MASTERARBEIT

The potential of descriptive building quality specifications as an alternative to the detailed calculation

ausgeführt zum Zwecke der Erlangung des akademischen Grades einer **Diplom-Ingenieurin**

unter der Leitung von

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Dedicated to my family.

ZUSAMMENFASSUNG

Bestehende Berechnungsverfahren für Energieausweise von Gebäuden sind in den vergangenen Jahren sukzessive komplexer geworden (z.B. wurde in Österreich das ursprünglich sehr einfache Heizperiodenbilanzverfahren durch ein Monatsbilanzverfahren ersetzt und damit die Anzahl der Eingabedaten vervielfacht). Die erhöhte Komplexität macht die Anwendbarkeit für Nicht-Spezialisten, wie z.B. ArchitektInnen, die Ihren Entwurf auf Übereinstimmung mit den Mindestanforderungen, schwierig. Wenn man sich die ursprüngliche Intention des Energieausweises vergegenwärtigt, nämlich auf der einen Seite Benchmarking für Gebäude, auf der anderen Seite eine Vergleichbarkeit von verschiedenen Gebäuden untereinander, stellt sich die Frage, ob die jetzt bestehende Komplexität der Berechnungsverfahren zielführend ist. In Anbetracht der anhaltenden Diskussionen über den Energieverbrauch von Gebäuden, ist es sicherlich zielführend ein Verfahren zur Bestimmung von Energiekennzahlen zu haben. Solche Berechnungsverfahren kann man als „performance-basiert“ bezeichnen. Planer beklagen jedoch oftmals die Sperrigkeit des Verfahrens und verwenden das Verfahren daher oftmals in den letzten Phasen der Planung zur Nachweisführung. Ein „präskriptiver“ Ansatz, der Planenden helfen würde, die Energieperformance Ihrer Gebäude anhand einfach zu verwendender Indikatoren abzuschätzen, könnte ein wesentliches Hilfsmittel darstellen.

Der Zweck dieser Master-These war es daher zu untersuchen, wie ein solcher präskriptiver Ansatz aussehen könnte, der zwar keine Energiekennzahlen liefert, aber Ergebnisse welche in einer ähnlichen Form als Benchmark dienen könnten. Zu diesem Zweck wurden eine Reihe von Berechnungen von Case-Study Gebäuden durchgeführt, wobei sowohl der performance-basierte Ansatz verfolgt wurde, wie auch, basierend auf den Ergebnissen des performance-basierten Ansatzes, versucht wurde passende präskriptive Indikatoren mit Hilfe von Rekombination von Eingabedaten zu entwickeln.

Diese präskriptiven Indikatoren können – wie auch in dieser Arbeit demonstriert – als ein Hilfsmittel für frühe Planungsphasen dienen, in dem Sie den Planern recht klar kommunizieren, dass die Einhaltung bestimmter Eingabedatenwerte mit großer Wahrscheinlichkeit in einer bestimmten Energiekennzahl bzw. Energieklasse des jeweiligen Bauwerks resultiert. Die vorliegende Arbeit zeigt – aufbauend auf einer umfassenden Hintergrundrecherche – die methodischen Ansätze und Ergebnisse, die für ein Gebäudesample errechnet wurden. Mit Hilfe von statistischen Methoden

(Regressionsanalyse) konnten geeignete präskriptive Indikatoren identifiziert und für die genannten Zwecke qualifiziert werden.

Stichwörter

Gebäude-Energieausweise, präskriptiver Ansatz, Bauvorschriften, Design-Parameter, Gebäudegeometrie, Gebäudemorphologie, Thermische Hüllfläche, Heizwärmebedarf.

ABSTRACT

Existing calculation methods in energy certificates are becoming increasingly complex. This raises a question if such complexity is appropriate if we consider the main purpose of energy certificate, namely the benchmarking of the thermal design. To reach the goal of reducing energy demand in residential buildings, most developed countries comply with performance-based standards, which dictate comprehensive, qualitative energy efficiency goals. Although the performance-based approach is a most accurate method to predict quantifiable energy usage, it is time-consuming and cost associated with this approach can be significantly high. On the other side, there is a prescriptive path, which is an easy to follow and conservative approach.

The aim of this thesis was to explore the question if the prescriptive approach can be more time and cost effective solution towards energy efficiency than the calculation method. To address this question, this thesis will compare the results of both detailed calculation method of energy certificates and prescriptive method in view of consistency of their outcome. Toward the end, the output of energy certification method, namely heating demand was used as a reference.

The results show that buildings that comply with prescriptive requirements in early stages of design can indeed reach high energy efficiency level, and based on analyzed sample of residential buildings, a prescriptive requirements index has been derived. This index can help planners in making decisions in early stages of design or can be useful for further research. This method can be used when no thermal simulation takes places and derived prescriptive index gives information about expected energy efficiency category in buildings. The additional step of this research was introducing a simplified method for predicting heating demand, based on multiple regression analysis of observed sample.

Keywords

Energy certificates, prescriptive approach, building codes, design variables, building's geometry, thermal envelope, heating demand

CONTENTS

ABBREVATIONS

BRR	Building regulation for resilience
CEN	European Committee for Standardization
EBC	Energy Building codes
EEBC	Energy Efficiency Building codes
EP	Energy performance
EPBD	Energy Performance of Buildings Directive
EPI	Energy performance index
ERED	Envelope Related Energy Demand
ERS	Energy rating system
EUI	Energy use Intensities
GHG	Greenhouse gas
HERS	Home energy rating system
HVAC	Heating, ventilation and air conditioning
HWB	Heizwärmebedarf
LEED	Leadership in Energy and Environmental Design
LEK	Line of European K values
OIB	Österreichisches Institut für Bautechnik
RC	Relative Compactness
SHGC	Solar heat gain coefficient
SPSS	Statistical Package for Social Science
WWR	Window to wall ratio

NOMENCLATURE

A	Area [m^2]
d	Thickness [m]
f	Correction factor [-]
g	Shading Coefficient [-]
l_c	Characteristic Length [m]
T	Temperature [°C]
U	Thermal transmittance value [$W.m^{-2}.K^{-1}$]
V	Volume [m^3]

1 INTRODUCTION

1.1 Overview

World energy crises, such as the 1979 oil shortage, or the drastic increase in the price of oil in the early 1990s raised governmental concerns over the supply of and access to worldwide energy resources. European nations, highly dependent on energy resources from politically unstable areas, were particularly affected. It was under such circumstances that a new concept relating to energy efficiency in buildings emerged in the early 1990s as an essential method of reducing energy use and CO2 emissions: energy certification for buildings (Lombard et al. 2009).

Energy certification is mainly a market mechanism whose main objective is to promote higher energy performance standards than the regulated ones. To reach this objective, energy certification must provide a clear and detailed information about the building's energy performance (energy labeling), allowing for the straight comparison between different buildings. The appropriate assessment of building operational energy requirements, and especially of those designs with a higher energy saving potential, requires the use of a complete and detailed dynamic energy simulation tool (Casals 2006).

Although the performance-based approach is the most accurate method to predict quantifiable energy usage, it is time-consuming and the cost associated with this approach can be significantly high. Alternatively, a prescriptive approach is another path to increase a building's energy efficiency. The prescriptive approach describes the way a building has to be constructed and it is related to type and quality of materials, a method of construction, workmanship. Such approach is strictly mandated by law, codes, standards, regulations and it is based on past experience and know-how approach.

Prescriptive building energy codes often set requirements concerning thermal properties of building components, requirements for building equipment and building morphology. Materials must meet certain levels of stringency, which are quantified in tables that list the minimum and maximum requirements for the R- and U-values of materials and building elements. The prescriptive analysis, while it may not predict accurate energy consumption, eliminates the energy modeling step hence lowering time and cost of implementation. The final goal of this thesis is to test the outcome of prescriptive method comparing to the calculation method of building simulation. Using extensive parametric thermal simulations, the future thesis should examine the reliability of such prescribed requirements for buildings, should examine the limitations of the approach and the future of the method alongside with performance-based oriented building codes and standards.

1.2 Motivation

Difficulties because of the large variety of data, complex factors and uncertainties are one of the concerns in building energy simulation. Worldwide there is hundreds of building evaluation tools that focus on different areas of sustainable development and are designed for different types of projects. By March 2010, there were 382 registered building software tools for evaluating energy efficiency, renewable energy, and buildings' sustainability (Nguyen 2011).

Taking Austria for an example; the system to calculate energy demand for heating and cooling in buildings, in compliance with the ''OIB-Guideline'', includes nine laws and over 200 mathematical algorithms in order to provide a detailed specification of a building's characteristics (Andaloro et al. 2010).

