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**Relaxierte energetische Simulation des Energiebedarfs
in Gebäuden**
**Relaxed energetic simulation of energy demand in
buildings**

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Contents

1	Introduction	1
1.1	Motivation	1
1.2	Related work	1
1.3	Contribution	4
1.4	Outline of this work	4
2	Current version of the DIN V 18599 norm	4
2.1	Terminology	5
2.1.1	Influence of the buildings architecture	7
2.2	The procedure of the algorithm	9
2.3	Updates to the old version of the algorithm	9
2.3.1	Solar systems	10
2.3.2	Heat Pumps	11
3	Implementation of the algorithm	11
3.1	Validation	12
4	Relaxation of the algorithm	13
4.1	Goal	13
4.2	Procedure	14
4.3	Overview of the simplifications	14
4.3.1	Building architecture	14
4.3.2	Overview components	16
4.3.3	Walls	17
4.3.4	Cellar	18
4.3.5	Windows	18
4.3.6	Roof	20
4.3.7	Heating system	22
4.3.8	Tap water system	24
4.3.9	Ventilation System	26
4.3.10	Solar system	26
4.4	Implementation	26
4.5	Runtime	28
5	Validation of the relaxation	29
5.1	Reference buildings and test cases	29
5.2	Deviation from existing test cases	31
5.3	Influence of the building architecture	32
5.3.1	Usable area	33
5.3.2	Net volume	34
5.3.3	Cellar	35
5.3.4	Attic	36

5.4	Influence of the construction year	37
5.5	Influence of the heating system	37
5.6	Influence of the missing ventilation	39
5.6.1	Year of the heating system	39
5.7	Comparison to the EVA Leuchter simplification	40
6	Conclusion	42
6.1	Future Work	43
	References	44

1 Introduction

1.1 Motivation

In times of global climate change, buildings are required to meet a certain standard of energetic efficiency. In Germany, funding projects create incentives for building owners to build and renovate their houses to meet a certain efficiency standard. The better the energy efficiency of a building, the higher the funding for the project. In addition, building owners can save money by having an energy-efficient building if their systems do not require high amounts of energy and the building itself works efficiently with the provided energy and the building's energy losses are reduced. Starting in 2024, the only official method for evaluating the energetic efficiency is the procedure shown in the DIN V 18599 norm. The presented procedure requires detailed information about the building and the building's systems, like the heating or tap water systems. Collecting those data points is connected with effort and often has to be done by experts. Also, the calculation requires computer programs, which in most cases require a profound knowledge of the matter. This overall complexity leads to the problem that the average building owner needs help to evaluate their building. Although the energetic evaluation, which is required by German law, has to be done by an appointed person. A method usable for non-expert users can help to give a first indication of the energetic evaluation and can show which changes to the building and the building's systems help to increase the building's efficiency concerning energetic efficiency.

The existing algorithms' complexity and the goal to provide easy access to the energetic evaluation leads to a simplified version of the algorithm. Especially the problem of the amount of data required for the evaluation has to be reduced so that simple knowledge about building, which can be gathered quickly, is enough for a first rough evaluation.

This work will show how a simplified version of the given algorithm based on the procedure the DIN V 18599 norm can be adapted so that a simplified input is sufficient for calculating a first approximation of the energetic evaluation of a building. With the help of existing reference results, the approximation will be validated, and a factor for uncertainty will be classified.

1.2 Related work

The idea of simulating and evaluating a building concerning its energetic efficiency with the help of algorithms and data has also been evaluated by other works. In the following section, these works will be discussed.

The simulation of buildings, in general, has been explored in different aspects. Wang and Zhai [17] show that there have been two methods for simulating a building. The first is an analytical approach with formulas based on environmental assumptions, and the other is based on computational fluid dynamics, which can help simulate airflow in the building.

Optimising the calculation for the simulation of buildings has been the goal of Wetter

et al. [19]. The authors show that using an equation-based modelling language can lead to 2200 times faster solutions when simulating certain aspects of buildings.

In general Sokolova and Aksanli [14] show that the energy consumption of a building can not be determined by one factor, but multiple factors impact the energy consumption.

Different algorithms for evaluating buildings' energy efficiency are shown by Tsala and Koronaki [15]. The authors present the procedure of different algorithms and find that the choice of algorithm is based on the given limitations in the optimisation problem.

For calculating the energy efficiency of a building, the first step is to gather data about the building. Regel [12] describes a procedure for a simplified approach to assess the energetic usage of university buildings. In his work, the author states that existing methods for determining energy efficiency require much effort, especially for specific benchmarks.

A similar approach is chosen by Lichtmeß [9], who created a method for a simplified zoning mechanism for non-residual buildings for handling the required separation of a building into usage areas. Only the outer shell of the building is required, while information about inner zones is not necessary, as zoning can be done by the presented algorithm based on the given outer shell.

The works presented above mainly apply to non-residential buildings. In Germany, energetic evaluation is also required for residential buildings. Wenninger and Withe [18] show that data-driven methods like artificial neural networks present an approach with higher accuracy than the method for calculating the energy efficiency required by German law.

The VDI 3807 norm presents a different approach for calculating the consumption values of buildings. Based on the users' input, the algorithm calculates a specific building type for the input. If the building's energy consumption values exceed a predefined norm value, the savings potential can be calculated [16].

Another method for simulating buildings and their energy use is thermal simulations for buildings. Instead of using static formulas with correction factors like in other building simulation norms, this method simulates the building over time. Additionally, the method can simulate solar heat protection for windows [13]. For buildings not perfectly covered by static methods, like in the previously mentioned building simulation norms, this method can help generate more accurate simulation results.

With the help of neural networks Biswas et al. [1] show that the energy consumption of residential buildings can be predicted. Problems with calculating non-linear data can be addressed by using neural networks.

The building simulation norm from the DIN V 18599 norm describes a procedure for calculating the energy efficiency of buildings [4]. Various programs have implemented the algorithm. This work will base its implementation on the work of Nick Feiereisen [11]. The author describes the *EnerEval*-Algorithm as an algorithm for a norm-compliant implementation. By showing the validation with the help of test cases and runtime measurements, he can show that an efficient and quick implementation is possible.

The norm used in the *EnerEval*-Algorithm is considered time-consuming and error-prone [8]. However, this specific building simulation norm provides an additional method with a table procedure, where the calculation is done with the help of defined tables to offer an alternative way of calculation with a less time-consuming approach. This method presents an approach with a slight deviation of about one percent to the original calculation [8].

Several software manufacturers have implemented the procedure in the building simulation norm. Some software manufacturers created the *18599 Gütegemeinschaft*¹. The organisation's purpose is the quality assurance of software products for the norm. Therefore, test cases are created and provided to the software manufacturers to validate their products. The test cases of the *Gütegemeinschaft* define a building for each test case and intermediate values as well as final results for the energy efficiency [5]. One condition of the organisation is that the test cases are available in the product as example projects so that each user can validate the software product. However, only the values calculated by software products from the *Gütegemeinschaft* can be validated because the organisation's current, complete test case definitions are not publicly available. With this configuration, however, it is only possible to verify some calculated values because the user can only view some values calculated by the software products. Table 1 shows a list of software products that are part of the organisation.

Software Product	Manufacturer
EVEBI	ENVISYS
IBP:18599	Fraunhofer IBP
Energieberater 18599	Hottgenroth Software
Dämmwerk	Kern Ingenieurkonzepte
EnEV-Wärme & Dampf	ROWA-Soft
GEG Pro	Visionworld
EVA die Energieberaterin	Ingenieurbüro Leuchter
BKI Energieplaner	Lieb Obermüller + Partner
Energiepaket	SOLAR-COMPUTER GmbH
Helena	ZUB Systems GmbH

Table 1: Software manufacturers with their products which are part of the *18599 Gütegemeinschaft*.

This work will use the program *EVA die Energieberaterin* from the engineering office Leuchter². The program evaluates buildings' energy efficiency using the DIN V 18599 norm. As part of the *18599 Gütegemeinschaft*, the program guarantees its correctness with the help of test cases from the Gütegemeinschaft.

¹*18599 Gütegemeinschaft* - <https://www.18599si-egel.de/>

²*EVA die Energieberaterin* - <https://leuchter.de>

1.3 Contribution

This work contributes to a wide range of software products that help users evaluate a building concerning energetic efficiency. Like the other existing software products, algorithm changes will be revalidated to remain in conformance with the building simulation norm.

The use case is often separated between residential and non-residential buildings. This work will focus on residential buildings. Most existing software tools for a complete calculation require a profound knowledge of the matter and are mainly targeted at energy efficiency consultants.

For the average building owner, there exist tools for creating their energy efficiency certificate online. Those tools use an approach which creates a certificate based on the measured energy consumption over the last years. This method is used because of its simplicity but does not guarantee exact results as the other method, which is the demand-based approach. This approach is more elaborate, as it requires more data about the building and the systems of the building than the approach based on energy consumption. The fact that the method based on consumption is more straightforward for the average building owner leads to the fact that many tools targeted more toward the average building owner use this approach instead of the more accurate one based on energy demand.

This work tries to close the gap between the more elaborate approach to energetic evaluation based on the energy demand and the average building owner by using the demand-based method with a simplified input to give the user a first approximation of a detailed view of the building.

1.4 Outline of this work

This work is structured into five main sections. In Section 2, the underlying algorithm will be discussed. Besides the general functionality of the *EnerEval*-algorithm, the implemented changes to the existing implementation to meet current changes to the norm are discussed in the Section 3. Section 4 will show the modifications to simplify the user input so that the existing algorithm can work with a simplified user input format. Section 5 will validate the modifications made in the previous section by showing how different parameters will affect the overall result and how this affects the accuracy of the approximation. Section 6 will conclude the result and show options for future work.

2 Current version of the DIN V 18599 norm

This work is based on an existing DIN V 18599 standard implementation by Nick Feiereisen [11]. The author describes the *EnerEval*-algorithm, which in his work describes how the version from 2011 of the DIN V 18599 can be implemented. The first goal of this work is to update the code from Nick Feiereisen [11] to fit the requirements of the current version from 2018.

The DIN V 18599 standard has had several updates over the years. The versions from 2011, 2016 and 2018 are relevant to this implementation. The main focus is the 2018 version and the comparison to the existing implementation of the 2011 standard version. Here, some changes will be discussed.

This section will introduce the necessary knowledge by giving an overview of the *EnerEval*-algorithm and explaining essential values.

2.1 Terminology

The goal for the user of *EnerEval*-algorithm is to evaluate the energy efficiency of a building. If a person wants to sell a building, they must create an energy efficiency certificate for that building. With the beginning of the year 2024, the DIN V 18599 norm is the only allowed method for calculating the energy efficiency according to the German law³.

The following formulas in this section are based on [4], to display the general concept of the procedure used in *EnerEval*.

Two values determining the energy efficiency are the final and primary energy demand in $kWh/(a\ m^2)$. Both values are based on the net energy demand, which is the energy required to run different parts of the building. The net energy demand is calculated for different aspects of the building (e.g. heating or cooling). It takes the energy sinks and sources into account for the specific part. As an example, the net heating demand, which is part of the iterative process described in Figure 2, is calculated with (1).

$$Q_{h,b} = Q_{\text{sink}} - \eta \cdot Q_{\text{source}} \quad (1)$$

where:

- $Q_{h,b}$: The net heating demand.
- Q_{sink} : Sum of all heat sinks.
- Q_{source} : Sum of all heat sources.
- η : Usage factor for the heating source.

With the net energy demand for different parts of the building, the final energy demand can be calculated, as it describes the required energy for the building to satisfy the net energy demand [4]. The final energy demand in general shown in (2).

$$Q_{h,f} = Q_{h,f,\text{in}} + Q_{h,f,\text{prod}} - Q_{h,f,\text{out}} \quad (2)$$

where:

³Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen. Gesetz zur Vereinheitlichung des Energieeinsparrechts für Gebäude und zur Änderung weiterer Gesetze: GEG, 08.08.2020.

- $Q_{h,f}$: The total final energy demand for the system.
- $Q_{h,f,in}$: The final energy supplied for the system by outside systems.
- $Q_{h,f,prod}$: The usable final energy supplied by this system.
- $Q_{h,f,out}$: The final energy produced by this system, which is not used in this area.

