at the computer model, to evaluate the energy flexibility of the building a computer model of the case study has been created to generate the load curve of different building configurations. These building configurations were created by adjusting a parameter within the reference model to than create a flexible model. The parameters taken into account by Annex 67 [12] are:

- Insulation level
- Thermal Inertia
- Heating/cooling system
- Control strategy/penalty signal
- Building type
- Outdoor Temperature
- Solar Radiation

These parameters all have a substantial influence [10] on a buildings energy flexibility. There are multiple possibilities to increase a building's energy flexibility such as flexible time schedules (control) and energy storage (thermal inertia). When designing a building with the goal of increasing its energy flexibility it is of importance for the designer/engineer to be able to view the Influence of the parameters on the buildings energy flexibility.

In order to evaluate the impact of the parameters on the energy flexibility, flexible models were created. When analyzing the sensitivity chart from Junker et al. [11] three parameters were derived as being most applicable for this case study. Therefore these three parameters were analyzed within the case study: isolation, thermal inertia and the control. This has resulted in three variant "flexible" models, each with one adjustment.

Table 2
Flexible model(s) paramters

Parameter	Adjustment from Reference model
Insulation	Rc_value
Thermal inertia	Wall thickness (brick)
Control	Pre heating

Setup

These models were simulated in a worst case condition, this being on a day without sunshine and an outside temperature of -10 degrees Celsius. The penalty signal has been implemented by lowering the user requirements temperature to 19.5 degrees Celsius. This research focusses on the reaction of the models, therefore the initiation of this reaction has been taken as a binary signal. Furthermore the simulation was executed for 14 hours to simulate a hypothetical time frame from 08:00 till 22:00, this was done to properly measure the rebound effect.

Data analysis

From the reference model and variable "flexible" models the energy load data needed to be processed. The energy load produced with the different computer models has been exported to Excel to produce the comparison graphs. From these comparison graphs the time and quantity of energy load could be displayed.

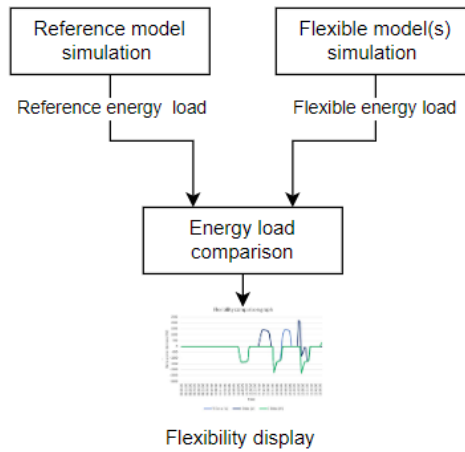


Fig. 4. Data analysis

To properly display this data a visualization with graphs was chosen together with the shifted amount of energy and the rebound effect. From this visualization three types of graphs were concluded as useful for a designer.