That raises a question is such a complexity really necessary for energy efficiency evaluation if, on the other side, there is a prescriptive path, which is a fast, definitive, and conservative approach.

Prescriptive criteria are straightforward for a builder or designer to follow. However, there are some fundamental difficulties associated with the use of prescriptive criteria. The most serious problem with the prescriptive approach is that it can act as a barrier to innovation, limits design's freedom and it makes it very difficult to cost-optimize building construction. The performance approach is concerned with what a building or building product is required to do, rather than prescribing how it is to be constructed. In the prescriptive approach, the building parts are described, specified and procured, resulting in a building with an implicit set of attributes. In the performance approach, the building attributes are described and specified, and many combinations of different building parts can be procured for which it can be demonstrated that the specified attributes will be provided (Foliente 2000).

A huge number of performance-based codes have some of the prescriptive criteria associated with the key requirements, such as maximum permitted U-values. These U-values as a stand-alone measure would not necessarily mean that a building meets the overall performance-based requirements in the respective country.

Energy efficiency measures are most cost-effective when implemented at an early stage in building project development, from the design phase. Thus, once a building is constructed, it is more expensive and complicated to reduce its energy consumption. That is why it has to be done from the early beginning. Energy efficiency requirements in building codes ensure that the energy efficiency measures are taken into account from the very beginning (Mourtada 2016).

The EPBD introduced certificates which indicate the Energy Performance of the building as a numeric value, allowing for benchmarking. On the other hand, the prescriptive approach does not give a benchmark or prediction of energy performance level. Toward these days, numerous studies have been carried out towards a universal energy efficiency index for buildings.

Today, energy performance models and computer tools are being developed in many regions. International standardization has been introduced with the aim of developing and harmonizing models to calculate energy performance. At the same time, countries have decided to have several methods for compliance with norms which allow builders and developers to choose. This is especially the case for small residential buildings where it is recommended to make simple and comprehensive rules (Mourtada 2016).

The two developed regions (the United States and the European Union) differ importantly in the characteristics of their building stock and in the policies and institutions that underlie their efforts to reduce energy use in buildings. The other developing regions differ from each other in current and future buildings, in the energy use of space conditioning, as well as their policies, institutions, and numbers of trained building professional that influence building energy use.

Despite the great potential identified for energy simulation, currently, it has been used only for analysis of energy performance, rather than being used for the design of a building envelope (Yi and Malkawi 2012). The envelope of a building has a significant impact on thermal comfort and sizing of the HVAC system. In most cases, architects design the envelope, which is then forwarded to the designers of the HVAC system to develop it (Ellis and Mathews 2001). Thus, the thermal analysis is performed on a stage that most design decisions have already been taken (Holm 1993).

Taking all of this into account; huge differences between countries who comply with prescriptive codes, problems with implementing building standards in developing countries, and not paying enough attention to design variables of thermal envelope in early stages of design; raises a question if there is a possibility to simplify all those discrepancies and make a step forward to internationalizing building standards. This thesis will test the method of prescribing design variables in early stages of design, compare their influence on overall building performance, and test their ability to predict building's heating demand.

2 BACKGROUND

2.1 Building energy certification

"Energy certification schemes for buildings emerged in the early 1990s as an essential method for improving energy efficiency, minimizing energy consumption and enabling greater transparency with regards to the use of energy in buildings. However, from the beginning their definition and implementation process were diffuse and, occasionally, have confused building sector stakeholders. A multiplicity of terms and concepts such as energy performance, energy efficiency, energy ratings, benchmarking, labeling, etc., have emerged with sometimes overlapping meanings. This has frequently led to misleading interpretations by regulatory bodies, energy agencies and final consumers" (Lombard et al. 2009, p.272).

Almost ten years later, the EU acknowledged the need for a new regulatory instrument and introduced Directive 2002/91/EC on the energy performance of buildings. Directive 2002/91 was ambitious, although lacked sufficient detail for a clear and consistent implementation across the EU members. Among other objectives, it contained the requirement for a building energy performance certificate as *"a certificate recognized by the Member State which includes the energy performance of a building calculated according to a methodology..."*

This second approach to an energy certification definition perpetuated two unresolved issues: how to define and how to measure building energy efficiency. It also introduced a new term energy performance referring to building energy use. In this context, European energy performance indicators (EPI) and American energy intensity indicators or energy use intensities (EUI), are equivalent since both are ratios of energy use input to energy service output (site energy per square meter, CO2 emissions per home, etc.) (Lombard et al. 2009).

"The new European standard EN 15217 is an attempt to describe methods for expressing energy efficiency and certification of buildings. Energy Performance Certificates are redefined within the development of a certification scheme (Figure 1) which must contain at least:

- *An overall energy performance index (EPI) stated in terms of energy consumption, carbon dioxide emissions or energy cost, per unit of conditioned area to allow the comparison between buildings.*

- *An overall minimum efficiency requirement to be established by the legislation as a limit of the energy performance index (EPIMAX). The standard recommends its correlation with other parameters (such as climate and building type) or a self-reference method.*
- *A label based in the A–G bands to achieve a suitable grading of buildings. A key issue is a definition of the scale that should make reference, at least, to the building energy regulations (Rr), the existing building stock (Rs) and the zero-energy building (R0).*
- *Energy consumption by the main building components, such us building envelope and services, together with recommendations for energy efficiency measures for building owners' consideration." (Lombard et al. 2009, p.273).*

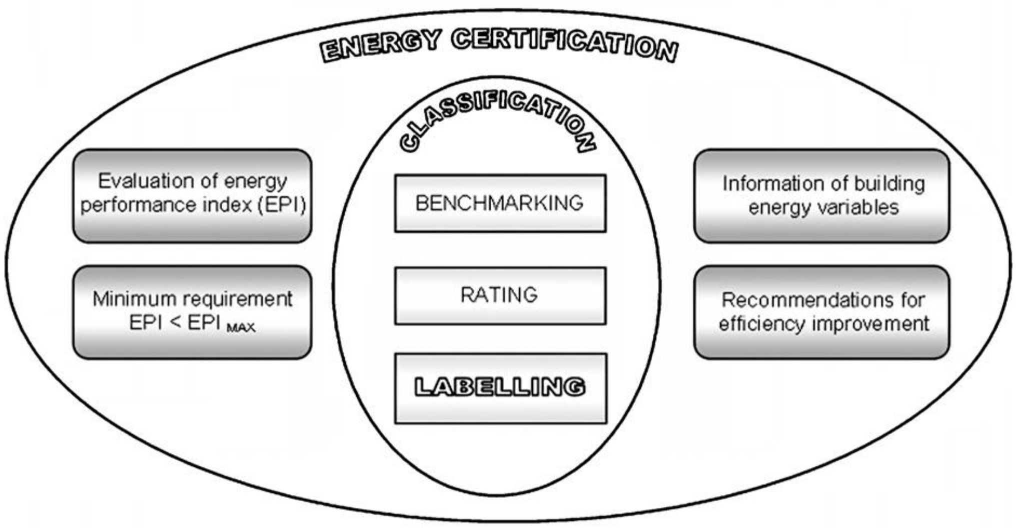


Figure 1. Scope of the new European building energy certification scheme (Lombard et al. 2008)

In the European and national context, the specialists have already prepared the energy performance calculation methodology whose scheme is represented in Figure 2. The scope of the certification is therefore extended not only to the energy performance of the building but also to include a minimum requirement and a label or class that allows users to compare and assess prospective buildings. The certificate must contain, amongst other information, a classification of the building energy efficiency based on an energy label.