For the heating system, (3) gives a specific formula for the final heating demand.

$$Q_{h,f} = (Q_{h,outg} + Q_{h,gen}) \cdot f_{gen,PM} \quad (3)$$

where:

- $Q_{h,f}$: The total final energy demand for the heating system.
- $Q_{h,outg}$: The usable heating energy for the building produced by the heating system.
- $Q_{h,gen}$: Heat losses for the heating systems in the heating room.
- $f_{gen,PM}$: Correction factor for heating systems with integrated pump management.

The net heating demand from (1) is then used for the usable heating energy, which is calculated in (4) by adding losses and gains from the heating system and the net heating demand.

$$Q_{h,outg} = Q_{h,b} + Q_{h,ce} + Q_{h,d} + Q_{h,s} \quad (4)$$

where:

- $Q_{h,outg}$: The usable heating energy for the building produced by the heating system.
- $Q_{h,b}$: The net heating demand from (1).
- $Q_{h,ce}$: Heat losses of transmission to environment.
- $Q_{h,d}$: Heat losses of heat distribution.
- $Q_{h,s}$: Heat losses of heat storage.

After calculating the final energy demand of the building, the primary energy demand is calculated in (5). The primary energy demand is the energy demand, which includes the energy required for the building and the energy required by systems outside the building.

$$Q_p = Q_{p,in} - Q_{p,out} \quad (5)$$

where:

- Q_p : The primary energy demand referred to heating.
- $Q_{p,in}$: The primary energy demand of the energy sources supplied from outside for the building.
- $Q_{p,out}$: The primary energy demand for energy sources outside of scope.

The final energy demand is then used for the calculation of $Q_{p,in}$ and $Q_{p,out}$ like it is displayed in (5) and (7).

$$Q_{p,in} = \sum_j (Q_{f,in,j} \cdot \frac{f_{p,j}}{f_{HS/Hi,j}}) \quad (6)$$

where:

- $Q_{p,in}$: Primary energy demand of the energy sources supplied from outside
: for the building.
- $Q_{f,in,j}$: Final energy provided from outside for the energy source j .
- $f_{p,j}$: Factor for the primary energy.
- $f_{HS/Hi,j}$: Conversion factor for the final energy.

$$Q_{p,out} = \sum_j (Q_{f,out,j} \cdot f_{p,j}) \quad (7)$$

where:

- $Q_{p,out}$: Primary energy demand for processes outside of the scope of the building.
- $Q_{f,out,j}$: Final energy provided from processes outside of the scope of the building
: for the energy source j .
- $f_{p,j}$: Factor for the primary energy.

After calculating the final and primary energy demand, an evaluation of the building according to the German law is possible. There is a mandatory form for the report stated by the federal Ministry of economic affairs in Germany, which helps to classify the energy demand into an energy efficiency class like it is shown in Figure 1.

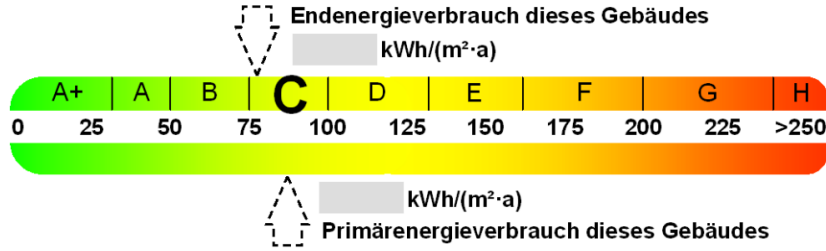


Figure 1: The scale for determining the energy efficiency class of a building is based on regulations from the federal Ministry of economic affairs in Germany. The top row classifies the final energy demand of the building, and the bottom one classifies the primary energy demand.

2.1.1 Influence of the buildings architecture

The building's architecture is necessary to calculate the basic properties of the building regarding its energy usage. This section will display how the building's components contribute to the energetic evaluation of the building to show the influence of specific parameters of the building's components.

(1) requires the heat sinks and sources. Those two values describe the energy produced and consumed by the building. Based on (8) and (9), it is evident that heat sinks and sources are dependent on the architecture of the building.

$$Q_{\text{source}} = Q_{\text{S}} + Q_{\text{T}} + Q_{\text{V}} + Q_{\text{I,source}} \quad (8)$$

where:

- Q_{source} : Sum of all heat sources in the building.
- Q_{S} : Heat sources due to solar radiation.
- Q_{T} : Heat sources due to transmission (heat transfer through building materials).
- Q_{V} : Heat sources due to ventilation.
- $Q_{\text{I,source}}$: Internal heat sources.

$$Q_{\text{sink}} = Q_{\text{T}} + Q_{\text{V}} + Q_{\text{I,sink}} + Q_{\text{S}} \quad (9)$$

where:

- Q_{sink} : Sum of all heat sinks in the building.
- Q_{T} : Heat sinks due to transmission (heat transfer through building materials).
- Q_{V} : Heat sinks due to ventilation.
- $Q_{\text{I,sink}}$: Internal heat sinks.
- Q_{S} : Heat sinks due to solar radiation.

The components of a building are measured with different values, which are explained in detail in Section 4.3.2. Those values mainly determine the heat sinks and sources. Besides the dimensions of a building's components, the heat transfer coefficient is required for many components. The heat transfer coefficient describes the ability of a material to conduct heat. It is measured in $W/(m^2K)$; the smaller the value, the better the component's insulation. The heat transfer coefficient is used to calculate heat sinks and sources due to transmission by calculating the heat transmission coefficient of the complete component with (10).

$$H_{\text{T,D}} = \sum (U_j \cdot A_j) \quad (10)$$

where:

- $H_{\text{T,D}}$: Heat transmission coefficient.
- A_j : Area of the component.
- U_j : Heat transfer of the coefficient.

$H_{\text{T,D}}$ is then used to calculate the amount of heat sinks and sources due to transmission shown in (11):

$$Q_{\text{T}} = \sum_j H_{\text{T,D}} \cdot (\theta_i - \theta_j) \cdot t \quad (11)$$

where:

- Q_{T} : Heat sinks due to transmission.
- $H_{\text{T,D}}$: Heat transmission coefficient.
- θ_i : Temperature inside the building.
- θ_j : Average temperature outdoors.
- t : Duration of the step ($t = 24h$).

(11) also applies for heat sources with the same formula only θ_i and θ_j are swapped.

For transparent components like windows, the heat sinks and sources due to solar radiation account for the heat generation or loss of those components. Instead of the heat transfer coefficient, the energy throughput of the glass is determined. With the help of this energy throughput factor, the heat sinks and sources required in (9) and (8) can be calculated shown in (12).

$$Q_{S, \text{tr}} = F_F \cdot A \cdot g_{\text{eff}} \cdot I_S \cdot t \quad (12)$$

where:

- $Q_{S, \text{tr}}$: Heat gain due to solar radiation.
- F_F : Reduction factor for the size of the window border.
- A : Area of the component.
- g_{eff} : Effective energy throughput factor.
- I_S : Average solar radiation during the month of calculation.
- t : Duration of the step ($t = 24h$).

2.2 The procedure of the algorithm

After gathering the necessary data about the building, the *EnerEval*-algorithm starts by calculating the net energy demand of the building. The net energy demand describes the energy required by the house's different parts. For example, parts of the net energy demand are the net heating or the energy demand required for tap water heating.

Parts of the calculation of the net energy demand are an iterative procedure, where the algorithm needs the inner heat sources of the building for the net heating demand. However, the amount of the produced energy by heat sources is only known when the algorithm calculates the power of the heating system. This calculation, in turn, needs the required energy for heating in the building, calculated by knowing the heat sinks and sources, part of which is the heating system. This iterative procedure is shown in Figure 2.

Differences in the conditions over the year are considered in the algorithm using a procedure where each intermediate and final value is calculated for each of the twelve months [11].

Furthermore, the algorithm requires the user to determine usage areas in the building, which are called zones. Areas with the same usage are grouped into one zone [4]. Each calculation is then run per zone and later combined.

With the help of the net energy demand, the algorithm calculates the final energy [4]. Which in turn is used for calculating the primary energy.

2.3 Updates to the old version of the algorithm

The currently implemented algorithm uses from the year 2011 of DIN V 18599 norm [11]. In the following sections, this work will describe some of the changes made in comparison to the 2018 version of the norm.

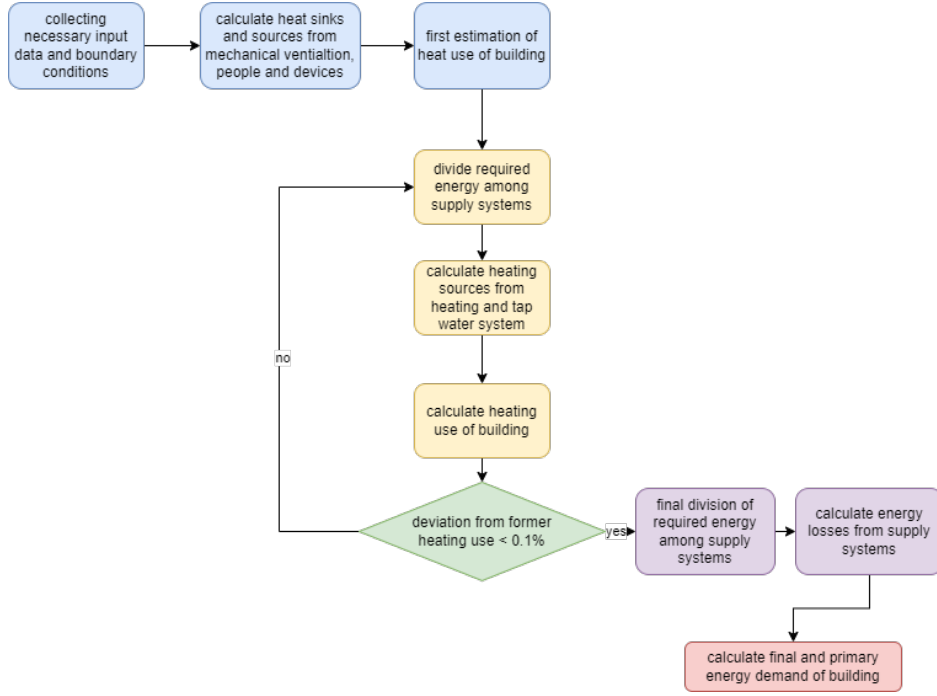


Figure 2: The process of calculating the energy demand of a building according to [4]. After collecting the necessary data and a first estimation of the heat use, the iterative process is started by dividing the heat use among heating systems and recalculating the heat use. If the deviation of the newly calculated heat use to the old one is greater than 0.1%, the procedure is repeated.

2.3.1 Solar systems

The section for solar systems in parts 5 and 8 in the DIN V 18599 was reworked. Instead of default values, the norm calculates the needed collector size depending on the degree, orientation and radiation values [4]. The radiation values are given in the norm and describe the average solar radiation onto a solar collector per hour in $Wh/(m^2h)$. The necessary input stays the same with the year of construction, the pitch of the collectors in degrees and the deviation from the south orientation in degrees. The calculation of the average required collector size is displayed in (13).

$$A_c = \frac{(Q_{w, \text{outg}, d} + Q_{h, \text{outg}, d}) \cdot e_{\text{sol}, \text{ce}} \cdot e_{\text{sol}, d}}{\max(\bar{q}_{\text{sol}, d, \text{mth}})} \quad (13)$$

where:

- A_c : The average collector size in m^2 .
- $Q_{w, \text{outg}, d}$: Daily heat emission for the tap water heating in $kWh/(m^2 \cdot d)$
- $Q_{h, \text{outg}, d}$: The daily heat emission for the heating system in kWh/d
- $e_{\text{sol}, \text{ce}}$: Factor for the heat transfer in the heat cycle.
- $e_{\text{sol}, d}$: Factor for the heat loss in the heat cycle.
- $\bar{q}_{\text{sol}, d, \text{mth}}$: The average daily energy gain from solar radiation per month in kWh/d .

The goal for calculating the solar system is to compute the monthly energy output of the solar system for tap water and heating. Those values are denoted with $Q_{w,sol}$ and $Q_{h,sol}$ and, in this work's implementation, have the unit Wh .