- Single graph
- Multiple parameter graph
- Adjusted parameter graph

-END -

3. Results

Conclusion/Discussion

Bibliography

- [1] United Nations. (2021). *The Paris Agreement*. Retrieved 29 March 2022, from <https://www.un.org/en/climatechange/paris-agreement>
- [2] Achakulwisut, P. et al., (2021). *The Production Gap Report 2021*, SEI: Stockholm Environment Institute. Retrieved from <https://policycommons.net/artifacts/1865084/the-production-gap-report-2021/2613472/> on 27 May 2022. CID: 20.500.12592/4z4qz6.
- [3] Renewables 2021 - Analysis and Forecast to 2026', 2021, 175.
- [4] H. (2022, March 18). *Grid Stability Issues With Renewable Energy Sources, How They Can Be Solved*. Hive Power. Retrieved 29 March 2022, from <https://hivepower.tech/grid-stability-issues-with-renewable-energy-how-they-can-be-solved/>
- [5] Energy Efficiency – Buildings. Eur Comm – Policies, Inf Serv; Retrieved 29 March 2022 from 2018 <https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings>
- [6]
- [7] Reynders, Glenn, Rui Amaral Lopes, Anna Marszal-Pomianowska, Daniel Aelenei, João Martins, en Dirk Saelens. 'Energy Flexible Buildings: An Evaluation of Definitions and Quantification Methodologies Applied to Thermal Storage'. *Energy and Buildings* 166 (mei 2018): 372–90. <https://doi.org/10.1016/j.enbuild.2018.02.040>.
- [8] Six D, Desmedt J, Vanhoudt D, Van Bael J. Exploring the flexibility potential of residential heat pumps combined with thermal energy storage for smart grids. In: 21st International conference on electricity distribution; 2011. p. 0442–0442
- [9] Thomas Nuytten, Bert Claessens, Kristof Paredis, Johan Van Bael, Daan Six, Flexibility of a combined heat and power system with thermal energy storage for district heating, *Applied Energy*, Volume 104, April 2013, Pages 583-591
- [10] Junker, Rune Grønberg, Armin Ghasem Azar, Rui Amaral Lopes, Karen Byskov Lindberg, Glenn Reynders, Rishi Relan, en Henrik Madsen. 'Characterizing the Energy Flexibility of Buildings and Districts'. *Applied Energy* 225 (september 2018): 175–82. <https://doi.org/10.1016/j.apenergy.2018.05.037>.
- [11] Vigna, Ilaria, Roberta Perneti, Wilmer Pasut, en Roberto Lollini. 'Literature Review on Energy Flexibility Definitions and Indicators for Building Clusters', z.d., 28.
- [12] IEA and Annex 67. (2017). *Annex 67: Energy Flexible Buildings Energy Flexibility as a key asset in a smart building future*. <https://annex67.org/media/1470/position-paper-energy-flexibility-as-a-key-asset-i-a-smart-building-future.pdf>
- [13] Reynders, Glenn, Jan Diriken, en Dirk Saelens. 'Generic Characterization Method for Energy Flexibility: Applied to Structural Thermal Storage in Residential Buildings'. *Applied Energy* 198 (juli 2017): 192–202. <https://doi.org/10.1016/j.apenergy.2017.04.061>.
- [14] Marotta, Ilaria, Francesco Guarino, Maurizio Cellura, en Sonia Longo. 'Investigation of Design Strategies and Quantification of Energy Flexibility in Buildings: A Case-Study in Southern Italy'. *Journal of Building Engineering* 41 (september 2021): 102392. <https://doi.org/10.1016/j.jobbe.2021.102392>.
- [15] *Modelica*, (n.d.). IBSA. Retrieved 25 April 2022, from <https://build.openmodelica.org/Documentation/IBPSA.html>
- [16] Vöth, Stefan, en Maria Vasilyeva. 'Potential of Modelica for the Creation of Digital Twins'. In *Advances in Raw Material Industries for Sustainable Development Goals*, onder redactie van Vladimir Litvinenko, 1ste dr., 386–89. CRC Press, 2020. <https://doi.org/10.1201/9781003164395-48>.
- [17] Nul op de Meter. (2018, December). *De Goede Woning*. Retrieved 14 February 2022, from <https://www.dgw.nl/nul-op-de-meter>
- [18] Karaca, C., Oey, R., & Gadjiedas, S. (in press). Factory Zero. *iCEM 3005-e*.