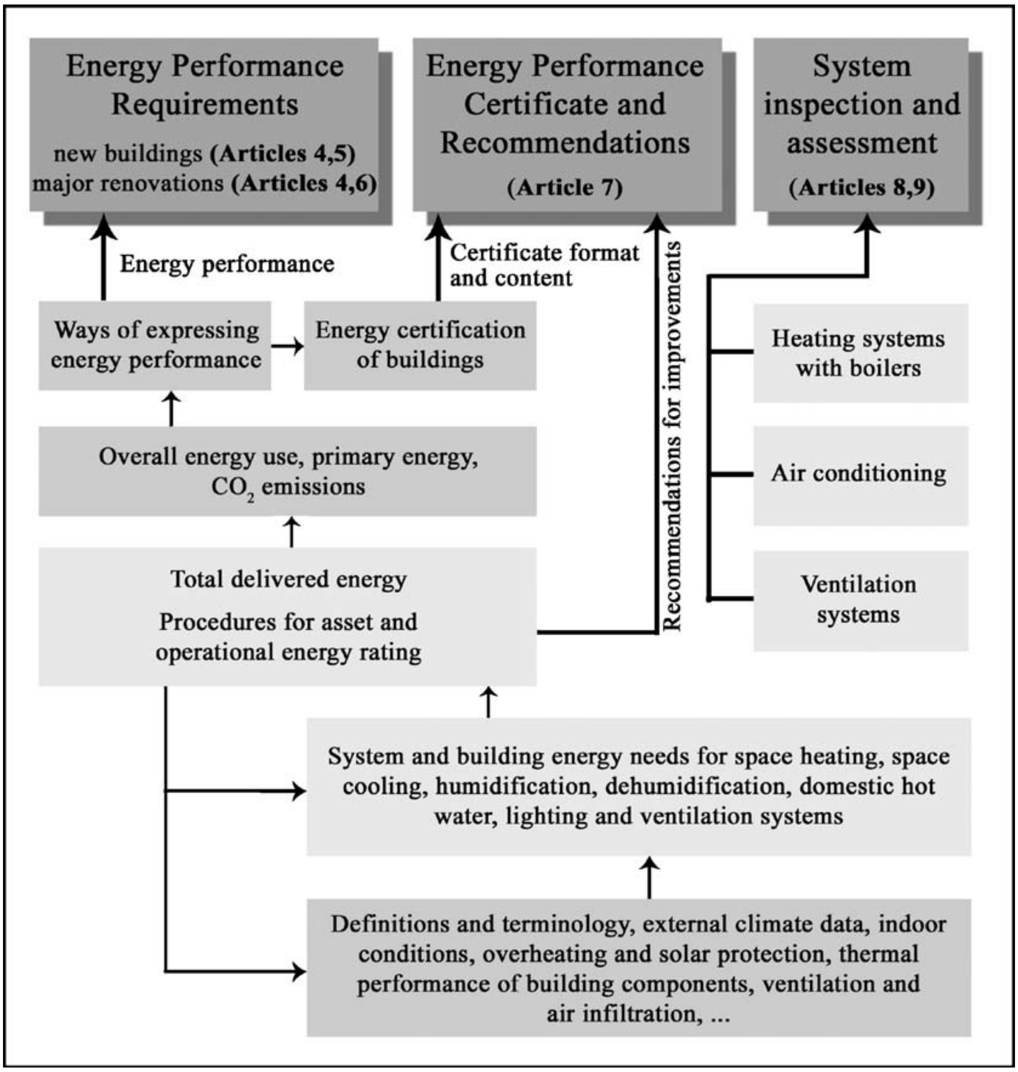


Figure 2. Methodology for calculating the energy performance (EN 15603:2008)

Benchmarking process

In the 1990s, the term building energy benchmarking started to be used to refer to the comparison of energy use in buildings of similar characteristics. Basically, it consists of a comparison of the EPI of a building with a sample of similar buildings. A common EPI used for many building types is annual energy use per unit area but others may also be used. At the design stage, energy performance indices for different designs are of great use when choosing suitable technologies, particularly if benchmarks for similar buildings are available.

Matson and Piete (2005) state that, the benchmarking process consists of four stages. First, it is necessary to hold or develop a database with information on the energy performance of a significant number of buildings. This information should be categorized, at least, by building type and size. Second is gathering the relevant information for the evaluation of the EPI for the actual building. Third, a comparative analysis of the building energy performance against the samples held in the database gives a quantification of the quality of the building in terms of energy use. Finally, energy efficiency measures that are feasible from both technical and economical perspectives should be recommended.

Table 1 shows that energy consumption of the actual building can be predicted via a computer-simulation-method or measured on site. Lombard et al. (2008) state that energy simulation offers detailed information and a wide variety of outputs, however, it may require a great number of inputs, skilled users and a significant amount of time to gather and input the necessary data, all of which can make the process expensive. Measured consumptions can be obtained from energy bills or monitoring.

Table 1. Comparison of energy use estimation methods (Lombard et al. 2008).

Concept	Simulation	Measured on-site
Input data	Detailed information	Energy bills or metering
Output data	Detailed and split	Global and non-split
Weather and use	Standard	Actual
Energy use	Estimated	Measured
Scope	New and existing buildings	Existing buildings
Cost and user skill	High	Low

In any case, there are always discrepancies between predicted and measured energy use. Some sources of error are natural uncertainties like the differences between real weather and typical simulation climate data. Others, like the use of default data for internal loads, may be reduced by adjusting the building model to the existing building real conditions. The influence of occupant behavior on energy performance is considerable. Variables like a number of people and activity, thermostat set points, equipment usage, natural ventilation, hot water demand, etc. are strongly dependent on the occupants or owner and can result in large variations in energy use, even for the same climate and building type (Lombard et al. 2008).

Energy rating

In general, the expression energy rating system (ERS) may be used as a synonym of energy classification, that is, a method for assessing energy quality. Examples can be found in both the Home energy rating system (HERS) of the Energy Star program and the US Green Building Council LEED building rating system.

Within the framework of Directive 2002/91, energy rating means an evaluation of the building energy performance. In the standard EN 15603, European Committee for Standardization (CEN) proposes two types of ratings: (1) calculated ratings, based on computer calculations to predict energy used by a building for HVAC systems, domestic hot water and lighting and (2) measured (or operational) ratings, based on real metering on-site. Calculated ratings are subdivided into a standard (also called asset) and tailored ratings. The asset ratings use the calculation procedure within standard usage patterns and climatic conditions not to depend on occupant behavior, actual weather and indoor conditions, and are designed to rate the building and not the occupant.

Energy efficiency certification schemes for new buildings are usually implemented by asset ratings. For existing buildings, both calculated and measured ratings are applicable, but the later is preferred to reduce energy performance discrepancies and limit consumer risks due to uneconomic retrofit investment or credibility problems if stakeholders conclude that energy rating system is less accurate than expected (Lombard et al. 2008, Ballarini and Corrado 2009).

2.2 Types of Energy Building Codes

Energy Building codes (EBC) are minimum requirements for energy-efficient design and construction for new and renovated residential and commercial buildings. A component of a complete set of building regulations that govern all aspects of the design and construction of buildings, building energy codes set an energy-efficiency baseline for the building envelope, systems, and equipment (Laustsen 2008).

Quite comprehensive in nature, the energy codes apply to:

- Envelope: Wall, floor, ceiling, doors and windows

- Heating, ventilating and cooling systems and equipment

- Lighting systems and equipment

- Water-heating systems and equipment

"In order to compare building codes, the different types can be simplified into two basic forms. Building codes which are based on energy efficiency requirements for individual building parts - “EEBCs based on threshold values” - and the codes for which these requirements set the overall frames in order to calculate energy consumption - “Performance-based building codes”" (Moutada 2016, p.16).

EEBCs based on threshold values

"The Prescriptive Method and the Trade-off Method are all based on standard maximum values for transmission (U-values) coefficients, energy efficiency values and similar values which can easily be compared. Whether trade-offs are possible will accordingly influence the level of the values" (Moutada 2016, p.16).

Calculation or performance based building codes

"The Model Building, Energy Frame and Energy Performance methods are all based on calculated energy consumption and all require calculation models and computer tools. The calculation procedures are normally set national, regional or local. These types of regulations have to be compared based on total performance or the total frame, but again climate conditions must be taken into account" (Moutada 2016, p.16).

2.2.1 Prescriptive codes

Prescriptive codes contain a menu of options describing minimum or maximum values for various elements in a construction project from which the designer or building owner can choose. Common prescriptive measures include minimum R-values for insulation or elements of thermal envelope, acceptable infiltration rates, and efficiency requirements for mechanical systems such as water heaters and HVAC equipment. Inspectors and code officials are tasked with enforcing code compliance by verifying that items on the list have been included in the project.

Benefits

Prescriptive codes are often considered easy to follow because they clearly state what is acceptable. They are simple to follow for code officials to confirm compliance during plan review. Items required on prescriptive lists use commonly used framework and products that meet code compliance. Building owners and designers know what is expected and they provide a clear description of accepted energy efficiency measures.

Drawbacks

Prescriptive codes, however, have several shortcomings. First, the process of selecting items off of a list does not encourage a whole building approach to achieving energy savings. As such, opportunities to maximize energy efficiencies are often missed (CGBCR 2011).

Second, prescriptive codes do not require that a prescribed menu item actually function properly over time, nor do they typically require commissioning or testing of systems once installed. The code is set up to assume that all equipment is installed correctly and performs as specified by manufacturers. This is frequently not the case (CGBCR 2011).

Prescriptive codes can also fall short simply based on efficiency strategies and energy end uses that are often overlooked. Few prescriptive codes provide credit for effective building orientation and daylighting, thermal mass, natural ventilation, or integration of appliances and mechanical equipment—all of which can contribute significantly to reducing a building's overall energy demand.