2.3.2 Heat Pumps

In parts 5 and 8 of the DIN V 18599, heat pumps are discussed as a heat and heating tap water generator. This part was also revised [4], mainly calculating the heating load of the heat pump with maximal power consumption.

The most notable difference to other calculations of the DIN V 18599 is the use of temperature classes. Those classes represent predefined temperatures, where the heating power of the heat pump is known [3]. Temperature bins are calculated to determine the heat pump's performance at different monthly temperatures, [4]. Temperature bins represent an interval of temperatures around a central temperature. The given norm uses the frequency of each temperature for each month to calculate the temperature bins for each temperature class to calculate the number of hours for each temperature bin per month. The bins for each temperature class are then used to calculate runtimes for the heat pump and the time until a second heat source has to be used when the heat pump's heat generation is insufficient due to low outside temperatures.

3 Implementation of the algorithm

This section will give an introduction to the implementation of the algorithm as well as its performance.

The algorithm described above has been implemented in Python, and the input file format is JSON. After reading the input, the program saves all the necessary information in the `Building` class. This class is also the baseline for all calculations for the required values, as it holds the necessary functions for running the individual steps shown in 2. The input files are based on the reference buildings from [5] and store general information about the building, the heating and tap water system and the building components. In addition, some of the default values used in the implementation are stored in JSON files.

The intermediate values for the different calculations are also stored in the `Building` class. After the final values are calculated, the reference results from the EVA Leuchter program are used to calculate the different deviations (see Section 3.1). The reference results from EVA Leuchter are stored in JSON files as well.

Besides the input file with the complete building information, the user can also state the norm version that the algorithm should use so that every change made by this work to the existing implementation is non-destructive. The old implementation can still be used by selecting an older norm version.

The implementation also has been profiled in terms of runtime. One of the main goals of this project is that the simulation is quick. An analysis in [11] showed that

comparable programs have higher runtimes for the same calculations than the implementation of Nick Feiereisen [11].

This work uses cProfile and SnakeViz to profile the runtime in milliseconds. Each test case will be run a thousand times to accommodate any fluctuations on the test computer.

Table 2 displays the profiling results. Comparing the run times to the times from the EVA Leuchter program, which have been measured by [11], this work implementation is quicker than the EVA Leuchter implementation. It has to be noted that the profiling done by Nick Feiereisen [11] and this work has been measured on different machines, and minor deviations can be expected when comparing the run times of the version of Nick Feiereisen [11] and this works run times. No significant difference is visible in comparing the updated and old versions of the algorithm.

Figure 3 displays the visualisation of the profiling in an icicle diagram. In this diagram, it is visible that generating the output file takes about 40% of the complete run time. This part is an extra step in the EVA Leuchter program, which is not counted in the run time calculation.

	5	6	7	8	11
runtime single family building [ms]	86.7	110	130	101	92.1
runtime apartment building [ms]	67.1	75.6	86.3	92.2	62

Table 2: Showing the run time of the implemented DIN V 18599 algorithm for different test cases in milliseconds. The run time includes the time for generating an output file. The test cases are taken from [5] with a slight adaption for the 2018 norm version. There are test cases for single-family and apartment buildings. The cases with the same index can be different scenarios for single-family and apartment buildings.

3.1 Validation

The updates made to the existing algorithm have to be validated. The version of Nick Feiereisen [11] used the reference result from the *18599 Gutegemeinschaft* [5]. However, this validation can not be used for the 2018 norm version, as the reference results from the *18599 Gutegemeinschaft* are no longer publicly available for the new version. Instead, this work uses the EVA Leuchter software, discussed in Section 1.2, by utilizing the *Berechnungen 18599* export functionality to get the final results and some interim results. With the help of a self-written Python parser, the results from the EVA Leuchter software are parsed into a format that the algorithm can use to compare its results.

According to the *Gutegemeinschaft* [5], a value is valid if the calculated value does not deviate more than one per cent from the reference value. For this work, the validation has to be done to mark the algorithm as din conform. However, the EVA Leuchter

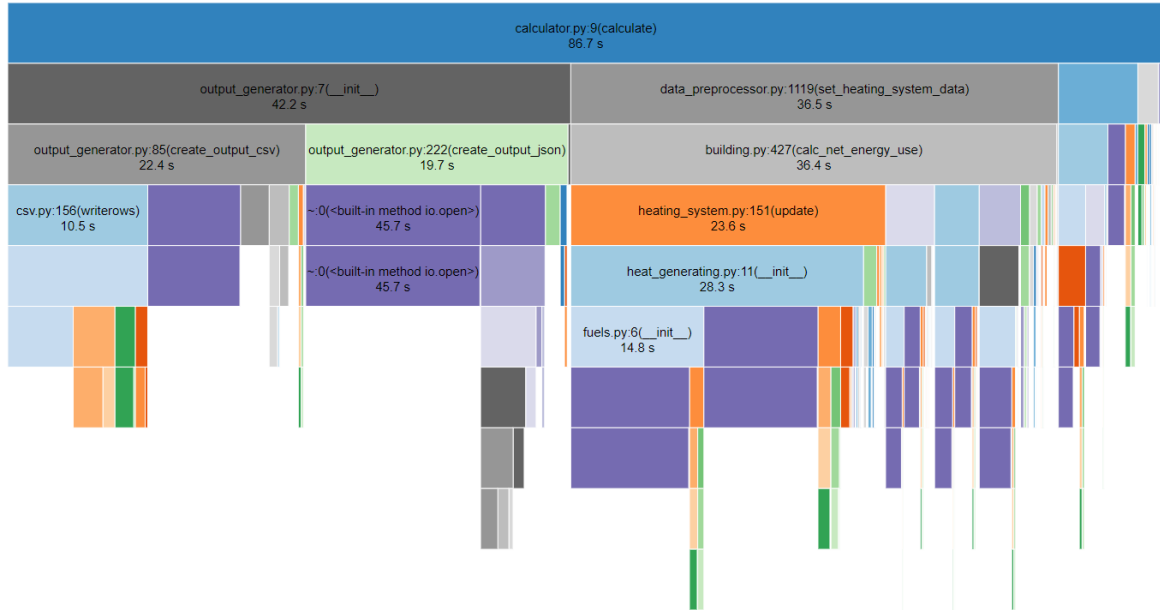


Figure 3: The profiling for the single-family building case 5 from [5]. This figure displays the runtimes for running the test case a thousand times to consider variations in the testing system.

output is incomplete because not all values used for the validation are given by the EVA Leuchter program. As the software itself has been validated in conformance with the *Gutegemeinschaft*, this work uses the values from the software for validation. It tests the implementation so that this work’s calculated values stay within one per cent of the results from the EVA Leuchter software.

4 Relaxation of the algorithm

This section will describe the relaxation made to the existing algorithm. Modifications and assumptions made by this work will be discussed and justified. The modifications will be validated in Section 5.

4.1 Goal

In the implementation from Nick Feiereisen [11] the algorithm needs the complete input of the calculation. This input file is about 600 lines long and requires significant work to create for a new building. In order to simplify this process with a more consumer-friendly approach in mind, this work will show a way to simplify the input data by using a relaxed building model for the *EnerEval*-algorithm.

In the second step, the modifications and simplifications will be analysed so that assumptions about the quality and uncertainty of the presented changes can be made.

4.2 Procedure

The predefined goal of this work is to implement a consumer mode and an expert mode for the input. For each of the two modes, there exists an input file format. The program parses the simple input into an input readable by the existing implementation from Nick Feiereisen [11] to use the simplified input in the relaxed model of the *EnerEval*-Algorithm. The general overview of the process is shown in Figure 4.

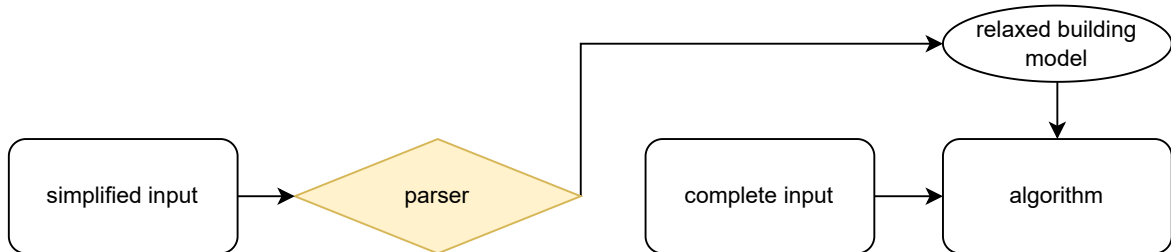


Figure 4: The process of using a simplified user input for the algorithm. With the help of a parser, a relaxed building model is created and given to the algorithm.

The relaxed building model created from the simplified input can also be converted to a complete input to make an expert mode possible.

4.3 Overview of the simplifications

In this section, the process of the parser will be discussed. This work will show the procedure of creating a relaxed building model form the simple input format and explain the reasons for relaxations and modifications.

4.3.1 Building architecture

The *EnerEval*-algorithm and its implementation by Nick Feiereisen [11] require specific figures about the building. This work uses a building model shown in Figure 5 to calculate these numbers from a simplified input.

The algorithm requires the following values about the building:

1. The external volume describes the volume of the building, including outer walls and roof (V_e).
2. The net volume describes the volume of the buildings heated air (V).
3. The usable area in the heated space in m^2 (A_N).
4. The storey height is the average height of storeys in the building (h_G).
5. Length and width describe the characteristic length (L_{char}) and width (B_{char}) of the building.

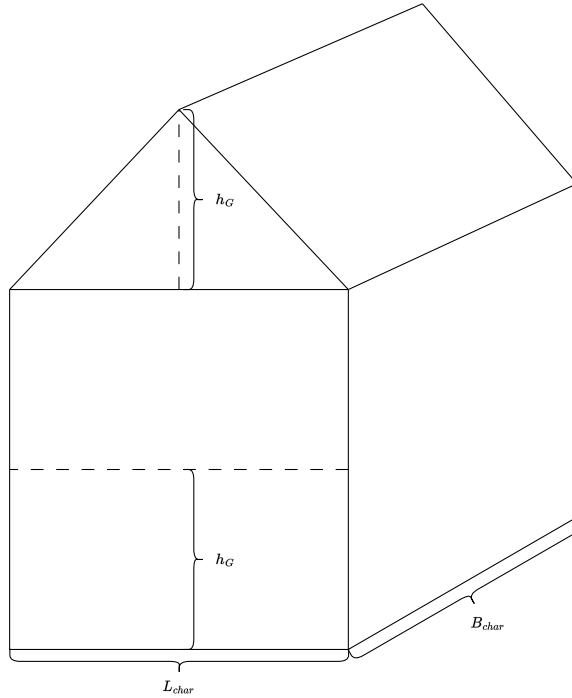


Figure 5: The idealistic building used for the relaxed building model. The building has a pitched roof, two full storeys, and an additional attic. The building could also have a flat roof, and the number of storeys and the dimensions can vary. h_G is the storey height. L_{char} and B_{char} are the length and width of the building.

In the simplified version of the input, the goal is to ask for as few parameters as possible about the building. The parameters which are required in the simplified version for the building dimensions are:

1. The amount of conditioned storeys
2. Whether there exists an additional attic in the building, which is heated as well.
3. The average storey height in m .
4. The lengths of the building in m .

The building model asked for is only the part of the building that is heated and used. Besides the cellar, the relaxed building model will not consider unheated areas.

In the first step, an approximation of the living area is calculated in (14).

$$A_{living} = L_{char} \cdot B_{char} \cdot \#\text{storeys} \quad (14)$$

where:

A_{living} : The living area in m^2 .
 L_{char} : The characteristic length of the building in meter.
 B_{char} : The characteristic width of the building in meter.
 $\#storeys$: The number of full storeys.

If the input also states that the house has an additional heated attic, it is counted as an additional storey, so $A_{living} = A_{living} + L_{char} \cdot B_{char}$ for the additional attic.

In a second step, the external volume is calculated:

$$V_e = A_{living} \cdot h_G \quad (15)$$

where:

V_e : The external volume in m^3
 A_{living} : The living area in m^2 .
 h_G : The average storey height in m .