VIII. Reference model description

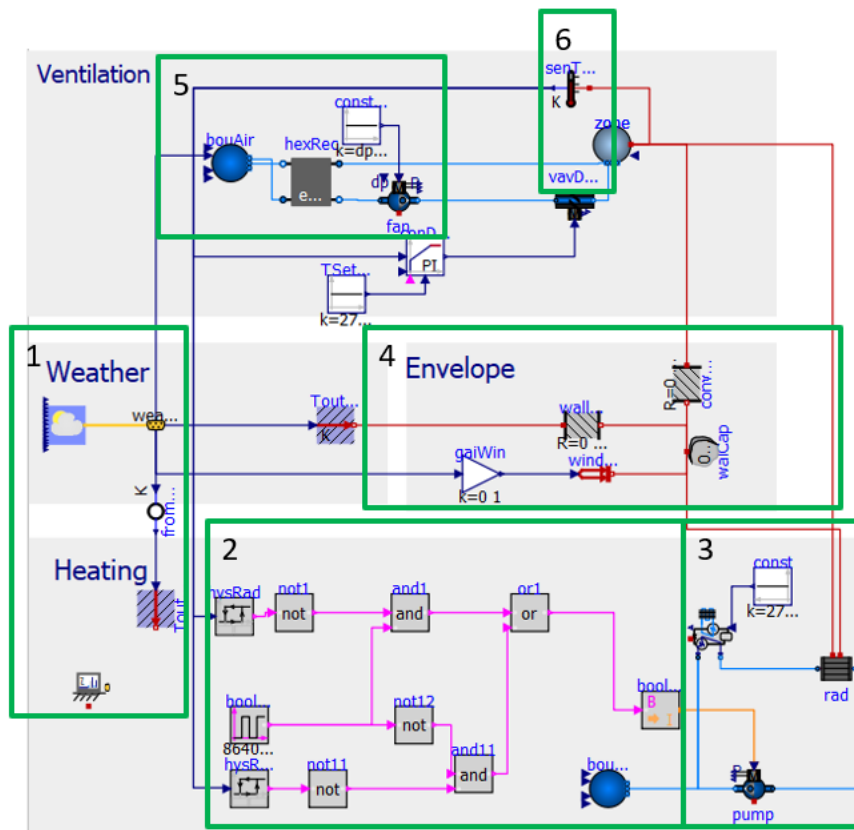


Figure VII.1 reference model

1. Weather

The weather data from Rotterdam in 2019 has been imported to the reference model. This being the closest weather station from the case study with the correct data from the KNMI. See appendix II and IV, *How-to Modelica weather file* on how this data was imported.

In the model the horizontal global radiation was the input detriment the heating caused through the windows, and the outdoor temperature to the wall for the heat transmission.

2. Thermostat

In number 2 the thermostat is outlined. This thermostat is divided into two streams in order for a day and night temperature to be configured, this is done by a booleanpulse making time steps with 8 hour nights and 16 hour of daytime. The thermostat compares the temperature from the house (zone) and the set temperature. If the zone temperature does not meet the setpoints temperature the pump attached to the heat pump gets the signal of being turned on.

3. Heating

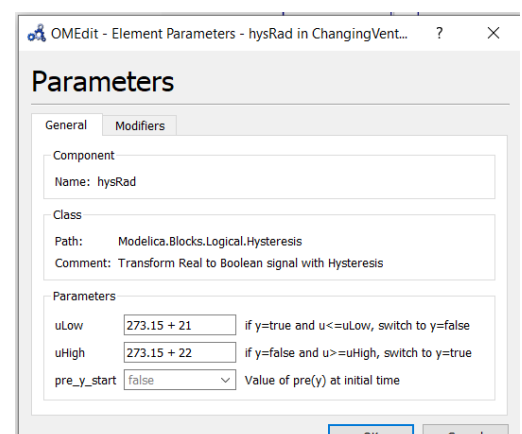


Figure XII.2 Booleanpulse

Here an air-water heat pump and radiator are attach to the model. The heat pump has a heating element of 2 kW and a heating capacity of 5 kW in the case study (Cagan et al., 2020). This was also inserted into the heat pump within this model. Furthermore the floor heating has been replaced by a standard radiator, due to the available components in the IDEAS library. The insert temperature is set on 60 °C.

4. Envelope

When taking a critical look at the data that is available of the case study mainly the measurements of the building are known. The volume, surfaces of wall and windows have been implemented in the model. To incorporate the transmission of the house a simple 2 resistor 1 capacitor wall simulation was made, because the exact materials and wall properties are unknown the Rc value is estimated, this estimation was based on the general Rc value of NZEB type houses (Passiefbouwen, n.d). Lastly the construction of the walls was taken based on the database of Passive House Institute Dr. Wolfgang Feist (n.d) and on the usage of bricks in the original construction. The main importance for this variable was the thermal mass it included into the model. Because of that 50 mm thick brick thickness was included of all the walls plus additional isolation material.

5. HRI and ventilation

For the heat recovery an efficiency of 95% was implemented into the model, this is equal to the one used in the ventilation of the case study (Cagon et al. 2020). Furthermore the ventilation capacity has been set on 300 m³/h also similar to the case study. Though this is the pump viewable in he outline of number 5.

6. Zone and temperature sensor

Connected to the envelope and heating systems is the indoor volume of the house, this has been set equal to the volume 330 m³. Furthermore the temperature of this volume is measured to compare the temperature of the house to the desired temperature.