Lastly, as energy reduction goals become more stringent, prescriptive codes must be reviewed and updated continually. The updating process for prescriptive codes can be a time consuming and complicated.

2.2.2 Performance-based codes

Performance-based codes contain broad, qualitative energy efficiency goals that require computer modeling to verify compliance. Performance-based codes are sometimes called "Modeled Performance" codes or paths within codes (Hewitt et al. 2010). This distinction is made to clarify that building "performance" is not being guaranteed; rather it is predicted based on simulation by designers and energy modelers. Performance-based codes require that a reference building is defined in order to create a baseline energy budget for comparison. The modeling process provides a rating valuation demonstrating both the proposed and the baseline buildings' energy use. Performance-based codes require that new buildings are equal to, or lower than, the baseline reference building.

Through the use of computer modeling software, building energy consumption is calculated based on inputs describing materials, systems, climate, and expected use (e.g. occupancy schedules and internal gains). Building data is entered into the appropriate software and components and systems are manipulated until the desired efficiency goal is met.

Benefits

Performance-based codes are a common alternative method to prescriptive codes for creating flexibility within the compliance path (CGBCR 2011). This pathway allows for design innovation and the integration of energy efficiency technologies. It is often perceived as a more expensive option over prescriptive codes due to the cost of energy modeling which frequently requires a trained energy specialist. However, once familiar with modeling software, design teams often prefer the performance-based path because the modeling tool allows them to evaluate various combinations of design strategies, components, and technologies until they arrive at a satisfying solution that provides the greatest energy savings for the least cost (Harris et al. 2010).

Drawbacks

Performance-based codes usually incorporate prescriptive requirements as well, which can be time-consuming to update. These mandatory measures are required so that basics such as insulation aren't completely left out of projects even though the modeling demonstrates that they are not necessary to achieve the targeted energy use.

Performance-based codes present a number of challenges related to how well they are able to predict actual building energy use. One consistent drawback is that modeling results are only as good as the data input. Even accurate data entry does not account for the likelihood that equipment will not always perform as specified by manufacturers, either because the system was faulty or because it was not properly installed (CGBCR 2011).

Another challenge is that modeling software requires the reference options. This can make it more challenging for a project that includes passive solar orientation or natural ventilation to demonstrate savings beyond code since these elements must also be modeled in the baseline building (CGBCR 2011).

Like prescriptive codes, performance-based codes typically do not address plug loads. As a result, they also do not accurately account for how occupant behaviors and building management will impact energy use over time. This was reinforced by a study done by Turner and Frankel (2008) which showed that buildings performed below their modeled targets and in some cases even below the levels projected by code baseline compliance. This is often the result of inconsistent building operation, unpredictable schedules, variable equipment performance, and other issues, like plug loads, not anticipated in the energy modeling (Turner and Frankel 2008).

2.2.3 Outcome-based codes

The most commonly used approaches for achieving compliance with energy codes are prescriptive and performance-based. Prescriptive and performance-based pathways are the current models used by most jurisdictions, with prescriptive being the most common and performance-based an accepted alternative. Both of these code systems would ensure energy efficiency in buildings.

More recently the outcome-based code systems emerged, due to the fact that neither one of these two, takes into consideration how a building is operated and how it functions over time.

An emerging alternative to prescriptive and performance-based energy codes is outcome-based codes. This framework considers the whole building's energy use over a consecutive 12-month period.

Outcome-based codes will require that buildings do not exceed a maximum annual operating energy use. This pathway guarantees that actual energy efficiency is achieved by requiring a one-time reporting for compliance verification, though it may take a few years to obtain consecutive 12-months of qualifying energy data. While this pathway has the potential to help buildings achieve energy savings by assuring performance, it is still under development and has yet to be adopted by any jurisdiction (CGBCR 2011).

Benefits

Outcome-based codes offer a highly flexible regulatory pathway that will actually address energy use. Utilizing both prescriptive and energy modeling measures, designers can use the most appropriate means to predict and achieve maximum energy efficiency efforts.

One of the most important aspects of this compliance path is its inclusion of all energy loads, including currently unregulated plug loads, in the equation for overall energy reduction.

It compiles useful data that can be used by building managers in analyzing whole building performance while also providing opportunities to educate building occupants about their energy use.

Drawbacks

Outcome-based codes rely on regulatory authorities to set the allowable energy use. Extra guidance for designers and building owners will be needed to ensure energy efficiency measures are met. Practical performance tests are key components to making sure a building is functioning as intended. However, these tests are often perceived to cost prohibitive from the standpoint of conventional code compliance paths. Further, they require a fundamental shift in the way that energy codes function (CGBCR 2011).

2.3 Energy efficiency requirements in Austria

"Within Europe, Austria has one of the most proactive and comprehensive approaches to reducing energy use in buildings, which has resulted in significant energy-efficiency improvements during the past 20 years" (Mourtada 2016, p.30). Public procurement guidelines include ambitious standards for new buildings and retrofits. Meanwhile, higher thresholds for obtaining housing subsidies were introduced for single- and multi-family buildings to accelerate the phasing-out of oil heating and to improve energy efficiency in building renovation through new regulations on space and water heating.

"Although Austria's focus on improving the energy performance of buildings predated its accession to the European Union in 1995, the country's program is now to a large extent based on implementing the suite of EU Directives that target improving energy efficiency. Nonetheless, the Austrian government continues to aim for its long-term goal of a fossil-free building sector by 2050, continuing Austria's leading role in cutting GHG emissions from buildings. Of particular note is Austria's leadership in the construction of very-low-energy buildings" (Mourtada 2016, p.31).

"In Austria, the implementation of the EPBD (2002/91/EC) was completed in 2008, after a difficult process of harmonization within the country – previously the nine "Länder" (provinces) had nine different building codes, including quite different regulations concerning energy. It has to be mentioned that (various) energy certificates had been in use beforehand in some of the federal Länder, referring only to the heat demand of buildings caused by the envelope, not including Heating and Ventilation/ A/C systems, etc., like the current certificate does (this being the reason why the heat demand is still the energy rating of the current certificate) " *(Jilek 2010, p.1).*

According to EPBD requirement, Austria has reported specific mandatory building codes associated with improving the energy performance of existing buildings. As a Member State, Austria has introduced minimum component performance standards when building elements (e.g. windows, doors etc.) or energy using plant (boilers, a/c equipment etc.) are being replaced (Mourtada 2016). Table 2 shows an example of Austria of performance-based requirement as well as requirements for any component that is replaced or refurbished.

Table 2. Summary of building energy code requirements and prescriptive criteria (Mourtada 2016)

Building code requirements:	New Buildings Renovations	YES YES
Performance Based Requirements:	New Buildings Renovations	YES YES
Prescriptive/element-based criteria in building codes:	Thermal Insulation Air permeability Ventilation Requirements Boiler /AC system efficiency Lighting efficiency	YES YES YES YES NO
Other requirements:	Summer comfort requirements	

"As a federal country, Austria produced the document ‘‘Austrian Institute for Structural Engineering Guidelines—Cited standards and other technical regulations’’ drawn up by the Austrian Institute for Building (Österreichisches Institute für Bautechnik—OIB) in order to harmonize the nine ‘‘building codes’’ and other laws. This document set out the current standards and technical regulations that would serve as a common starting point. The system to calculate energy demand for heating and cooling, in compliance with the ‘‘OIB-Guideline’’, includes nine laws and over 200 mathematical algorithms in order to provide a detailed specification of a building's characteristics. The methods adopted apply to both residential and non-residential buildings, with the latter being divided into 12 categories: office buildings; nurseries and compulsory schools; secondary schools and colleges; hospitals; care homes; guesthouses; hotels; bars and restaurants; event venues; sports facilities; sales outlets; indoor swimming pools and other air-conditioned structures. Those eligible to issue certificates (generally architects, engineers, master builders and other specialists) are authorized by law to practice this profession, for this reason, there are no provisions made for other specific professional training or examinations; any training, albeit on-compulsory, to be provided by regional Governing bodies together with Chambers of Commerce and civil engineers" (Andaloro et al. 2010, p.5848).

The energy performance certificate

The energy certificate is based on calculated values only and assigns an energy performance label to residential and non-residential buildings or building units. The energy label classifies the buildings on an efficiency scale ranging from A++ (high energy efficiency) to G (poor efficiency). Page one of energy certificate in Austria shows the general data of the building of the qualified expert, the heat energy demand in kWh.m^{-2} per year as a key factor for the labeling (HWB), the primary energy demand (PEB), the CO2 emissions and the total energy efficiency factor

(f_{GEE}). Page 2 shows detailed data concerning (final) energy demand of the envelope as well as of the HVAC systems, based on specific climate data of the site. The values are assigned with "Is fulfilled" or "not fulfilled". The validity of energy certificates is 10 years.