According to the EVA-Leuchter program, the height of a ceiling is estimated at 0.25m. This work expects the user to input the clear room height as the storey height. In order to compensate for the ceiling height, 0.25m per storey is added to the height of the building.

$$V_e = V_e + L_{char} \cdot B_{char} \cdot \#storeys \cdot 0.25 \quad (16)$$

where:

V_e : The external volume in m^3
 L_{char} : The characteristic length of the building in meter.
 B_{char} : The characteristic width of the building in meter.
 $\#storeys$: The number of full storeys.

Until now, the building roof is missing in the calculation. However, suppose the user input states that there is an additional heated attic within the building. In that case, there is additional volume in the attic, which must also be taken into account. This work assumes that the volume of the attic is half of the volume of a complete storey. However, the additional attic is already included in A_{living} , V_e has to be reduced by half of the average storey volume.

With the help of this estimation of the external Volume V_e [4] gives in section 8.2 formulas for the remaining values A_N , V , A_{NGF} .

4.3.2 Overview components

In the complete input used in the implementation of Nick Feiereisen [11], each component has to be given explicitly, with its size and specific values like the heat transfer coefficient. This work assumes that the user of the simplified version cannot identify each value, so this work estimates most of the necessary data based on a reduced amount of questions and the dimensions of the building, given in section 4.3.1.

The required values for the different components are displayed in Section 2.1.1.

4.3.3 Walls

This work only considers the outer building walls as walls and disregards inner walls. The size of the building determines the size of the walls. Four walls are created for each side of the building, each representing one cardinal direction. The dimensions are read from the height and length of the building. The algorithm also requires the heat transfer coefficient for each component [4]. In the complete input for the algorithm, this value is given for each component, as it depends on the composition of the component [2]. There are three fields in the simplified input to estimate the heat transfer coefficient:

1. The year, the house was build
2. The approximate thickness of the outer wall in centimeter.
3. The predominant material, the wall is made of.

In implementing the parser, there are two ways to determine the heat transfer coefficient. The first one requires all three parameters from above and determines the heat transfer coefficient with the help of key-value stores, where the implementation maps the thickness and material of the walls to a predefined heat transfer coefficient value. The key-value store is created with the help of [2], where interpolations for different building materials and their corresponding heat transfer coefficient at a specific thickness are displayed. The values are shown in Table 3. However, as it is impossible to copy the interpolation from the source into this works code, five typical wall thicknesses are picked⁴. The key-value store saves the heat transfer coefficient for each wall thickness, and the parser fits the input wall thickness to the closest thickness from the five typical thicknesses.

thickness [cm]	24	30	36.5	42.5	49
	$[W/(m^2K)]$	$[W/(m^2K)]$	$[W/(m^2K)]$	$[W/(m^2K)]$	$[W/(m^2K)]$
brick	2.4	2	1.8	1.6	1.5
sandstone	2.5	2.2	1.9	1.7	1.6
concrete block	1.1	0.9	0.8	0.8	0.8
pumice	1.2	1.	0.8	0.7	0.7

Table 3: The outer wall heat transfer coefficient values depend on the material and the thickness. Source [2]

Another method for calculating the heat transfer coefficient is to use the value required by laws in the respective country. For this work, the target country is Germany. The country first introduced a law which sets a maximum for different heat transfer coefficients in 1977 [6]. Buildings built before 1977 are not applicable here and need to use the first method for calculating the heat transfer coefficient presented before. The maximal heat transfer coefficients for each version of the law are presented in Table 4.

⁴hausjournal.net. Mauerwerk: welche Dicke ist üblich? - <https://www.hausjournal.net/mauerwerk-dicke>

year of heat insulation ordinance	heat transfer coefficient [W/m^2K]
1977	0.9
1984	0.6
1994	0.5

Table 4: Different maximal heat transfer coefficients required by law for outer walls. Each new version of the heat insulation ordinance required a lower heat transfer coefficient than the maximal heat transfer coefficient of the building’s outer walls.

4.3.4 Cellar

The cellar of a building can be heated or not heated. In both cases, an influence on the final energetic evaluation can not be ruled out, so the unheated cellar is also considered. The simplified input, therefor can take the following inputs:

1. If the building has a cellar.
2. If the cellar is heated.

The total area under the building is considered for the cellar if it exists. Additionally, the average storey height is taken as the height of the cellar, combined with the characteristic length and width to calculate the area of the cellar’s walls. The heat transfer coefficient used for the cellar’s walls is shown in 5. The displayed heat transfer coefficients are for an interval period when the specific ordinance was valid.

year of heat insulation ordinance	heat transfer coefficient [W/m^2K]
1977	0.99
1984	0.55
1994	0.35

Table 5: The heat transfer coefficient required by law for wall components which are connected to the earth. Based on [2].

Baseplate The baseplate, which connects the cellar to the floor, is calculated with the help of the living area per storey. Furthermore, the heat transfer coefficient is taken from Table 6.

4.3.5 Windows

To include the windows of a building in the calculation, the following parameters are required by for the *EnerEval*-algorithm [4]:

construction year	heat transfer coefficient $[W/m^2K]$
until 1918	1.6
1919-1948	1.6
1949-1957	2.3
1958-1968	1.2
1969-1978	1.2
1979-1983	0.8
1984-1994	0.6
1995-2001	0.6
since 2002	0.5

Table 6: The heat transfer coefficient of baseplate components for buildings. Based on data given by the federal Ministry of economic affairs in Germany.

1. The area of the window in m^2 .
2. The heat transfer coefficient of the component.
3. The total energy transmittance for perpendicular incidence of solar radiation.
4. The temperature correction factor.

The heat transfer coefficient is determined with the help of information given by the federal Ministry of economic affairs in Germany ⁵. This regulation gives orientation values for the heat transfer coefficient for windows depending on the frame material and the year the window was built, shown in Table 7.

border type	until 1978	1979-1983	1984-1994	1995-2001	from 2002
	$[W/(m^2K)]$	$[W/(m^2K)]$	$[W/(m^2K)]$	$[W/(m^2K)]$	$[W/(m^2K)]$
wood	5.0	5.0	5.0	5.0	5.0
wood double window	2.7	2.7	2.7	1.6	1.5
plastic	3.0	3.0	3.0	1.9	1.5
aluminium	4.3	4.3	3.2	1.9	1.5

Table 7: The heat transfer coefficient for different types of windows depending on their border material and the year, the window was built. Based on data from the federal Ministry of economic affairs in Germany.

The total energy transmittance of the window is determined similarly, but in this case, Table 8 in part two of the DIN V 18599 norm [4] is used. For different glass types, there are the values for the total energy transmittance shown. In addition, there are

⁵Bundesministerium für Wirtschaft und Energie and Bundesministerium des Innern, für Bau und Heimat. Bekanntmachung der Regeln zur Datenaufnahme und Datenverwendung im Wohngebäudebestand, 8.10.2020.

different values of energy transmittance for windows with and without sun protection. Those are depicted in Table 8 as well. Table 8 shows the values used for this work.

type of glass	with sun protection	without sun protection
single-glass	0.12	0.87
double-glass	0.1	0.78
heating-protection-glass	0.08	0.72

Table 8: The total energy transmittance for different types of glass.

The temperature correction factor depending on the glass type is depicted in Table 9.

type of glass	temperature correction factor
single-glass	0.8
double-glass	0.7
heating-protection-glass	0.5

Table 9: The temperature correction factor for different types of windows. Based on Table 5 in part two of [4]

The area of the windows is calculated for each side and not for each window. This work uses the area of the outer building wall from section 4.3.1 for the respective side to estimate the window area. This work assumes that 30% of each side of the building is used by windows. This assumption is based on data from the federal Ministry of economic affairs in Germany, which states that for a simplified procedure, the percentage of windows in the facade is not greater than 30%.

With the help of the above assumptions, the necessary input for the simplified version can be created:

1. The year the house was built or the year the windows were changed.
2. Whether there is sun protection in front of the windows.
3. The type of window glass.
4. The type of window border.

4.3.6 Roof

The roof of the building can either be a flat roof or a peaked roof. If the user input states that the building has an additional attic, this work assumes that the building has a peaked roof.

If the building has a flat roof, the area is computed with (17).

$$A_{roof} = L_{char} \cdot B_{char} \quad (17)$$

where:

A_{roof} : The area of the roof in m^2 .

L_{char} : The characteristic length of the building in meter.

B_{char} : The characteristic width of the building in meter.

If the building has a peaked roof, the area of the roof has to be calculated with the theorem of Pythagoras. As the height of the attic, the average storey height is assumed. This work assumes that the top of the roof, where both sides connect, is located at the centre of one side of the building, and the other side is the length of the roof, as shown in Figure 5. The area for one side of the peaked roof is calculated in (18).

$$A_{roof} = (h_G^2 + (\frac{L_{char}}{2})^2) \cdot B_{char} \quad (18)$$

where:

A_{roof} : The area of the one side of the peaked roof in m^2 .

L_{char} : The characteristic length of the building in meter.

B_{char} : The characteristic width of the building in meter.

h_G : The average storey height in meter.

For the heat transfer coefficient of the roof, this work uses the values from [2]. The values for a flat roof and a peaked roof are different, and the values are shown in table 10.

year	peaked roof [W/(m ² K)]	flat roof [W/(m ² K)]
until 1918	2.1	2.1
1919-1948	2.1	2.1
1949-1957	2.1	2.1
1958-1968	1.3	2.1
1969-1978	1.3	0.6
1979-1983	0.6	0.6
1984-1994	0.4	0.3
1995-2001	0.3	0.3
since 2002	0.2	0.2

Table 10: The heat transfer coefficient for a flat roof (outer ceiling) and a peaked roof component. Based on [2].

4.3.7 Heating system

According to [4], the heating systems split into the following parts: Transfer, Distribution, Storage and Generating.

All of these parts require different parameters as an input. This work uses different cases for heat generation, and, with the help of the existing test cases from [5], the complete input is created. This work assumes that the test cases cover various building scenarios and most building types in Germany.

The simplified input takes the following parameters for the heating system.

1. Type of heating generator (oil, gas, district heating, heat pump ...).
2. The year the heating system was installed.
3. The type of transfer (wall radiator or floor heating).
4. Whether the majority of pipes are insulated.
5. Whether there exists a heating storage.

For each type of heat generator [5] presents at least one test case. With the help of those cases, this work creates different configurations for the heat generators. Additionally, parameters are required for each part of the heating system mentioned above. Except for the values in the simple input, those parameters for the different systems are also based on the test cases in [5]. However, in the following, this work will discuss specific parameters for heating, which can be derived from the simplified user input.

Supply and return temperature The supply and return temperature in $^{\circ}C$ describes the ingoing and outgoing temperatures of the heating system. Depending on the type of heat generation, default values for the supply and return temperatures for floor heating and wall radiator can be used, like it is show in Table 11.

type	supply temperature [$^{\circ}C$]	return temperature [$^{\circ}C$]
floor heating	45	35
wall radiator	70	55

Table 11: The supply and return temperatures for different types of heat transfer systems ⁶. This work only takes the radiator type to determine the temperature because a floor heating needs a lower temperature than a wall radiator, as the heating surface is larger.

For the required energy of the heating system, the temperature difference between return and supply temperature is relevant ⁷. The higher the difference, the higher the

energy required to produce the required heat.

To consider the temperature differences between the room temperature and the temperature supplied by the heating system, [4] uses the overtemperature to determine the differences in the version of Nick Feiereisen [11], this value was supplied in the input. The simplified version calculates the value according to (19).

$$\Delta\theta_A = \frac{\theta_{VA} + \theta_{RA}}{2} - \theta_{I,h,soll} \quad (19)$$

where:

$\Delta\theta_A$: The average overtemperature in $^{\circ}C$.

θ_{VA} : The supply temperature in $^{\circ}C$.

θ_{RA} : The return temperature in $^{\circ}C$.

$\theta_{I,h,soll}$: The room temperature in $^{\circ}C$.

Heat transfer Heat transfer describes the part of the heating system which transfers the heat to the room. In this work, there are two different options for the heat transfer. The first one is a wall radiator. The second option for heat transfer is floor heating. This method integrates heat pipes in the floor and heats a room by utilizing the floor as a heating surface.

Net type Another variable factor for the heating configuration is the net type, so the type of heat distribution in the building. Its value is, among other things, used for calculating the pipe length of the heating system. This work considers two types of distribution defined in [4] (floor and wall) shown in Figures 6 and 7. For floor heating, this work uses the distribution type type II; type I is used for everything else.