CODE written behind model, important to note is that this model is derived from the SimpleHouseModel created by Micheal Thetter within the IBPSA development project.

```

3 model Referencemodel"Reference model of case-study Zoetermeer"
4   package MediumAir = IDEAS.Media.Air;
5   package MediumWater = IDEAS.Media.Water;
6
7   //-----parameter-----//
8
9   parameter Modelica.SIunits.Area A_wall = 185 "Wall area";
10  parameter Modelica.SIunits.Area A_win = 25 "Window area";
11  parameter Real g_win(min = 0, max = 1, unit = "1") = 0.5 "Solar heat gain coefficient of window";
12  parameter Modelica.SIunits.Volume V_zone = 6 * 10 * 5.5 "Wall area";
13  parameter Modelica.SIunits.HeatFlowRate QHea_nominal = 500 "Nominal capacity of heating system";
14  parameter Modelica.SIunits.MassFlowRate mWat_flow_nominal = QHea_nominal / 10 / 4200 "Nominal mass flow rate for water loop";
15  parameter Modelica.SIunits.MassFlowRate mAir_flow_nominal = V_zone * 2 * 1.2 / 3600 "Nominal mass flow rate for air loop";
16  parameter Modelica.SIunits.PressureDifference dpAir_nominal = 200 "Pressure drop at nominal mass flow rate for air loop";
17  parameter Boolean allowFlowReversal = false "= false because flow will not reverse in these circuits";
18
19  //-----components-----//
20
21 > Modelica.Thermal.HeatTransfer.Components.HeatCapacitor walCap(C = A_wall * 0.1 * 840 * 3000 + A_wall * 0.02 * 1300 * 1200, T(fixed =
true, start = 293.15)) "Thermal mass of walls" annotation( ...);
23 > IDEAS.Fluid.MixingVolumes.MixingVolume zone(redeclare package Medium = MediumAir, T_start = 293.20, V = V_zone, energyDynamics =
Modelica.Fluid.Types.Dynamics.FixedInitial, m_flow_nominal = mAir_flow_nominal, massDynamics =
Modelica.Fluid.Types.Dynamics.DynamicFreeInitial, nPorts = 2) "Very based zone air model" annotation( ...);
25 > Modelica.Thermal.HeatTransfer.Components.ThermalResistor convRes(R = 1 / A_wall) "Thermal resistance for convective heat transfer with
h=2" annotation( ...);
27 > IDEAS.Fluid.HeatExchangers.Radiators.RadiatorEN442_2 rad(redeclare package Medium = MediumWater, Q_flow_nominal = QHea_nominal,
T_a_nominal = 273.15 + 50, T_b_nominal = 273.15 + 40, allowFlowReversal = allowFlowReversal, energyDynamics =
Modelica.Fluid.Types.Dynamics.FixedInitial) "Radiator" annotation( ...);
29 > IDEAS.Fluid.Sources.Boundary_pT bouAir(redeclare package Medium = MediumAir, nPorts = 2, use_T_in = true) "Air boundary with constant
temperature" annotation( ...);
31 > IDEAS.Fluid.Sources.Boundary_pT bouWat(redeclare package Medium = MediumWater, nPorts = 1) "Pressure bound for water circuit"