Class boundaries shown in Table 3 are defined for the graphical representation, on the energy efficiency scale on the first page of the energy certificate.

Table 3. Energy label criteria (OIB-Richtlinien 6)

Klasse	**$HWB_{Ref,SK}$ [kWh/m²a]**	**PEB_{SK} [kWh/m²a]**	**$CO2_{SK}$ [kg/m²a]**	**f_{GEE} [-]**
A++	10	60	8	0.55
A+	15	70	10	0.70
A	25	80	15	0.85
B	50	160	30	1.00
C	100	220	40	1.75
D	150	280	50	2.50
E	200	340	60	3.25
F	250	400	70	4.00
G	> 250	> 400	> 70	> 4.00

Calculation method by OIB-Richtlinien 6

Requirements for the heating demand for newly constructed residential buildings

During the construction of residential buildings the following maximum permitted annual heating demand is allowed $HWB_{max,Ref,RK}$ (Heizwärmebedarf) per m^2 of heated gross floor area, depending on the geometry (characteristic Length l_c) and based on the reference climate (RK):

$$HWB_{Ref,RK} = 16 \bullet (1+3.0/l_c)\ [kWh.m^{-2}.a^{-1}] \quad (1)$$

but $HWB_{max,Ref,RK}$ not more than 54.4 $[kWh.m^{-2}.a^{-1}]$ [(1)]

(1) except in case for buildings with a conditioned gross floor area of not more than 100 m².

The value above was valid until 31.12.2016, and since 01.01.2017 the new requirement came into power:

$$HWB_{Ref,RK} = 14 \bullet (1+3.0/l_c)\ [kWh.m^{-2}.a^{-1}] \quad (2)$$

but $HWB_{max,Ref,RK}$ not more than 47.6 $[kWh.m^{-2}.a^{-1}]$ [(1)]

(1) except in case for buildings with a conditioned gross floor area of not more than 100 m²).

Requirements for building components

For newly constructed or renovated buildings or building components in conditioned spaces following heat transfer coefficients (U-value) must not exceed values given in Table 4.

Table 4. Requirements for heat transferring components of building envelope (OIB-Richtlinien 6)

	Building component	**U-value $[W.m^{-2}.K^{-1}]$**
1	WALLS against outside air	**0.35**
2	WALLS against unheated or not equipped attics	**0.35**
3	WALLS to unheated, frost-free-held parts of buildings (Attics) as well as against garages	**0.60**
4	WALLS in the ground	**0.40**
5	WALLS (partition) between residential or business units or conditioned Stairwells	**0.90**
6	WALLS against other buildings	**0.50**
7	WALLS small area against outside, the 2% of the walls of the not exceed the entire building against outside air	**0.70**
8	WALLS (partitions) within residential and commercial	**-**
9	WINDOWS, French doors, glazed doors respectively in residential buildings against outside air	**1.40**
10	WINDOWS, French doors, glazed doors respectively in non-residential premises against outside air	**1.70**
11	other transparent components vertically against outside	**1.70**
12	other transparent components horizontally or slants against outside air	**2.00**
13	other transparent components vertically against unheated parts of buildings	**2.50**
14	skylights against outside air	**1.70**
15	DOORS unglazed, against outside air	**1.70**
16	DOORS unglazed, unheated parts of buildings	**2.50**
17	gates, Rolling doors against outside air	**2.50**
18	INTERIOR DOORS	**-**
19	CEILINGS and roof pitches each against outside air and against roof spaces	**0.20**
20	CEILING unheated parts of buildings	**0.40**
21	CEILING against separate living and operating units	**0.90**
22	CEILING within residential and commercial units	**-**
23	CEILING over outdoor air (e.g. crossings, parkings)	**0.20**
24	CEILING against Garages	**0.30**
25	FLOORS on the ground	**0.40**

Alongside above-mentioned criteria, OIB-Guideline 6 prescribes requirements and recommendations regarding: Heating system and hot water supply; Air conditioning installation; Natural and Mechanical Ventilation; Lighting; Design, Position & orientation of building; Passive solar systems and solar protection; Indoor & outdoor climatic conditions; Air -Tightness; Thermal bridging; Summer overheating protection and other requirements.

2.4 Building regulations in developing countries

Most of the developed countries are implementing building energy regulations such as energy standards, codes etc., to reduce building energy consumption. The position of developing countries with respect to energy regulations implementation and enforcement is either poorly documented or not documented at all. In addition, there is a lack of consistent data, which makes it difficult to understand the underlying changes that affect energy regulation implementation in developing countries (Iwaro and Mwasha 2010).

Energy consumption in developing countries has been increasing rapidly due to recent economic growth and development. In developing countries, the number of new buildings is growing rapidly and the energy prices and the market often do not encourage the use of efficient technologies (Hui 2000). In view of these facts, there is a pragmatic shift to the use of building energy standards and codes to reduce building energy consumption in developing countries.

However, the effectiveness of building energy standards varies significantly from country to country, mainly due to difficulties and resulting differences in compliance and enforcement. In developing countries, building energy standards are often ineffective or much less effective than predicted (UNEP 2009). Deringer et al. (2004) argued that while building energy standards exist in a number of developing countries, they are often only on paper due to insufficient implementation and enforcement, corruption, and other problems. Building energy standards in developing countries are usually promoted by and developed with support from international donor agencies, but if this support does not cover the implementation period, prospects are rather negative.

The BRR World Bank report (2016) states some of the reason why building regulation has not reduced disaster and chronic risk in low- and middle-income countries, which are the same reasons why building regulations in developing countries are often dysfunctional and poorly implemented.

Building regulations in developing countries are typically prescriptive; they specifically describe and require the design solution that meets the standard. Prescriptive codes are assumed to meet the intended safety standard and can be easily observed and measured to assure compliance. Prescriptive codes are relatively straightforward and amenable to review and inspection-but they are also restrictive and may inhibit innovation in design and construction. In response to this limitation, developed countries are moving toward the use of performance codes. Performance codes define the performance objective rather than the specific solution. This means that any solution that meets the performance requirement can be deemed to conform to code.

One of the major problems of implementing building codes in developing countries is inadequate building codes. Most codes are inappropriately transferred from high-income countries. Such codes often set the bar too high and thereby increase the dependency of developing countries on imported industrialized building materials and design practices. Furthermore, these codes frequently create high costs of compliance with a result of driving construction to the informal sector.

Building codes transposed from higher-income settings frequently reference technical standards for a limited range of construction materials and methods. This problem is particularly evident when examining the absence of more localized technical standards. In addition, the requirements for professional qualification and licenses are problematic. They tend to be based on professional practice in the developed world and do not require knowledge of relevant local, vernacular construction. The BRR World Bank report (2016) states that the majority of building codes in developing countries typically fail to recognize locally available building materials or prevalent forms of vernacular construction, such as adobe and non-engineered construction. Such forms of construction typically account for 70 to 80 percent of residential construction in developing countries. By ignoring or even prohibiting the types of construction that low-income groups can afford, codes effectively limit research and development for improving traditional techniques, materials testing, and quality control. The failure to address vernacular technologies in building codes has been an impediment to the understanding and improvement of those building traditions (BRR 2016).

Building codes typically fail to recognize the incremental process of construction. Incremental construction refers to the gradual step-by-step process in which owner-builders append or improve building components as funding, time, or materials become available (BRR 2016).

A critical factor in building performance, aside from design and construction practice, is the quality of building materials. There is a lack of quality control for building materials and equipment, and in order to assure design performance of buildings, materials must be tested and certified to meet design specifications.

Corruption is at the heart of failed regulatory frameworks, as it undermines all aspects of good regulations. Corruption is strongly correlated with poverty, and in low-income countries, it may seem to be an intractable problem for efforts to create a robust environment for building regulatory compliance (Deringer et al. 2004, BRR 2016).

Unnecessarily complex administrative procedures to obtain land titles and building permits contribute to increased construction cost without clear safety improvement. In many countries, the administrative procedures to obtain a formal building or occupancy permit are so complex, costly, and time-consuming that they inhibit code compliance.

Oftentimes, information on administrative procedures and compliance requirements for building permits is difficult to access or unintelligible to non-professionals.

Transaction costs borne by owners and builders for construction permits and inspections continue to be high in proportion to construction costs in developing countries.