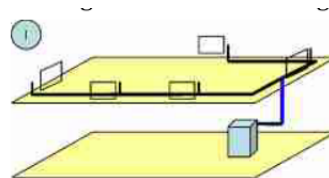


Figure 6: Net type I for distribution according to [4]. It is characterised by on single line per storey.

Heat generation This work uses predefined configurations for different heating systems in terms of heat generation. The current version supports the following types: Oil, gas, district heating and heat pump. For each of the heating types, this work has a predefined configuration. This configuration is the same for oil and gas, except

⁷energie-experten.org. Regelung und Kennzahlen der Vorlauftemperatur in Heizungsanlagen - <https://www.energie-experten.org/heizung/heizungstechnik/heizungskreislauf/vorlauftemperatur>

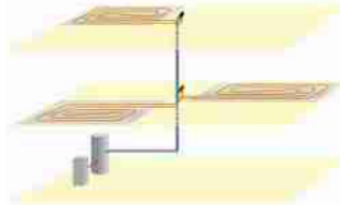


Figure 7: Net type II for distribution according to [4]. In general, this type of distribution uses one distribution unit per storey. In this case, floor heating is used for transfer.

that the heat generation fuel is either oil or gas. In addition, the generator type is an improved condensing boiler.

For the district heating, there exists a difference between fossil and renewable district heating. As most of the district heating in Germany is based on fossil fuels⁸, this work also estimates that if the user uses district heating, it is fossil-based.

If the user specifies that the building uses a heat pump, additional factors must be considered. There are different types of heat pumps, but the majority of heat pumps in Germany are air-water heat pumps [7], so this work uses air-water as the default type. For some heat pumps, there is also the possibility for a so-called *EVU-Lock*, and it enables grid operators to turn off the heat pump with an electrical signal if the electrical grid is overloaded. The average time for this EVU shutoff per day must also be considered in the DIN V 18599 norm. Most grid operators use a 6-hour shutoff per day [10]. Additionally, the bivalence temperature has to be considered. This temperature describes the outdoor temperature when it is too cold for the heat pump to generate the required energy, and a second heat generation source has to be used. This temperature is dependent on the technical details of the heat pump. This work uses $-2^{\circ}C$ as the bivalence temperature⁹.

4.3.8 Tap water system

The tap water system is responsible for heating the tap water of the building. The system can be divided into two categories. Central tap water heating systems have one heating unit, and the hot water gets distributed through pipes in the building. Decentral solutions heat the water at the destination, or for apartment buildings, heat the water per living unit. According to the *Bundesverband der Energie- und Wasserwirtschaft e.V.*¹⁰, most of the residential buildings in Germany have a central tap water heating system. Based on this statistic, this work does not require any

⁸Bundesministerium für Wirtschaft und Energie. Was ist eigentlich "Fernwärme"? <https://www.bmwi-energie-wende.de/EWD/Redaktion/Newsletter/2021/03/Meldung/direkt-erklart.html>

⁹energie-experten.org. Bedeutung des Bivalenzpunktes für verschiedene Wärmepumpenarten - <https://www.energie-experten.org/beitrag/waermepumpe/planung/bivalenzpunkt>

input about the tap water system for the simplified input format but instead assumes a central tap water heating unit connected to the heating system.

Like the heating system, the tap water system also separates into different parts:

Distribution The tap water distribution mainly includes the pipes and kind of distribution. Based on the test cases in [5], this work assumes The net type II for the distribution shown in Figure 8.

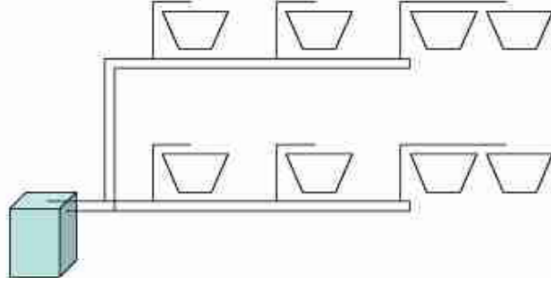


Figure 8: The net type II for the distribution of tap water systems. This type is characterised by a distribution per storey. Image from [4].

Furthermore, the length of the pipes is also calculated according to the DIN V 18599 part five [4], like it is shown in (20).

$$L_{\max} = 2 \cdot \left(L_{\text{char}} \cdot \frac{B_{\text{char}}}{2} + n_G \cdot h_G + l_d \right) \quad (20)$$

where:

L_{\max} : The maximal pipe length in the building.

L_{char} : The characteristic length of the building.

B_{char} : The characteristic width of the building.

n_G : Number of heated storeys.

h_G : Average storey height.

l_d : (= 10) Factor for attachment for heating systems with two pipes.

Storage Two storage the generated heated tap water. This work assumes and indirectly heated bivalent storage.

Generating Because this work assumes that the heating is central and in combination with the heating system, the heat generation part is similar to the one in Section 4.3.7 for the heating system.

¹⁰Bundesverband der Energie- und Wasserwirtschaft e.V.: Entwicklung des Wärmeverbrauchs in Deutschland, 16.03.2022

4.3.9 Ventilation System

About 96% of buildings in Germany are not equipped with mechanical ventilation¹¹. Because of this fact and also the fact that the simplified input would need additional parameters for mechanical ventilation, this work does not consider mechanical ventilation in the simplified version.

4.3.10 Solar system

The simplified input presents the possibility to state that the building has a solar system and, in that case, the year the solar system was installed. This information is then parsed into a solar system with a 45° pitch. Furthermore, this work assumes that the solar systems power the heating and tap water systems because this work assumes that both systems are combined.

4.4 Implementation

The implemented algorithm of the DIN V 18599 norm has been adapted to the simplified version so that the implementation can work with the simplified input and complete input without required changes to the code. The simple file type is marked with a flag `file_type`, which, if set to "simple" indicates that the input file is a simplified input file. An example of such a file is displayed in Listing 1. The JSON file consists of different parameters about the building, which are required to calculate the input data for the DIN V 18599 algorithm. Furthermore, the heating system is described as well.

¹¹Dr. Holger Cischinsky and Dr. Nikolaus Diefenbach. Datenerhebung Wohngebäudebestand 2016: Datenerhebung zu den energetischen Merkmalen und Modernisierungsraten im deutschen und hessischen Wohngebäudebestand. Institut Wohnen und Umwelt GmbH, 17.04.2018.

```

1 {
2   "file_type": "simple",
3   "climate_zone": 4,
4   "house_type": "single_family_house",
5   "construction_year": 2014,
6   "number_of_full_storeys": 1,
7   "additional_heated_attic": true,
8   "average_storey_height": 2.8,
9   "length1": 10,
10  "length2": 9,
11  "sun_protection_available": false,
12  "south_roof_orientation": true,
13  "wall_thickness": 50,
14  "wall_material": "none",
15  "window_border_type": "aluminum",
16  "window_glass_type": "double-glass",
17  "window_renovation_year": 2014,
18  "cellar_available": true,
19  "cellar_heated": true,
20  "solar_available": false,
21  "solar_system_building_year": 1998,
22
23  "heating_system": {
24    "generator_type": "district_heating",
25    "year": 2014,
26    "type_of_transfer": "wall_radiator",
27    "isolated": true,
28    "storage_available": false
29  }
30 }

```

Listing 1: Example for a simplified input form.

To convert an input file into a building class in Python, the file `data_preprocessor.py` contains two functions: `convert_simple()` and `convert_full()`, for converting the respective file type to a building object. After parsing the input file, the starting situation for the algorithm is the same, and the implemented algorithm for the DIN V 18599 calculates the required values.

```

1 def calculate(self,
2     input_file_path: str,
3     reference_file_path: str = None,
4     test_case_index: int = None,
5     din_standard: int = None
6 ):
7
8     # create preprocess class
9     self.processor = DataPreprocessor()
10
11    # conversion of input file
12    self.processor.convert(
13        input_file_path,
14        din_standard=din_standard
15    )
16
17    # approximate balancing of the energy use
18    self.processor.building.calc_approximate_energy_use()
19
20    # heating system data after energy requirement is known
21    self.processor.set_heating_system_data()
22
23    # calculate the final energy
24    self.processor.building.calc_final_energy()
25
26    # calculate the primary energy
27    self.processor.building.calc_primary_energy()
28
29    # calculate the primary energy per square meter (use area) and
30    # set the corresponding energy efficiency class
    self.processor.building.calc_energy_efficiency_class()

```

Listing 2: Necessary function calls for calculating the required values for the DIN V 18599 norm.

The main procedure of the algorithm is managed in the Calculator class. Listing 2 displays an extract from the calculate function in the Calculator class, which shows the different function calls to calculate the required values. Additionally, the algorithm gives the possibility to set reference results. With the help of those results, the implementation generates an output which displays all calculated values and their deviations from the reference results.

4.5 Runtime

This work takes a base case and compares the runtimes to a similar test case from [5]. The chosen test case is similar to the one in Figure 3, which describes a single-family building with a gas heating system. The same scenario has been created with the relaxed building model, and the calculation was profiled as described in Section 3. The

test case is run a thousand times. The profiling has been made with cProfile, and the visualisation with SnakeViz is shown in Figure 9.

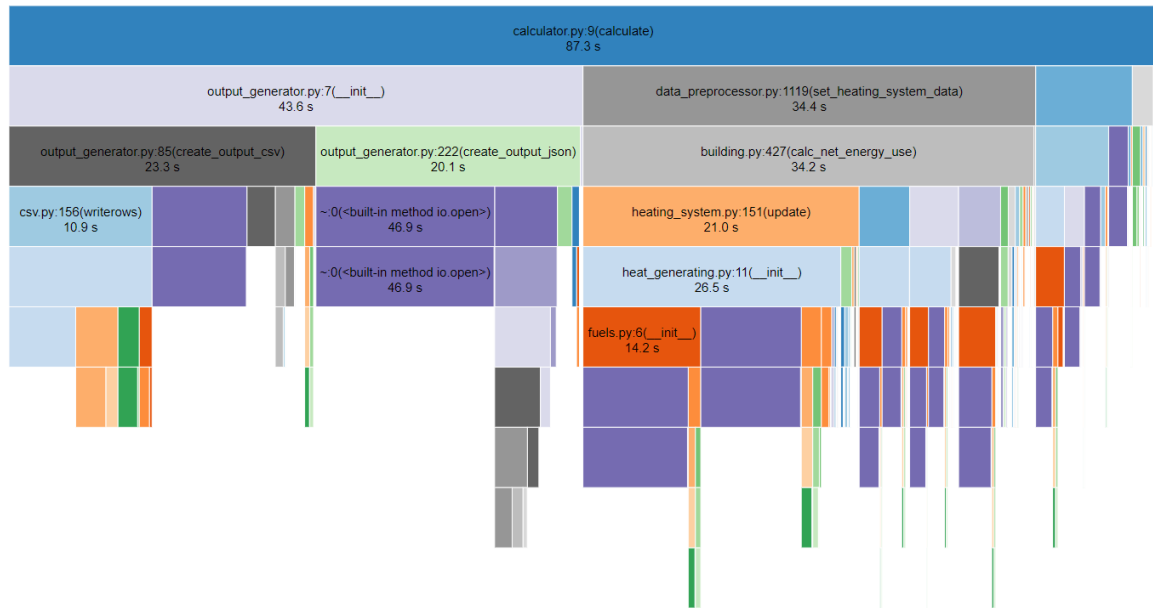


Figure 9: Profiling of the implementation with a simplified input. The program has been run a thousand times to generate an average result, which results are shown in this figure.

This base case displays that the relaxed building model’s runtime and complete input format do not differ. This result is not surprising, as the parser for the simplified input format does not contain any heavy calculations, and most of the required values are taken from existing value tables.