```

```

33 > IDEAS.BoundaryConditions.WeatherData.ReaderTMY3 weaDat(filNam = "C:/Users/isado/Documents/Stage/B4B/libraries/IDEAS24/IDEAS-2.2.1/
IDEAS/Resources/weatherdata/NLD_Amsterdam.062400_IWEC - kopie (2).mos") "Weather data reader" annotation( ...);
35 > IDEAS.BoundaryConditions.WeatherData.Bus weaBus "Weather data bus" annotation( ...);
37 > Modelica.Thermal.HeatTransfer.Components.ThermalResistor wallRes(R = 5 / A_wall) "Thermal resistor for wall: 25 cm of rockwool"
annotation( ...);
39 > Modelica.Thermal.HeatTransfer.Sources.PrescribedTemperature ToutKelvin "Exterior temperature boundary condition" annotation( ...);
41 > IDEAS.Fluid.Movers.FlowControlled_m_flow pump(redeclare package Medium = MediumWater, use_inputFilter = false, m_flow_nominal =
mWat_flow_nominal, energyDynamics = Modelica.Fluid.Types.Dynamics.SteadyState, allowFlowReversal = allowFlowReversal,
nominalValuesDefineDefaultPressureCurve = true, inputType = IDEAS.Fluid.Types.InputType.Stages, massFlowRates = mWat_flow_nominal * {1})
"Pump" annotation( ...);
43 > Modelica.Thermal.HeatTransfer.Sensors.TemperatureSensor senTemZonAir "Zone air temperature sensor" annotation( ...);
45 > IDEAS.Fluid.Actuators.Dampers.Exponential vavDam(redeclare package Medium = MediumAir, from_dp = true, m_flow_nominal =
mAir_flow_nominal, dpDamper_nominal = 10, dpFixed_nominal = dpAir_nominal - 10) "Damper" annotation( ...);
47 > IDEAS.Fluid.Movers.FlowControlled_dp fan(redeclare package Medium = MediumAir, dp_nominal = dpAir_nominal, use_inputFilter = false,
energyDynamics = Modelica.Fluid.Types.Dynamics.SteadyState, nominalValuesDefineDefaultPressureCurve = true, m_flow_nominal =
mAir_flow_nominal, show_T = true) "Constant head fan" annotation( ...);
49 > Modelica.Thermal.HeatTransfer.Sources.PrescribedHeatFlow window "Very simple window model" annotation( ...);
51 > IDEAS.Fluid.HeatExchangers.ConstantEffectiveness hexRec(redeclare package Medium1 = MediumAir, redeclare package Medium2 = MediumAir,
dp1_nominal = 0, dp2_nominal = 0, eps = 0.90, m1_flow_nominal = mAir_flow_nominal, m2_flow_nominal = mAir_flow_nominal) "Heat exchanger
for heat recuperation" annotation( ...);
53 > Modelica.Blocks.Logical.Hysteresis hysRad(uHigh = 273.15 + 22, uLow = 273.15 + 21) "Hysteresis controller for radiator" annotation( ...);
55 > Modelica.Blocks.Logical.Not not1 "negation for enabling heating when temperatur is low" annotation( ...);
57 > Modelica.Blocks.Sources.Constant const_dp(k = dpAir_nominal) "Pressure head" annotation( ...);
59 > Modelica.Blocks.Math.Gain gaiWin(k = A_win * g_win * 0.8) "Gain for window solar transmittance and area as HGloHor is in W/m2"
annotation( ...);
61 > Modelica.Blocks.Math.BooleanToInteger booleanToInt "Boolean to integer" annotation( ...);
63 > IDEAS.Controls.Continuous.LimPID conDam(controllerType = Modelica.Blocks.Types.SimpleController.P, yMin = 0.1) "Controller for damper"
annotation( ...);
65 > Modelica.Blocks.Sources.Constant TSetRoo(k = 273.15 + 15) "Room temperature set point for air system" annotation( ...);
67 > IDEAS.Fluid.HeatPumps.HP_AirWater_TSet hP_AirWater_TSet(redeclare package Medium = MediumWater, QNom = 2000, cDry = 10000, mWater = 4,
m_flow_nominal = mWat_flow_nominal, tauHeatLoss = 3600) annotation( ...);

```

```

Resources/weatherdata/NLD_Amsterdam.062400_IWEC.mos") annotation( ...);
71> Modelica.Blocks.Sources.Constant const(k = 273.15 + 90) annotation( ...);
73> Modelica.Thermal.HeatTransfer.Celsius.PrescribedTemperature ToutCelcius annotation( ...);
75> Modelica.Thermal.HeatTransfer.Celsius.FromKelvin fromKelvin annotation( ...);
77> Modelica.Blocks.Logical.And andl annotation( ...);
79> Modelica.Blocks.Sources.BooleanPulse booleanPulse(period = 86400, startTime = 28800, width = 0) annotation( ...);
81> Modelica.Blocks.Logical.Hysteresis hysRadl(uHigh = 273.15 + 21, uLow = 273.15 + 20) annotation( ...);
83> Modelica.Blocks.Logical.Not notl1 annotation( ...);
85> Modelica.Blocks.Logical.And andl1 annotation( ...);
87> Modelica.Blocks.Logical.Not notl2 annotation( ...);
89> Modelica.Blocks.Logical.Or orl annotation( ...);
91
92 //-----Connections-----//
93
94 equation
95> connect(convRes.port_b, walCap.port) annotation( ...);
97> connect(convRes.port_a, zone.heatPort) annotation( ...);
99> connect(weaDat.weaBus, weaBus) annotation( ...);
101> connect(wallRes.port_b, walCap.port) annotation( ...);
103> connect(ToutKelvin.port, wallRes.port_a) annotation( ...);
105> connect(rad.port_b, pump.port_a) annotation( ...);
107> connect(senTemZonAir.port, zone.heatPort) annotation( ...);
109> connect(window.port, walCap.port) annotation( ...);
111> connect(bouAir.ports[1], hexRec.port_b1) annotation( ...);
113> connect(hexRec.port_a1, zone.ports[1]) annotation( ...);
115> connect(rad.heatPortCon, zone.heatPort) annotation( ...);
117> connect(rad.heatPortRad, walCap.port) annotation( ...);
119> connect(notl.u, hysRad.y) annotation( ...);
121> connect(const_dp.y, fan.dp_in) annotation( ...);
123> connect(gaiWin.y, window.Q_flow) annotation( ...);
125> connect(gaiWin.u, weaBus.HGloHor) annotation( ...);
127> connect(booleanToInt.y, pump.stage) annotation( ...);
129> connect(bouAir.ports[2], hexRec.port_a2) annotation( ...);
131> connect(hexRec.port_b2, fan.port_a) annotation( ...);
133> connect(vavDam.port_b, zone.ports[2]) annotation( ...);
135> connect(senTemZonAir.T, hysRad.u) annotation( ...);
137> connect(senTemZonAir.T, conDam.u_s) annotation( ...);
139> connect(conDam.y, vavDam.y) annotation( ...);
141> connect(TSetRoo.v, conDam.u_m) annotation( ...);