In low- and middle-income countries, the performance approach may be relevant as a means of recognizing the potential of indigenous building techniques and materials. To the extent that traditional building types can be demonstrated to provide required performance, they can be considered in compliance. This flexibility may be important as an opportunity to improve safety and energy efficiency in buildings using local materials and building traditions. However, the performance approach requires considerable technical sophistication on the part of designers, builders, and regulators (BRR 2016).

2.5 Simplified models for analyzing energy performance of buildings

There is a lack of parametric design software that enables the analysis of the performance of the building in the early stages of architectural design to assist in the decision-making process (Toth et al. 2011). The initial design stages form the foundation of all new building designs. During these stages, the general size, orientation, and construction of the building are defined. All subsequent decisions and design calculations are based on these characteristics. It, therefore, becomes more difficult and costly to alter the design as it progresses (Ellis and Mathews 2001).

The European Directive on the energy performance of buildings (EPBD) requires that an energy performance certificate is made available when buildings are constructed, sold or rented out. The certificate has to express the energy performance (EP) of the building. The certificate has to be accompanied by recommendations for the cost-effective improvement of the energy performance. The calculation of the energy performance should be carried out according to a methodology based on a general framework set out by the EPBD. The implementation of Energy Performance of Building Directive (EPBD) has initiated the process of energy certification, aiming for the improvement of the average energy class of residential or services buildings (Dascalaki et al. 2010). The implementation of the EPBC orientations differs in each country of the EU, which also has different efficiency requirements (González et al. 2011).

The calculation model should guarantee the ‘‘globality’’ and the uniformity of energy performance evaluation: ‘‘globality’’ in reference to overall energy consumptions, and uniformity respect to different countries and local climate conditions.

Member States have different prescriptive, element-based requirements associated with building energy codes such as maximum U-values, minimum/maximum indoor temperatures, requirements for minimum ventilation rates and boiler and/or air conditioning plant efficiency. Given the diversity in climatic conditions, maximum U-value requirements vary widely across different countries where some countries have multiple maximum U-values due to the considerable variation in climatic conditions within each country. This was also one of the key findings of the Laustsen's (2008) paper on building codes where it was shown that existing U-value requirements for building components did not reflect the economic optimum.

The simulation should guarantee, for new and existing buildings, the correspondence between calculated and real energy consumptions by bills. The buildings energy certificate is similar to the household electric certification. Nevertheless, in buildings, the verification between real and calculated energy consumption has more variable factors, which make the evaluation complex. These variables depend on the building geometry and materials, the local climate and seasonal variation, the habit of users, the DHW consumption, the lighting use, and so on. All these variables are not comparable and standardizable (Tronchin and Fabbri 2008).

Toward these days, numerous studies have been carried out towards a universal energy efficiency index for buildings. Approaching that goal, some simplified models have been proposed to analyze the energy performance of buildings.

Ellis and Mathews (2001) developed a simplified tool for the analysis of the thermal performance of buildings in the early stages of the design envelope.

Some studies have shown that the building shape can have a significant impact on both construction costs and the energy costs of heating and cooling. Some studies have investigated the impact of the building shape on its thermal performance for selected climates in Europe. Depecker et al. (2001) studied the relationship between shape and energy requirements during the winter season in Paris and Carpentras, a town placed in southern France with a milder climate. Pessenlehner and Mahdavi (2002) examined the reliability of geometric compactness indicators for energy-related evaluative assessments based on extensive parametric thermal simulation studies. In particular, the method correlates the annual energy use to the relative compactness of the building. The relative compactness, a normalized ratio of the volume to the exterior surface area, is commonly used as an indicator of shape in buildings. Other, but limited, investigations have focused on optimization of building shape to minimize energy use and cost. The reported studies used rather simplified building thermal models. For instance, Jedrzejuk and Marks (2002) and Marks (1997) used a degree day (DD) based method to model the thermal performance of buildings.

Nielsen (2005) developed a simplified dynamic simulation tool with few input data, to evaluate the energy consumption and thermal comfort of buildings for use in the early stages of architectural design. Ourghi et al. (2007) developed a simplified method to estimate the impact of office buildings geometry on energy consumption. A simplified calculation estimates the annual total energy use for a commercial building relative to a reference building (with the same volume but which has a cubical form) as a function of the relative compactness, the window to wall ratio and the glazing solar heat gain coefficient. The method has been developed for limited building shapes (rectangular and L-shapes) and applied for several cities around the world and was found to be accurate for cooling dominated climates.

AlAnzi et al. 2009 extended the work of Ourghi et al. (2007) to include several building shapes, window areas, glazing types. According to Lopez et al. (2011), Brazilian regulation allows the energy efficiency level of a building to be rated by a prescriptive method, or alternatively, by building simulation method. Petersen and Svendsen (2010) proposed a method which consists of a program that uses simulation software to make performance predictions from variations of user-defined parameters. Yi and Malkawi (2012) created a methodology in which architects can generate geometry optimized energy from the energy simulation results Granadeiro (2013b) developed an indicator of energy performance for residential buildings (Envelope-Related Energy Demand – ERED). The inputs to ERED are areas of envelope elements (floor, walls, roofs and windows), U-values of envelope materials, solar heat gain coefficients (SHGC) of windows and site-related parameters, concerning temperature and solar irradiation. Results show that there is a strong correlation between ERED and simulated energy demand. Granadeiro (2013a) developed a methodology that involves a flexible system design, where alternative geometries are generated, and energy demand is calculated by employing energy simulation.

3 METHOD

3.1 Overview

The aim of this paper is to analyze and compare the outcome of the two methods; prescriptive based approach of descriptive building quality indicators and performance-based approach to energy efficiency on the same building sample. A sample of building shapes is selected, providing morphological variance.

The first step in methodology is calculating energy certificate for building sample. All the analyzed buildings comply with prescriptive building requirements of permitted max U-values in accordance with "OIB Guideline 6" and permitted design variables of physical properties of the envelope. The second step is creating a list of descriptive building indicators and manually calculating a set of chosen indicators for the whole sample. This step is done with the intention to examine which of these descriptive indicators give the most information about building thermal quality and to examine their influence on building performance. The energy certificate results, namely the energy load for heating demand [$kWh.m^{-2}.a^{-1}$] would be taken as representative of performance indicator and will be discussed and compared in the context of the sample's geometry design variables. The goal of this step is to test if, easier to calculate building indicators; give the same level and information regarding the thermal quality of a building as a performance-based method.

After finding the valid set of building indicators, the next step is a statistical evaluation of the data and finding statistically and practically the best fitting set of variables and creating multiple regression equation. This equation could deliver the possibility to predict building's thermal behaviour based on those simple descriptive indicators if we would eliminate the step of the thermal simulation.

After finding the best fitting model, final step in this research is creating a prescriptive based index which would consist of different values for chosen variables and would give the information, which combination of these values would give a certain level on energy efficiency scale.

Figure 3 shows most important steps of this work's method mentioned above in a simple graphic flow chart.