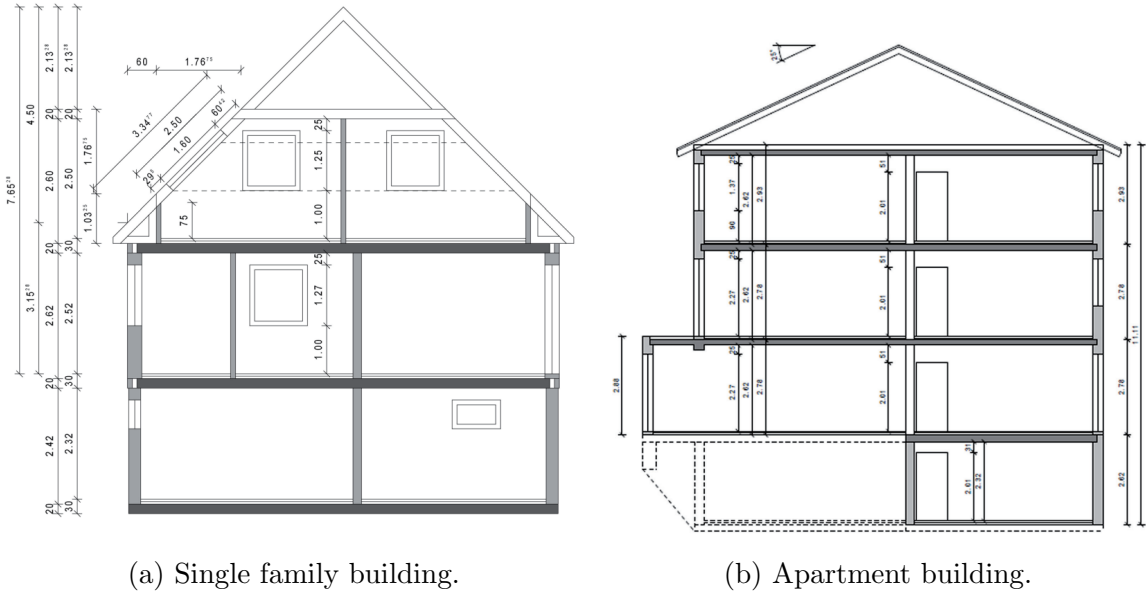
5 Validation of the relaxation

This section will show the accuracy of the presented simplification and the limitations of the presented approach.

5.1 Reference buildings and test cases

This work uses two reference buildings from the *Gutegemeinschaft* provided for validating the implementations of the DIN V 18599 norm. The two reference buildings cover the apartment and single-family building cases. The two buildings are shown in 10. For the single-family building, the cellar is heated, and the attic is heated as well. For the apartment building, the cellar is only partly heated to a small degree, and the attic is not heated. Furthermore, the attic in the single-family house is not fully used.

The previously discussed reference buildings are used in the test cases for single-family and apartment buildings. Each test case exists for the two building types



(a) Single family building.

(b) Apartment building.

Figure 10: The two reference buildings from [5].

and tests different configurations of the building systems. This work uses various test cases covering most of the available configurations. Table 12 shows the different configurations of the reference building taken from [5].

Test case index	Properties
5	gas heating, wall radiator
6	gas heating, wall radiator, solar
7	gas heating, wall radiator, solar, mechanical ventilation
8	oil heating, wall radiator
9	gas heating, floor heating
10	gas heating, wall radiator, mechanical ventilation (exhaust & supply)
11	heat pump, floor heating

Table 12: Displaying the different test cases and their configuration for the building systems. Adapted from [5].

The reference buildings have to be replicated with the help of the simplified input. This work estimates the best values for the building architecture for the simplified input because the reference buildings only provide a list of each component with its respective properties, like the heat transfer coefficient. However, this work implementation of the simplified input uses construction year values for the components to determine properties using predefined look-up tables. The simplified input's construction year and window renovation year are chosen to calculate the components with similar properties to those in the reference building. Table 13 displays the chosen values for the two building types.

Building Type	Construction Year	Window Renovation Year
Single Family House	2014	2014
Apartment Building	2014	2014

Table 13: The chosen construction year and window renovation year to rebuild the reference buildings with the help of the simplified input discussed in this work.

The construction materials for walls and windows are chosen, similar to the approach with the construction and window renovation year. In this case, the values for the single-family and apartment buildings are the same and are shown in Table 14.

Property	Value
wall thickness	50
wall material	none
window border type	aluminum
window glass type	double glass

Table 14: The properties for the single-family house and apartment building imitate the reference building.

Furthermore, the attic and cellar have to be considered as well. The attic is an extra storey with living space for the single-family building, so the simplified input will consider the attic as heated. The cellar in the single-family reference building is only partly heated. However, as the amount of heated space is greater than the amount of unheated space in the cellar, the simplified input will state that the building has a heated cellar. The attic is not heated for the apartment building, and the cellar is only to a small fraction, so the simplified input for the apartment building test cases will state that there is no heated attic and an unheated cellar.

The length and width of the building are taken from the characteristic length and width of the reference building.

5.2 Deviation from existing test cases

This section will use the previously discussed test cases with the two reference buildings to compare the calculation results with a simplified and complete input.

Table 15 displays the results for different test cases with a deviation when using a simplified input format for the test case compared to a complete input format.

The first of Table 15 shows that the deviation varies notably throughout the test cases. This variation indicates that the presented simplifications work in some instances with excellent accuracy, and in other cases, the accuracy is less precise. Furthermore, the apartment buildings display more precise results. Because the two reference buildings for single-family buildings and apartment buildings differ in dimensions and the

configuration for the test cases are similar for each test case for the two building types, this work assumes that the dimensions calculated by the parser from the simple input file format have a strong influence on the overall result. To investigate this assumption, Section 5.3 will examine the influence of the building’s architecture.

test case	type	complete input	simplified input	deviation
		final energy [$kWh/(m^2 a)$]	final energy [$kWh/(m^2 a)$]	[%]
5	SFB	130.16	162.99	-15.55
6	SFB	117.65	117.06	0.51
7	SFB	111.59	117.06	-4.90
8	SFB	107.35	112.41	-4.72
9	SFB	96.91	116.76	-20.48
10	SFB	108.97	162.99	-49.58
11	SFB	61.46	79.92	-30.04
5	AB	106.49	97.19	8.73
6	AB	92.00	71.92	21.83
7	AB	86.02	71.92	16.39
8	AB	70.09	69.34	1.07
9	AB	73.75	71.39	3.20
10	AB	84.73	97.19	-14.70
11	AB	94.71	97.19	-2.62

Table 15: The deviation of different test cases for the simplified input format from the same test case with a complete input format. The values are displayed for the final energy, the deviation in per cent. There exist test cases for single-family buildings (*SFB*) and apartment buildings (*AB*). The index of the cases is orientated at [5]. The deviations for the primary energy are similar to the ones for the final energy for each test case.

5.3 Influence of the building architecture

Besides the building systems with the heating system, the building architecture with its components and dimensions is the other relevant factor calculated when parsing the simplified input. The calculation of the building architecture and components and the resulting heat sinks and sources depend highly on the given input about the building in the simplified input format. In this section, the influence of the building architecture on the final result will be analysed to give an overview of the importance and influence of the uncertainty of specific parameters in the simplified input.

For the apartment and single-family building test cases, the Forschungsinitiative Bau [5] provides two reference buildings - one for the single-family building and one for the apartment building cases. Section 4.3.1 in this work describes that some of the building dimensions’ parameters are calculated based on the simplified input. Table

16 displays calculated building dimensions based on Section 4.3.1. Especially for the single-family reference building, the calculated area and volume deviate notably from the original value, partly due to the basement, which is only half heated. The relaxed building can not model this fact because only the option for heating the complete cellar can be selected. A similar case is with the apartment building, but because only the stairwell to the cellar is heated, the simplified input for the apartment test cases states that the cellar is not heated.

The high deviation for the volume and area in the single-family building cases shows that the building architecture can be an essential factor for the overall result. Furthermore, they can explain the differences in the deviations in Table 15 for the two reference buildings.

It should also be noted that, generally, the values of the calculated and actual dimensions of the building will differ, as this work only calculates the values based on a building model and real-world buildings often differ from this model.

	Complete Input	Simple Input	Deviation [%]
Single Family Building			
usable area [m^2]	148.51	126.36	-14.91
outer volume [m^3]	464.1	394.875	-14.92
inner volume [m^3]	349.26	300.105	-14.07
Apartment building			
usable area [m^2]	551.9	560.736	5.95
outer volume [m^3]	1724.7	1752.3	5.95
inner volume [m^3]	1318.51	1331.748	3.79

Table 16: Properties about the building dimensions for the two reference buildings in the single-family and apartment buildings test cases. The reference buildings are taken from [5]. In the complete input, the displayed values are directly taken from the reference and do not have to be calculated. For the simplified input format, the displayed values are calculated based on Section 4.3.1. The deviation is the value calculated from the simplified input format to the value from the complete input format.

5.3.1 Usable area

The usable area gives one indication of the influence of the building dimensions on the final result. The influence of the usable area was investigated by changing the value of the usable area in the reference building and comparing the results to the building created by the simple input parser. To show how the result of the energetic evaluation develops if the estimation of the usable area is less precise, Figure 11 displays the development of the deviation of the final energy if the relaxed model calculation is less precise.

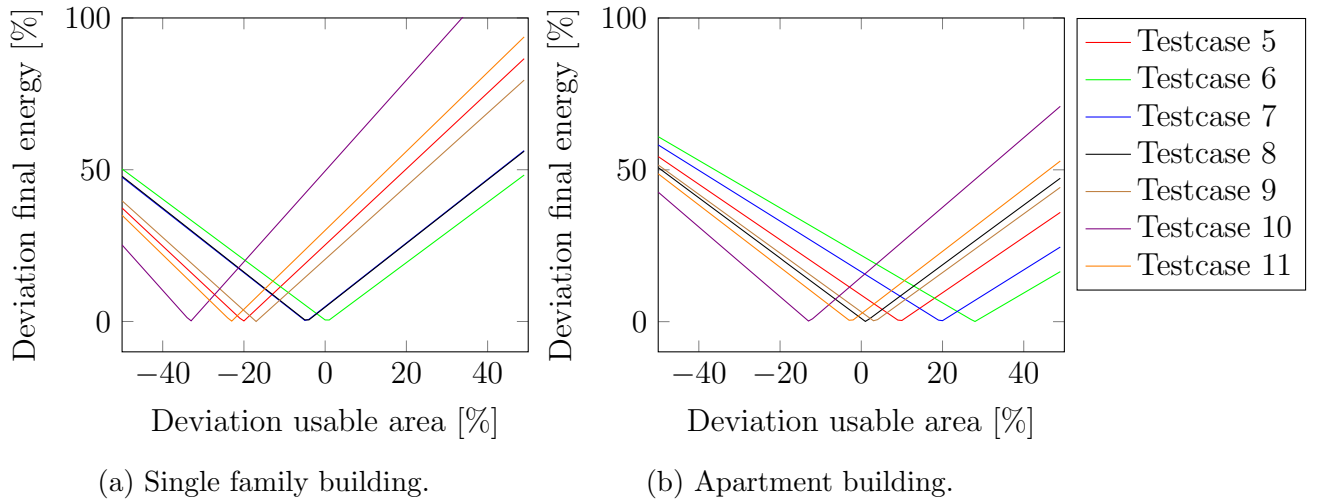


Figure 11: The deviation of the final energy between the reference buildings and the calculated building by the parser with the simplified input. The usable area in the reference building is changed to simulate a deviation between the calculated building and the reference building. The Graphs are split up into single-family and apartment buildings.

For each test case, the minimum deviation of the final energy should be at 0% of the deviation of the net volume, which would show a perfect deviation. However, this behaviour is not visible for every test case, as the overall result is not exactly precise and deviates like it is already shown in Table 15. However, besides the shift on the x-axis, the displayed behaviour is similar for test cases with the same reference building.

Generally, the difference between the single-family and apartment buildings is notable. Besides the overall higher deviation for the single-family buildings, the incline of the deviation is slighter in the apartment building cases. Minor errors in estimating the building dimension oppose a more negligible risk for a wrong estimation of the final result in the apartment building case than in the single-family building.

5.3.2 Net volume

To further investigate the robustness of the model, if the building dimensions are not calculated accurately, Figure 12 displays the deviations between a calculation with a simple input and one with a complete input for different test cases. By incriminating the net volume of the building in the reference model, a deviation from the simple input to the reference model is simulated.

Similar to the usable area displayed in Figure 11, a minimum at 0% deviation on the x-axis displays a perfect replication of the reference test case by the simple input parser.