```

Figure VIII Code Reference model

IX. Competence justification

In this appendix you can find the competence justification, because Dutch is my native language this has been done in Dutch.

Competence summary

Competence	Current level	Goal level	Examples of activities done to achieve the competence goals
Analyzing	3	3	I performed a problem analysis and defined the measurement methodology based on previous research. Furthermore a verification of the reference model was done by analyzing the available data in respect to the reference model.
Designing	3	3	Designing a code and attached model that fits the set requirements of the project, using Modelica.
Researching	2	2	A thorough literature review was performed.
Professionalizing	2	2/3	Writing a scientific paper, furthermore taking an overall professional attitude while making contacts, like with KU Leuven in order to have supporting contacts while developing the Modelica model.

Table IX. Competence summary

STARR competence analyzes

Competence	Start Level	Realized Level	Part	Explanation
1. Analyseren	3	3	1a	S: Het analyseren van de bestaande methodiek rondom energie flexibiliteit binnen gebouwen. T: Literatuur onderzoek A: Met een kritische houding de resultaten uit het literatuuronderzoek analyseren. R: Hoofdstuk 3: Methodology

				<p>R: Dit onderzoek heb ik zelfstandig uitgevoerd, ook is over de methodiek nog een relatief jonge informatiestroom. Hierdoor is niet alles bekend en stimuleert ook dit de zelfstandigheid tijdens het onderzoek. Verder is er een ruim aantal systemen actief rondom het onderwerp dit vergroot de complexiteit van het onderzoek. Hierom denk ik dat ik de competentie analyseren op niveau 3 heb toegepast</p>
			1c	<p>S: Een opzet creëren voor het onderzoek om goed te kunnen starten met de stage. T: Plan van aanpak opzetten. A: Literatuuronderzoek doen en meerdere gesprekken uitvoeren met mijn bedrijfsbegeleider zodat de opdracht en de gekoppelde doelen/probleemstellingen bij mij bekend waren. R: Plan van Aanpak en de revisie hiervan in week 2 van de stage R: Met name de gesprekken met mijn bedrijfsbegeleider vond ik hier als prettig, zo gaf dit mij een richting om vervolgens zelf de probleem en doelstellingen op te stellen en ook kon ik zo meer richting geven aan mijn literatuur onderzoek. Met name mijn hoofdvraag is nog een aantal keer beter geformuleerd nadat ik dieper in het onderzoek zat, dit was mede door de complexiteit die in dit onderzoek zat.</p>
			1e	<p>S: De energie flexibiliteit van een casus moeten meten T: Het maken van een computer model van de case studie A: Het opstellen van een Modelica computer model R: Hoofdstuk 4.2: Case study reference model simulation R: Doordat er niemand in het bedrijf de software gebruikte was het programmeren genoodzaakt een eenzaam proces, en dus ook erg zelfstandig. Om oplossingen te vinden heb ik op online platformen zoals Github en het Modelica forum veel vragen gesteld. Hier heb ik veel informatie uit kunnen halen maar vaak duurde het verwijderen van errors vrij lang. Ik denk dat mijn mate van zelfstandigheid en ondernemendheid zeer passen bij niveau 3 van analyseren.</p>
2. Ontwerpen	3	3	2d	<p>S: Het moeten kunnen verifiëren van het model T: Verifiëren van het model A: Het gecreëerde computermodel laten voldoen aan het plan van eisen en hier op reflecteren tijde. structureel verwijzen naar het plan van eisen (LoR). R: Hoofdstuk 4.2. Case study reference model simulation. R: Ontwerpen was niet het grootste onderdeel van mijn stage echter was ontwerpen van het computermodel door de gestelde eisen zeker complex, hierin zijn waar nodig concessies gemaakt</p>