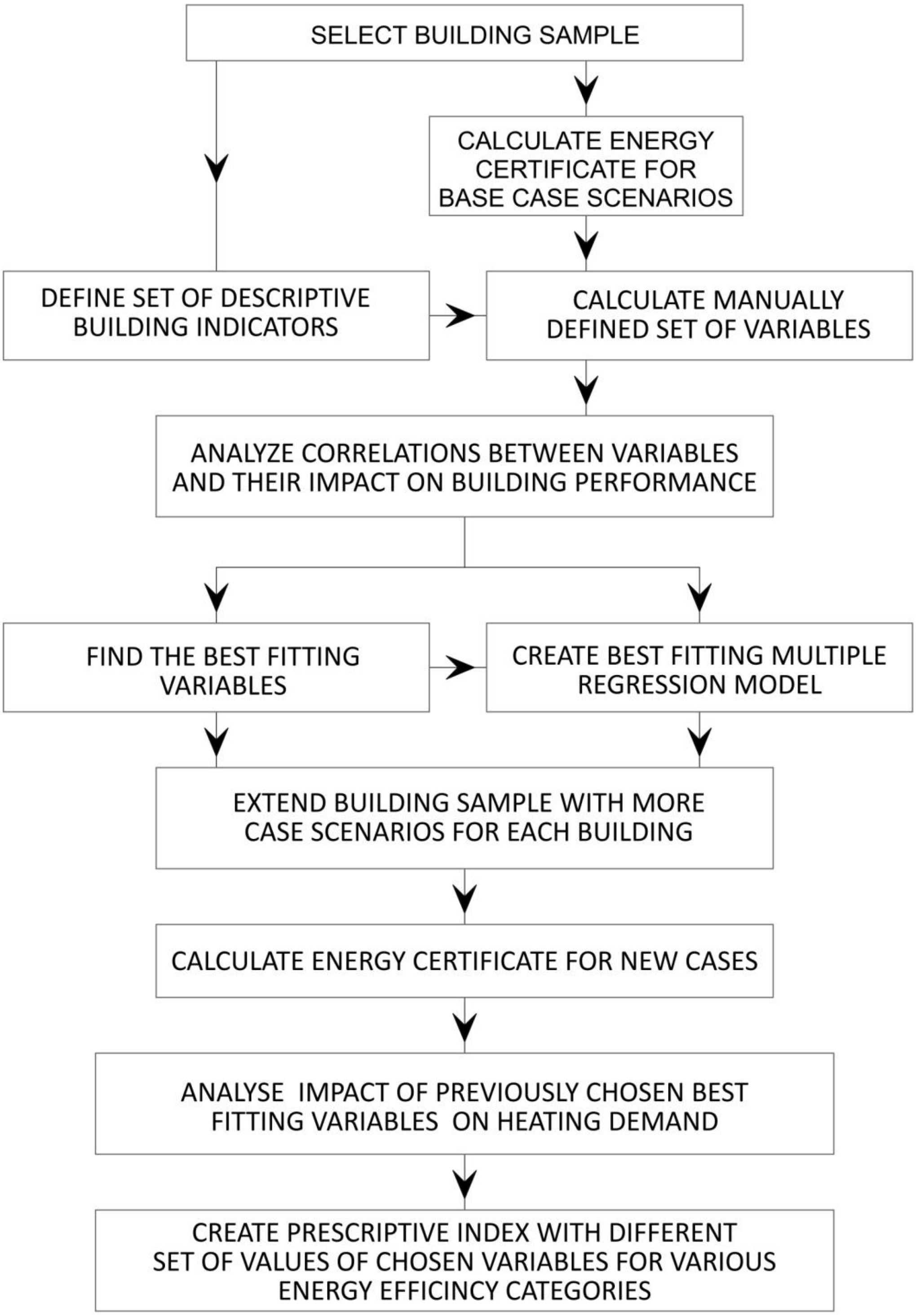


Figure 3. Methodology flow chart

3.2 Hypothesis

This research is based on a suggestion that the prescriptive method can be more time and cost effective solution towards energy efficient buildings than energy performance simulation method, or the calculation method of energy certificates respectively. It is assumed that in the early stage of design, buildings that comply with descriptive building quality specification, can meet same energy efficiency requirements of the reference building's calculated energy certificate.

Research questions

1. How do simple descriptive building indicators influence heating demand of the building?

2. Is there a way, based on those simple indicators, to predict the thermal quality of the building if we would eliminate the step of performance simulation or energy calculation?

3. How can the outcome of this approach be compared to the classical output of energy certificates?

4. If the method is shown to work, is it possible to simplify building performance standards and the process of energy certification and apply it to standards in developing countries, where there is no standardization regarding performance criteria?

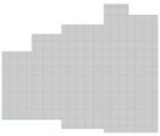
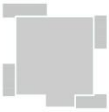
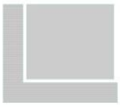
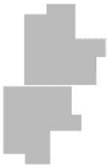
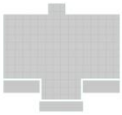
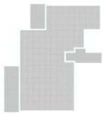
5. Can the method be a step forward towards universal energy efficiency predictions in early stages of design?

3.3 Building Sample

Verification of the hypothesis drawn above requires a practical approach. Therefore a building sample has been selected in order to test the hypothesis. The total set of 15 residential building has been collected, with regard to geometric characteristics. The sample provides enough variance in size, morphology, the number of stories, different orientations, variety in fenestration types, glazing area and orientation of the openings.

According to the type of build form, buildings fall into categories: semi-detached house, single family house, multi-family house and apartment building. All the types of building sample are shown in Table 5.

Table 5. Types of buildings and Shape of the Ground Floor (Footprint area)

 Project Name: P 01_1 Apartment building 4 apartments per floor Footprint area: 279 m2 Number of stories: 4 + Unheated Basement	 Project Name: P 01_2 Semi detached house 3 apartments per floor Footprint area: 337 m^2 Number of stories: 2	 Project Name: P 02 Single family house 2 apartments per floor Footprint area: 101.5 m2 Number of stories: 2 + Unheated Basement	 Project Name: P 03 Single family villa 1 apartment per floor Footprint area: 142 m^2 Number of stories: 2 + Unheated Basement	 Project Name: P 04 Single family house 1 apartment per floor Footprint area: 66 m^2 Number of stories: 2 + Unheated Basement
 Project Name: P 05 Apartment building 2-4 apartment per floor Footprint area: 194.7 m^2 Number of stories: 5 + Unheated Basement	 Project Name: P 06_1 Apartment building 2 apartments per floor Footprint area: 160 m^2 Number of stories: 3 + Unheated Basement	 Project Name: P 06_2 Single family villa 1 apartment per floor Footprint area: 80 m^2 Number of stories:2+ Unheated Basement	 Project Name: P 06_3 Single family house 1 apartment per floor Footprint area: 61 m^2 Number of stories: 2 + Unheated Basement	 Project Name: P 07 Single family house 1 apartment per floor Footprint area: 124 m^2 Number of stories: 2 + Unheated Basement
 Project Name: P 08 Single family house 1 apartment per floor Footprint area: 42.5 m^2 Number of stories: 1 + Unheated Basement	 Project Name: P 12 Apartment building 4 apartments per floor Footprint area: 313 m^2 Number of stories: 3 + Mezzanine + Unheated Basement	 Project Name: P 13 Apartment building 2 apartments per floor Footprint area: 117 m^2 Number of stories: 3	 Project Name: P 14 Apartment building 2 apartment per floor Footprint area: 114 m^2 Number of stories: 3	 Project Name: P 15 Apartment building 2 apartment per floor Footprint area: 147 m^2 Number of stories: 3

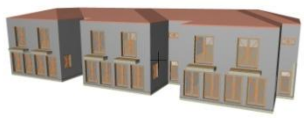
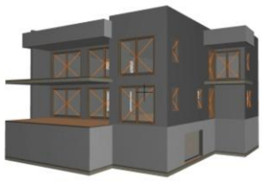
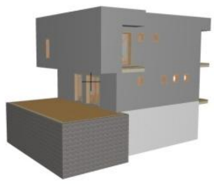
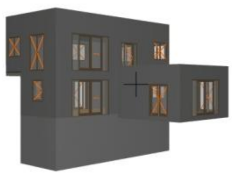
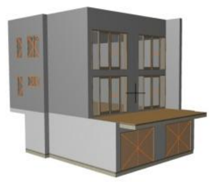
In terms of the roof conditions, three types are present: Pitched roof, green and flat roof. For all the buildings that in hold have a basement, apply that the basement space is unconditioned.

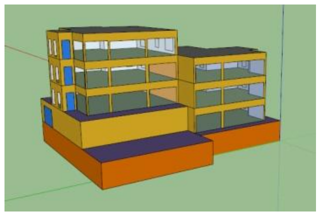
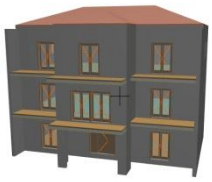
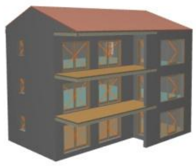
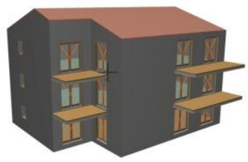
All buildings are realistic and comply with some standard universal properties of building design.

The smallest building in the sample has an envelope area of 254.1 m^2 and conditioned volume of 214.53 m^3, while the biggest building has a surface area of 2058.64 m^2 and conditioned volume of 5330 m^3.

Window to wall ratio range goes from 10 till 39%, while the window to heated gross floor area ranges from 14% as smallest value till 54% for highest. Table 6 shows some key properties of the analyzed sample.