Compared to the usable area, the deviation of the final energy is minor if the calculation of the net volume is incorrect. So, an overall area in the net volume less influences

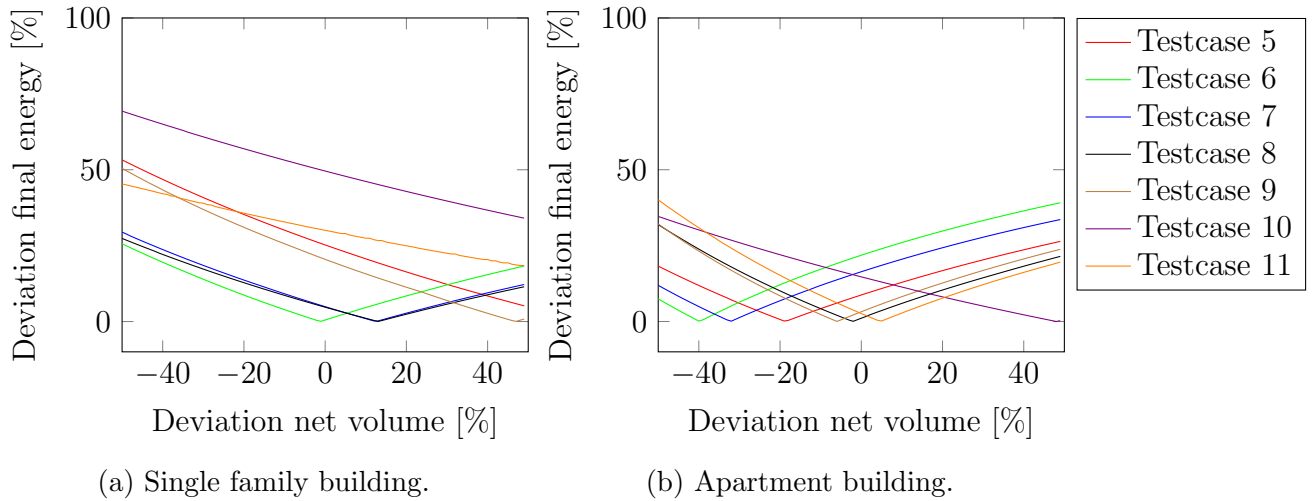


Figure 12: The deviation of the final energy between the reference buildings and the calculated building by the parser with the simplified input. The net area in the reference building is changed to simulate a deviation between the calculated building and the reference building. The Graphs are split up into single-family and apartment buildings.

the final result than an error in the usable area.

Furthermore, there is a difference between the single-family building and the apartment building. Some of the test cases for the single-family building do not display a minimum at all and show a negative incline, which indicates that factors during the calculation that are influenced by the net volume but not by the usable area account for the higher deviations in the single-family building cases. The calculated net volume of the single-family building only deviates about 14.07% from the reference building, so a minimum of the graph would be expected at around 14.07%. However, due to other deviations during the calculations, the overall result is also influenced by other aspects of the building.

A deviation in the net volume is less influential for the apartment building test cases than for the single-family building cases. Minimal deviations in the net volume only produce slight deviations in the final result.

In conclusion, an error during the calculation for the net volume would not be as influential to the final result as an error for the usable area.

5.3.3 Cellar

The configuration of the cellar in the simplified input has two properties. To give an overview of the influence of the cellar, Table 17 displays the deviations for different configurations for different test cases. For the single-family buildings, some of the test cases with a high deviation display higher accuracy if not cellar would be chosen in the simplified input format. However, this behaviour is unexpected, as the building does have a cellar and can be explained with high deviations in general for the test case,

which introduces side effects to the measurement, where a different cellar configuration acts as a configuration factor.

The chosen configuration with an unheated cellar is the most accurate for the apartment buildings. However, in test case 10, a similar problem is observed, as the test case displays a high deviation, and other cellar configurations display a much smaller deviation. Furthermore, the influence of the cellar is much smaller, as the difference in the deviations between the three configurations is smaller than in the single-family building test cases.

However, for more accurate results, a cellar area would be required, but that would require more input by the user because the cellar area itself is not an input for the DIN V 18599 norm but only its walls and base plates.

test case	building type	with heated cellar	with unheated cellar	without cellar
		deviation [%]	deviation [%]	deviation [%]
5	SFB	-15.55	-34.08	1.33
6	SFB	0.51	-18.15	17.50
7	SFB	-4.90	-24.57	13.02
8	SFB	-4.72	-25.13	13.33
9	SFB	-20.48	-43.10	0.14
10	SFB	-49.58	-73.70	-27.87
11	SFB	-30.04	-45.28	-15.58
5	AB	16.39	8.73	23.17
6	AB	29.63	21.83	36.46
7	AB	24.73	16.39	32.04
8	AB	11.26	1.07	20.09
9	AB	12.92	3.20	21.36
10	AB	-5.08	-14.70	3.44
11	AB	5.99	-2.62	13.62

Table 17: The deviation for different cellar configurations. The final energy is calculated for the simple and complete input file format for different test cases split into single-family buildings (SFB) and apartment buildings (AB). Changing the cellar configuration in the simple input format calculates a deviation from the reference building. The deviation of the final energy between simple and complete input file formats is shown for each configuration and test case. The grey cells mark the configuration closest to the reference building regarding properties.

5.3.4 Attic

Besides the configuration of the cellar, the simplified input also provides the possibility to state that the building has an additional heated attic. Suppose the building has

an attic which is not heated. In that case, the simplified input should state that no additional heated attic exists, and the simplification does not consider any components in the attic. However, considering the attic at all can lead to accuracy because not heated parts of the building, which are connected to heated parts, are also considered by the DIN V 18599 norm. Table 18 shows the influence of the attic configuration on the final result by comparing deviations from the reference building with different configurations for the attic. Generally, the deviations from the reference results do not change significantly if the attic configuration is changed. However, for the apartment building, the selected configuration has a poorer deviation if using no heated attic instead of a heated attic. This result is not expected because the reference building attic is not heated. The option of no heated attic should, therefore, be more accurate. As the attic in the apartment reference building is not significant compared to the rest of the building, the general influence is low, so the tiny space of the attic can be a correction factor for other not included spaces in the parsing of the simplified input. For instance, the left-out volume of the small portion of the heated cellar can be corrected by stating that an additional attic exists.

5.4 Influence of the construction year

The construction year of the building influences several factors concerning the calculation of the building components. A perfect year estimation cannot always be possible, especially for older buildings. However, in those cases, if the building was constructed before 1977, the insulation of the building in general can be expected to be low, with a low energetic efficiency for the building in general. Therefore, uncertainty in the construction year is not really influential if the building was built before 1977. Furthermore, Figure 13 provides an overview of the influence of the construction year on the final result. The influence on the construction year can be shown by changing it and measuring the final energy consumption with its deviation from the reference result.

Figure 13 shows that the influence of the construction year on the final energy consumption is not linear but stepwise. As the different values for the building components are based on intervals of the construction year, the final result does not change if the construction year is changed within its current interval. Therefore, the construction year in the simplified input does not have to be exact but only a year within this interval.

5.5 Influence of the heating system

Different configurations are available for configuring the heating system in the simple input format. The heating system is expected to influence the energetic efficiency of a building significantly. Although this work does not expect that the user input states the wrong heating system for their building, an analysis of the different configurations can reveal errors and will deliver the possibility to weigh the importance of heating

test case	building type	with heated attic deviation [%]	without heated attic deviation [%]
5	SFB	-15.55	-29.16
6	SFB	0.51	-17.12
7	SFB	-4.90	-23.48
8	SFB	-4.72	-23.03
9	SFB	-20.48	-41.80
10	SFB	-49.58	-67.98
11	SFB	-30.04	-47.98
5	AB	10.44	8.73
6	AB	24.72	21.83
7	AB	19.48	16.39
8	AB	4.78	1.07
9	AB	6.74	3.20
10	AB	-12.57	-14.70
11	AB	-0.71	-2.62

Table 18: The deviation for heated attic and no attic in the simplified building model compared to the reference building. The final energy is calculated for the simple and complete input file format for test cases split into single-family buildings (SFB) and apartment buildings (AB). Changing the attic configuration in the simple input format calculates a deviation from the reference building. The deviation of the final energy between simple and complete input file formats is shown for each configuration and test case. The grey cells mark the configuration which is closest to the reference building in terms of properties.

system and building architecture against each other. Therefore, Table 19 displays the deviations of different heating systems compared to the respective reference test case.

For the single-family house building, the test cases with a gas heating system display a low accuracy compared to other heating systems. This behaviour is unexpected, especially with the oil heating system displaying a higher accuracy in those test cases. Furthermore, the oil heating system should show higher deviations than the gas configuration because the previously discussed Table 15 shows that the calculation results with a simplified input format display a higher final energy than a calculation with the complete input format. So, as the oil heating system is expected to increase the final energy consumption of the building, the deviation should be higher. This assumption is also underlined with the district heating configuration, which displays less deviation as this configuration is more energy efficient and the final energy consumption is lowered. The required final energy for the heat pump configuration is much lower than the other test cases because heat pumps are seen as one of the most energy-efficient heating systems.

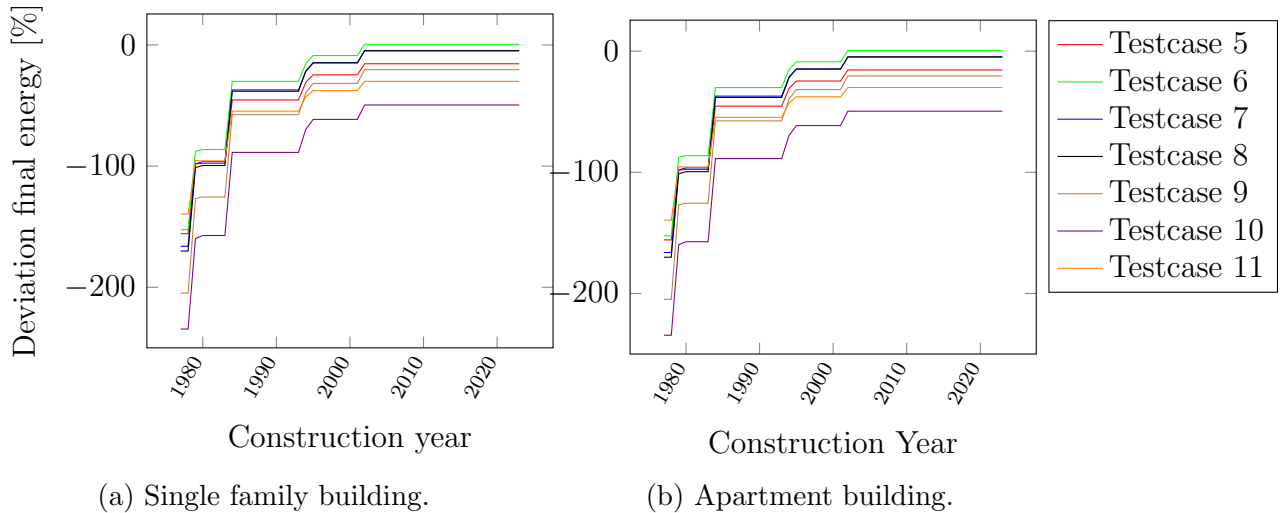


Figure 13: The deviation of the final energy between the reference buildings and the calculated building by the parser with the simplified input. The influence on the construction year is visualised by changing the construction year in the simplified input and measuring the deviation to the reference building. The Graphs are split up into single-family buildings and apartment buildings.

For the apartment building reference cases, Table 19 displays more accurate results and shows that the chosen configuration for each test case is correct.

Generally, the differences in the deviations of the final energy, except for the heat pump configuration, are notable. However, a change in the configuration does not significantly impact the specific configurations in the building architecture.

5.6 Influence of the missing ventilation

In Section 4.3.9, this work describes that most of the buildings in Germany do not have a ventilation system installed beside the natural ventilation with windows. Based on this statistic, it was decided that this work will not consider ventilation in the building. Test case 10 for the apartment and single-family building displays the deviation if the building uses an exhaust and supply-based ventilation system but still would uses the simplified input for calculating. Based on the respective test case, it is evident that a building with such a ventilation system would have a significant deviation in terms of its energetic evaluation to this work's calculated result. The single-family and apartment building test cases do not differ in building systems for the same reference building. So, differences in the deviation can only be based on the building dimensions themselves.