				echter voldeed het model aan alle harde eisen. Hierom denk ik dat door de complexiteit niveau 3 van ontwerpen is aangetikt.
			2f	<p>S: Het lectoraat moet verder kunnen met het onderzoek nadat ik vertrek.</p> <p>T: Het net documenteren van mijn modellen en hun proces.</p> <p>A: Gestructureerd opleveren van modellen en kritische proces stappen documenteren.</p> <p>R: Een overzicht in teams met namen en data van de modellen en bijlage II, III en IV Modelica how-to's.</p> <p>R: Naar mijn mening is het eindproduct net opgeleverd, met name de how-to's, door de complexiteit die Modelica als omgeving bracht denk ik daarom dat deze volledige documentatie in dit geval gepast is. Deze bijlages gaan een volgende student denk ik erg helpen, deze relatief kleine handelingen waren namelijk niet goed te vinden en waren hierdoor tijd consumerend. Door de volledigheid en zelfstandigheid denk ik dat ook deelcompetentie 2f op niveau 3 is voldaan.</p>
7. Onderzoeken	2	2/3	7b	<p>S: Onderbouwing moeten hebben voor het onderzoek.</p> <p>T: Literatuuronderzoek, met een focus op wetenschappelijke artikelen</p> <p>A: Aan de hand van gerichte zoektermen en zoekmachines en de beschikbare informatiebronnen goede literatuur vinden en verwerken.</p> <p>R: Hoofdstuk 2 <i>State-of-the-art</i> en het wetenschappelijk paper zie bijlage VII <i>Provisional scientific paper</i>.</p> <p>R: De literatuur vinden om en een wetenschappelijk paper te kunnen schrijven is een groot onderdeel van het paper. Ik merkte dat het lezen van de gevonden literatuur soms ook nog best uitdagend was, dit was mede door de complexiteit van het onderwerp. Uiteindelijk is ook de betrouwbaarheid van de literatuur aandachtig bekeken door verschillende literatuur te vergelijken en de leidende literatuur van Annex 67 nog extra te verifiëren als bron (paragraaf 2.2.). Dit is ook het onderdeel waarvan ik denk het meeste geleerd te hebben, aangezien ik deze vorm van onderzoeken niet gewend ben bij de opleiding werktuigbouwkunde. Hierom denk ik dat niveau 3 van onderzoeken is uitgevoerd.</p>
			7c	<p>S: Het kunnen delen van mijn onderzoek en een het onderzoek willen opsturen naar een wetenschappelijk blad.</p> <p>T: Het opstellen van een onderzoeksrapport en een wetenschappelijk paper.</p>