5.6.1 Year of the heating system

Another factor required for the heating system by the DIN V 18599 norm is the heating year. It describes the year the heating system was installed. This work also uses

test case	building type	oil deviation [%]	gas deviation [%]	district heating deviation [%]	heat pump deviation [%]
5	SFB	-20.89	-25.23	-15.55	39.87
6	SFB	4.45	0.51	8.68	39.15
7	SFB	-0.74	-4.90	3.72	35.85
8	SFB	-4.72	-9.05	-0.09	33.31
9	SFB	-15.88	-20.48	-11.18	25.31
10	SFB	-44.40	-49.58	-38.02	28.18
11	SFB	-157.30	-166.11	-146.41	-30.04
5	AB	11.56	8.73	15.73	51.73
6	AB	24.63	21.83	28.39	49.02
7	AB	19.39	16.39	23.41	45.47
8	AB	1.07	-2.60	6.01	33.08
9	AB	6.49	3.20	10.68	35.81
10	AB	-11.16	-14.70	-5.91	39.34
11	AB	0.56	-2.62	5.25	45.73

Table 19: Different heating system configurations. For each test case, different heating systems are tested. The test cases are separated between single-family buildings (SFB) and apartment buildings (AB). For each test case, each heating configuration, the final energy consumption is compared against the test cases reference results final energy consumption. The deviation of the two results is displayed in the respective column. The heating system configuration used in the reference test case is marked with a grey cell.

the heating system year for the year of installation for the heat distribution and the complete tap water system. However, changing the year for the heating system does not impact the deviation of the final result. By incriminating the year of the heating system in the simplified input and measuring the deviation of the calculation from the reference results, no change in the deviation appeared.

5.7 Comparison to the EVA Leuchter simplification

The EVA Leuchter program also provides the possibility for a simplified input. However, the software only gives the user a simplified building input. Heating systems and other systems still have to be entered manually. This section will compare the simplifications from the EVA Leuchter program to the simplification made with the help of this works relaxed model.

For the components and dimensions of the building, the EVA Leuchter program gives two options for defining the building. The first one is to input every component with the dimensions, heat transfer coefficient and other necessary values. The second is a simplified method to enter the building dimensions shown in Figure 14. With the

help of those inputs, the program calculates the list of components and their required values, as well as the building's architectural properties.

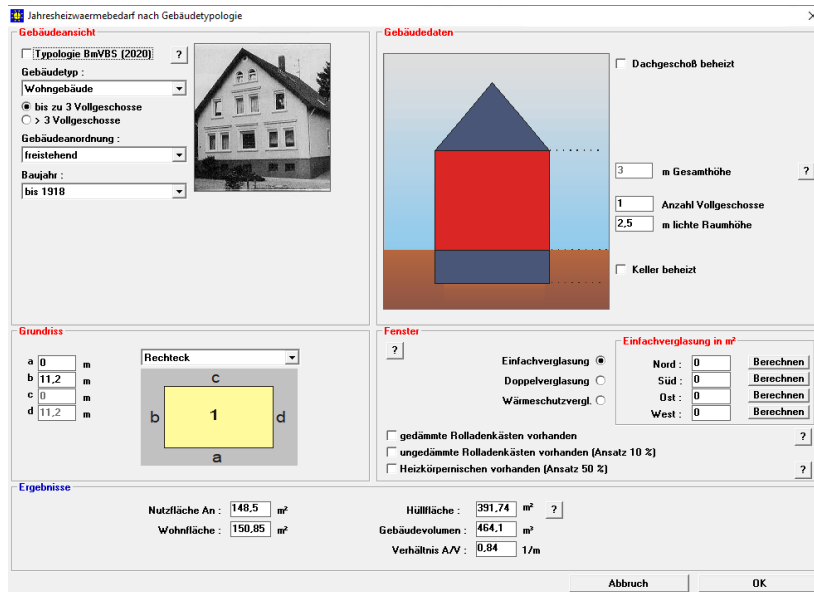


Figure 14: A simplified approach for defining the building dimensions in the EVA Leuchter program. By filling out the displayed fields, the EVA Leuchter program can calculate most building properties, including its components with their values, like the heat transfer coefficient.

The results of the calculation from the EVA Leuchter program are shown in Table 20. The table compares the calculation of the building parameters for the EVA Leuchter program and this work-relaxed model of the building. By comparing the two programs to the reference building, it is clear that in this specific case, this works model is more accurate for calculating the building dimensions than the EVA Leuchter program, which overestimates the values. This overestimation was also visible while testing other configurations.

	EVA Leuchter	Relaxed model	Reference building
net area [m^2]	201.4	115.83	150.85
usable area [m^2]	241.7	126.36	148.51
outer volume [m^3]	755.2	394.88	464.10

Table 20: Different parameters of the building calculated in the EVA Leuchter program, and this work relaxed model. The reference building can be used to compare the results from the two tools, as this building is modelled.

6 Conclusion

This work started by showing the modifications to the existing algorithm required for a norm conform calculation. After validating the updated implementation, the profiling revealed that the runtimes of the algorithm did not change and were still quicker than other already existing tools. Based on this algorithm, this work introduces a relaxed version. In the opening of this work, the objective for a simplified input for the energetic evaluation was articulated, which gives access to the energetic evaluation to non-expert users. This work introduces the simplified input format by calculating the building's dimensions and the values of the building architecture. Based on these estimations, the components of the building can be calculated, and in the last step, the building systems are added. These three steps reveal that the previously defined objective can be achieved, and a more user-friendly approach to calculating the energetic evaluation is possible. Especially with the help of default values for different properties of the building, which are dependent on the components' construction year, many previously required values can now be estimated. This work also shows that using a relaxed model does not influence the runtimes of the program significantly. In the last step, the relaxed model is validated. By comparing the relaxed input model to the complete input model, deviations based on the relaxation can be shown. In general, the accuracy of the relaxation highly depends on the accuracy of the calculated building model and its architectural properties. In contrast, the influence of building systems besides the ventilation systems is lower than the architectural properties. Therefore, the calculation of the building model must be done accurately, especially as the potential for inaccurate user information concerning the dimensions of the building is considerable. In conclusion, this work showed a working solution for a relaxed model and achieved the objective of creating a simple-to-use solution for the energetic evaluation. The validation showed that a first approximation of the energetic efficiency of a building is possible.

6.1 Future Work

There are two main aspects for future work to improve the usability and performance of the presented algorithm. One possibility is the improvement of the accuracy of the calculated energetic evaluation. This goal can be achieved using more test cases and adding new building models. Currently, only quadratic buildings fit this work building model, and different building shapes can produce high deviations. Additionally, more test data can help improve the accuracy and present more data for configurations of the building systems, which could help improve the prediction of the systems based on the simplified input. Furthermore, values used for the building components, like the heat transfer coefficient, could be more accurate and granular to predict the insulation properties better. The second possibility for improvement is the refinement of the input format for the relaxed model. For example, the length and width of the building could be estimated with the help of satellite images. Similarly, the existence of a solar array could be determined. Furthermore, imagery of the building shell could determine the height and the window area.

References

- [1] Rafe. Biswas, Melvin D. Robinson, and Nelson Fumo. Prediction of residential building energy consumption: A neural network approach. *Energy*, 117:84–92, 2016. ISSN 03605442. doi: 10.1016/j.energy.2016.10.066.
- [2] Deutsche Energie-Agentur GmbH. Leitfaden Energieausweis: Teil 1 - Energiebedarfsausweis: Datenaufnahme Wohngebäude., 2015.
- [3] Deutsches Institut für Normung e. V. *DIN EN 14511: Luftkonditionierer, Flüssigkeitskühlsätze und Wärmepumpen für die Raumbeheizung und -kühlung und Prozesskühler mit elektrisch angetriebenen Verdichtern: Teil 2: Prüfbedingungen*. Beuth Verlag GmbH, August 2023. doi: 10.31030/3020670.
- [4] Deutsches Institut für Normung e.V. *DIN V 18599: Energetische Bewertung von Gebäuden - Berechnung des Nutz-, End- und Primärenergiebedarfs für Heizung, Kühlung, Lüftung, Trinkwarmwasser und Beleuchtung*. Beuth Verlag GmbH, September 2019. doi: 10.31030/2874317.
- [5] Dipl.-Ing. Torsten Schoch and Jörg Trapp. Erarbeitung einer Software-Lösung für die Anwendung der DIN V 18599 für den Wohnungsbau für Zwecke der Vergleichsrechnung für Förderfälle. Forschungsinitiative Zukunft Bau, 2014.
- [6] Nabil A. Fouad, editor. *Energieeffizienz Kommentar DIN V 18599*, volume 19. Jahrgang (2019) of *Bauphysik-Kalender*. Ernst & Sohn, Berlin, 2019. ISBN 3433032653.
- [7] Nicolas Glaesmann. *Wärmepumpenheizungen: Planungshilfe und Ratgeber für Neubauten und Bestandsgebäude*. Springer Fachmedien Wiesbaden GmbH, Wiesbaden and Heidelberg, 2022. ISBN 9783658390303. doi: 10.1007/978-3-658-39031-0.
- [8] Rainer Hirschberg. Energetische Bewertung von Gebäuden: Tabellenverfahren für Wohngebäude (DIN V 18599–12). In Nabil A. Fouad, editor, *Bauphysik Kalender 2019*, pages 361–379. Wiley, 2019. ISBN 9783433032657. doi: 10.1002/9783433609842.ch15.
- [9] Markus Lichtmeß. *Vereinfachungen für die energetische Bewertung von Gebäuden*. Dissertation, Bergische Universität Wuppertal, Wuppertal, 2010.
- [10] Michael Becker, Patrick Wintzek, Tobias Müller, and Prof. Dr.-Ing. Markus Zdrallek. Analyse der in Deutschland angewendeten Sperrzeiten für Wärmepumpen und deren Auswirkungen auf den Stromsektor. In *Tagungsband der Tagung Zukunfftige Stromnetze 2023*, 2023.
- [11] Nick Feiereisen. *Energetische Bilanzierung von Gebäuden*. Bachelorarbeit, RWTH Aachen University, Aachen, Januar 2023.

- [12] René Regel. *Die Referenzraummethode als eine vereinfachte Bewertung komplexer Liegenschaften im Quartier am Beispiel von Hochschulen*. Dissertation, Technische Universität München, München, 2016.
- [13] Kai Schild and Wolfgang M. Willems. *Wärmeschutz: Grundlagen { Berechnung { Bewertung*. Detailwissen Bauphysik. Vieweg+Teubner Verlag, Wiesbaden and Heidelberg, 3 edition, 2022. ISBN 9783658382735. doi: 10.1007/978-3-8348-8145-8.
- [14] Alice Sokolova and Baris Aksanli. Demographical Energy Usage Analysis of Residential Buildings. *Journal of Energy Resources Technology*, 141(6), 2019. ISSN 0195-0738. doi: 10.1115/1.4042451.
- [15] S. Tsala and I. P. Koronaki. Optimization Algorithms for Energy Building Applications. *IOP Conference Series: Materials Science and Engineering*, 1037(1): 012040, 2021. ISSN 1757-8981. doi: 10.1088/1757-899X/1037/1/012040.
- [16] Verein Deutscher Ingenieure e.V. *VDI 3807 Blatt 2: Verbrauchskennwerte für Gebäude: Verbrauchskennwerte für Heizenergie, Strom und Wasser*. Beuth Verlag GmbH, November 2014.
- [17] Haidong Wang and Zhiqiang Zhai. Advances in building simulation and computational techniques: A review between 1987 and 2014. *Energy and Buildings*, 128: 319–335, 2016. ISSN 03787788. doi: 10.1016/j.enbuild.2016.06.080.
- [18] Simon Wenninger and Christian Wiethe. Benchmarking Energy Quantification Methods to Predict Heating Energy Performance of Residential Buildings in Germany. *Business & Information Systems Engineering*, 63(3):223–242, 2021. ISSN 2363-7005. doi: 10.1007/s12599-021-00691-2.
- [19] Michael Wetter, Marco Bonvini, and Thierry S. Noidui. Equation-based languages – A new paradigm for building energy modeling, simulation and optimization. *Energy and Buildings*, 117:290–300, 2016. ISSN 03787788. doi: 10.1016/j.enbuild.2015.10.017.