				<p>A: De resultaten samenvatten, structureren en interpreteren en conclusies trekken om zo tot de antwoorden van de onderzoeksvragen te komen.</p> <p>R: Dit onderzoeksrapport en bijlage VII <i>Provisional scientific paper</i>.</p> <p>R: Uiteindelijk ben ik tevreden over de rapportage ik denk dat alle kritische onderdelen in het rapport zijn verwerkt zonder over de 50 pagina's heen te gaan. De juiste structuur aanhouden voor de verslaglegging vond ik complex door het aantal onderdelen, uiteindelijk denk ik dat alle kritische onderdelen in het rapport zijn verwerkt zonder over de 50 pagina's heen te gaan. Tijdens de rapportage van het wetenschappelijk paper heb ik wel veel begeleiding gekregen van mijn begeleiding meneer Salcedo Rahola, dit had ik niet zelfstandig gekund. Hierom denk ik dat niveau 2 van onderzoeken behaald betreffende de rapportage.</p>
			7e	<p>S: Binnen B4B gaan andere onderzoekers wellicht door op dit onderzoek.</p> <p>T: Bepalen waar de meeste waarde van het onderzoek zit in een vervolg fase.</p> <p>A: Analyseren van resultaten en betrouwbaarheid van het onderzoek met een focus op toekomstig onderzoek.</p> <p>R: Paragraaf 4.4 <i>future applicability</i> maar met name hoofdstuk 5 <i>Conclusion and recommendations</i>.</p> <p>R: Uiteindelijk is er een methode ontwikkeld en niet een werkelijke tool, voordat dit daadwerkelijk kan worden ontwikkeld wordt aanbevolen nog een extra verificatie te doen en om te kijken naar de waarde van zo'n tool op de voor deze bedoelde markt. Door de complexiteit van het gehele vraagstuk denk ik dat dit gedaan is tussen niveau 2 en 3 van onderzoeken.</p>
8. Professionaliseren	2	2/3	8b	<p>S: Tegen problemen aanlopen tijdens het maken van het Modelica model.</p> <p>T: Opzoek naar een oplossing.</p> <p>A: Active vragen stellen op forums als Github en contactpersoon bij de KU Leuven benaderen.</p> <p>R: Een computer model wat is gebaseerd op een voorbeeld binnen de IDEAS bibliotheek.</p> <p>R: In eerste instantie had ik het model graag vanaf nul opgebouwd i.p.v. met een voorbeeld echter was dit na het aantal obstakels niet mogelijk met betrekking tot de tijd. Door meerdere contacten te leggen was het werken met het voorbeeld wel een mogelijkheid. Er was flexibiliteit nodig tijdens deze ontwikkeling aangezien hier geen uitgelegd pad voor was. De uiteindelijke route heb ik zelfstandig gekozen en resulteerde in een model wat volwaardig was voor dit onderzoek. Dit vond ik een spannend onderdeel van het onderzoek maar ik denk hierin niveau 3 van professionaliseren heb laten zien.</p>

			8d	<p>S: Het houden van tussentijdse presentaties om de voortgang van het onderzoek te laten zien aan de bedrijfsbegeleider en mede stagairs.</p> <p>T: Feedback verwerken van mijn begeleiding en mede stagairs en feedback geven aan mede stagairs en.</p> <p>A: Tussentijdse presentaties goed voorbereiden zodat mijn begeleider en mede stagairs hier goed feedback op konden geven.</p> <p>R: Een beter niveau in mijn onderzoek en de eisen en wensen van de opdrachtgever in zicht hebben tijdens het onderzoek.</p> <p>R: Zelf vond ik het afstuderen af en toe best eenzaam, ik merkte dat de feedback sessies mij erg hielpen en soms ook wat nieuwe energie in het project bracht. Verder vond ik het voorbereiden van de presentaties erg leerzaam om zo een goed overzicht te krijgen van mijn to-do's en vorm te geven aan het onderzoek. Doordat ik deze taak serieus nam heb ik hier veel aan gehad en denk ik dit zeker op niveau 2 te hebben gedaan.</p>
			8f	<p>S: Onderzoekers willen informeren over mijn project of een antwoord zoeken op een vraag.</p> <p>T: Het geven van een eind presentatie aan de B4B onderzoeksgroep, het communiceren via email met KU Leuven en het communiceren met meerdere platformen zoals het Modelica forum en Github.</p> <p>A: Het voorbereiden van een presentatie, accounts aanmaken op platformen en contact zoeken met nuttige contacten aan het begin van de stage.</p> <p>R: Meerdere onderzoekers binnen B4B zijn geïnformeerd over mijn onderzoeksresultaten. Zonder de verdere communicatie was het mij niet gelukt dezelfde voortgang te hebben gemaakt.</p> <p>R: In de eerste week van mijn onderzoek ben ik opzoek gegaan naar mogelijke contactpersonen die zouden kunnen helpen met het onderzoek, dit bleek erg nuttig want toen is het contact met KU Leuven gemaakt. Door middel van nette en duidelijke schrijfwijze op zowel forums als mail heb ik vaak antwoord gekregen op mijn vragen. De vragen waren vaak complex en meestal in het Engels, ik denk hierdoor niveau 3 te hebben behaald binnen professionaliseren op het punt van communicatie.</p>

Table IX. Competence justification