Table 6. Key data of the Buildings

 P 01_1 Gross Floor Area: 1025.50 m^2 Heated Floor Area: 820.40 m^2 Volume: 3313.68 m^3 Building Envelope: 1521.01 m^2 Compactness (A/V): 0.46 1/m Characteristic Length: 2.18 m WWR: 32% South oriented windows : 87% North oriented windows : 0%	 P01_2 Gross Floor Area: 680.89 m^2 Heated Floor Area : 544.71 m^2 Volume: 2076.72 m^3 Building Envelope: 1658.21 m^2 Compactness (A/V): 0.80 1/m Characteristic Length: 1.25 m WWR: 22% South oriented windows : 78% North oriented windows : 16%	 P 02 Gross Floor Area: 202.82m^2 Heated Floor Area : 162.26 m^2 Volume: 613.54 m^3 Building Envelope: 659.51 m^2 Compactness (A/V): 1.07 1/m Characteristic Length: 0.93 m WWR: 29% South oriented windows : 58% North oriented windows : 8%
 P03 Gross Floor Area: 297.45m^2 Heated Floor Area : 237.96 m^2 Volume: 958.29 m^3 Building Envelope: 792.68 m^2 Compactness (A/V): 0.83 1/m Characteristic Length: 1.21 m WWR: 33% South oriented windows : 49% North oriented windows : 30%	 P 04 Gross Floor Area: 137.79m^2 Heated Floor Area : 110.23 m^2 Volume: 405.64 m^3 Building Envelope: 392.51 m^2 Compactness (A/V): 0.97 1/m Characteristic Length: 1.03 m WWR: 18% South oriented windows : 9% North oriented windows : 12%	 P 5 Gross Floor Area: 952.74m^2 Heated Floor Area : 762.19 m^2 Volume: 2859.96 m^3 Building Envelope: 1332.86 m^2 Compactness (A/V): 0.47 1/m Characteristic Length: 2.15 m WWR: 32% South oriented windows : 30% North oriented windows : 30%
 P 06_1 Gross Floor Area: 512.83m^2 Heated Floor Area : 410.26 m^2 Volume: 1620.01 m^3 Building Envelope: 1255.25 m^2 Compactness (A/V): 0.77 1/m Characteristic Length: 1.29 m WWR: 36% South oriented windows : 21% North oriented windows : 28%	 P 06_2 Gross Floor Area: 154.81m^2 Heated Floor Area : 123.85 m^2 Volume: 464.45 m^3 Building Envelope: 426.23 m^2 Compactness (A/V): 0.92 1/m Characteristic Length: 1.09 m WWR: 30% South oriented windows : 46% North oriented windows : 11%	 P 06_3 Gross Floor Area: 131.71m^2 Heated Floor Area : 105.37 m^2 Volume: 371.91 m^3 Building Envelope: 371.09 m^2 Compactness (A/V): 1.00 1/m Characteristic Length: 1.00 m WWR: 30% South oriented windows : 0% North oriented windows : 14%

 P 7 Gross Floor Area: 355.06m^2 Heated Floor Area : 284.05 m^2 Volume: 804.4 m^3 Building Envelope: 557.81 m^2 Compactness (A/V): 0.41 1/m Characteristic Length: 2.43m WWR: 30% South oriented windows : 79% North oriented windows : 11%	 P 08 Gross Floor Area: 96.52 m^2 Heated Floor Area : 77.21 m^2 Volume: 214.52 m^3 Building Envelope: 254.10 m^2 Compactness (A/V): 1.18 1/m Characteristic Length: 0.84 1m WWR: 13% South oriented windows : 71% North oriented windows : 15%	 P 12 Gross Floor Area: 1679.41m^2 Heated Floor Area : 1343.53 m^2 Volume: 3057.5 m^3 Building Envelope: 2058.64 m^2 Compactness (A/V): 0.39 1/m Characteristic Length: 2.59 m WWR: 29% South oriented windows : 30% North oriented windows : 6%
 P 13 Gross Floor Area: 379.49 m^2 Heated Floor Area : 303.59 m^2 Volume: 1214.36 m^3 Building Envelope: 742.38 m^2 Compactness (A/V): 0.61 1/m Characteristic Length: 1.64 m WWR: 10% South oriented windows : 64% North oriented windows : 19%	 P 14 Gross Floor Area: 341.06 m^2 Heated Floor Area : 272.85 m^2 Volume: 1023.20 m^3 Building Envelope: 722.99 m^2 Compactness (A/V): 0.71 1/m Characteristic Length: 1.42 m WWR: 21% South oriented windows : 14% North oriented windows: 86%	 P 15 Gross Floor Area: 440.70 m^2 Heated Floor Area : 352.56 m^2 Volume: 1322.12 m^3 Building Envelope: 919.19 m^2 Compactness (A/V): 0.70 1/m Characteristic Length: 1.44 m WWR: 16% South oriented windows : 75% North oriented windows : 25%

3.4 Energy certificate

3.4.1 Software

ArchiPHYSIK 13 simulation software was chosen, after study of all relevant parameters, as the most suitable for this thesis. The geometrical models of analyzed buildings were first created in ArchiCAD 18 and SketchUp and later imported to ArchiPHYSIK, through official ArchiPHYSIK's plug-ins for both software respectively.

ArchiCAD

ARCHICAD is the leading Building Information Modeling (BIM) software application used by architects, designers, engineers, and builders to professionally design, document and collaborate on building projects. For the purpose of this thesis, it was chosen as the most suitable and most precise software to model the geometry of building envelope for buildings. A new ArchiPHYSIK plug-in for ArchiCAD allows fast and accurate export off all elements of building thermal envelope, including thermal zones.

SketchUp

Although ArchiCAD was chosen as the most suitable software for creating building geometry, for some buildings from sample export was not possible, causing the software to crash and leaving out .aps file empty. Due to this unfortunate circumstance, the Sketch-Up software was used to model those buildings. SketchUp (formerly Google Sketchup) is a 3D modeling computer program for a wide range of drawing applications. It allows fast creation of building geometry and easy and fast export to ArchiPHYSIK. Thermal building surfaces are created with simple rectangles, and for each type of a building component or for each type of construction a different material type is assigned. The plug-in exports all the elements of building envelope, and has an option to select all the elements that count as conditioned floor area.

ArchiPHYSIK

ArchiPHYSIK is the standard software for standards-compliant building physics assessments and proofs of heat, sound, steam diffusion, energy certificates and ecology for single and multi-zone residential and non-residential buildings. It provides information on summer overheating and takes into account the promotion of residential buildings and building codes of all federal states of Austria.

ArchiPHYSIK provides simplified and detailed calculations for single-zone and multi-zone energy labels. Both residential buildings, non-residential buildings and other buildings are calculated according to the current OIB guideline 6.

3.4.2 Input parameters

A number of parameters were kept constant throughout the simulation, namely location (Vienna, Austria). Vienna's geographical coordinates are 48° 12′ 0″ N, 16° 22′ 0″ E, 48.2, 16.37, with an elevation of reference place used for simulation 158 m. Marine west coast climate: mild with no dry season, warm summers. Continentality type is continental, subtype subcontinental. According to the world map of Köppen-Geiger classification Vienna is Cfb.

- Main climates: C Warm temperate

Warm temperate climates −3 °C < T_{min} < +18 ° C

- Precipitation f: fully humid
- Temperature b: warm summer

The Table 7 below shows the climate zone number according to ANSI/ASHRAE/IESNA Standard 90.1-2013 for international climatic zones.

Table 7. Climate Zone (ASHRAE 90.1-2013)

Zone Number	Zone Name	Thermal Criteria (SI Units)
5B	Dry (5B)	3000 < HDD18ºC ≤ 4000

The assumptions regarding thermal properties, namely U-values [W.m^{-2}.K^{-1}] and thickness of insulation layer of the primary building components of the building envelope are summarized in Table 8. All the properties for the elements of the thermal building envelope are assigned so that they do not exceed the maximum allowed U-values prescribed by OIB-Guideline 6:2015 for new buildings.

Table 8. Base case building components properties

Project No. Building Component	U-Value [W.m^{-2}.K^{-1}]	Thickness of insulation layer d [m]
P 01_1		
Outside wall	0.245	0.15
Pitched roof	0.200	0.34
Attic floor	0.198	0.17
Flat Roof	0.140	0.25
Ceiling to unheated cellar	0.168	0.16
Windows	1.380	-
Doors	1.280	-
P 01_2		
Outside wall	0.245	0.15
Pitched roof	0.200	0.34
Ceiling to ground	0.210	0.15
Wall to ground	0.161	0.24
Windows	1.340	-
Doors	1.260	-
P 02		
Outside wall	0.155	0.25
Pitched roof	0.200	0.34
Attic Floor	0.198	0.17
Ceiling to unheated cellar	0.168	0.16
Wall to ground	0.152	0.25
Windows	1.270	-
Doors	1.270	-
P 03		
Outside wall	0.152	0.25
Green roof	0.136	0.25
Flat roof	0.141	0.25
Ceiling to unheated cellar	0.168	0.16
Windows	1.300	-
Doors	1.240	-
Garage door	1.100	-

P 04		
Outside wall	0.152	0.15
Flat roof	0.101	0.36
Ceiling to outside air	0.130	0.20
Ceiling to unheated cellar	0.168	0.16
Windows	1.320	-
Doors	1.250	-
P 05		
Outside wall	0.245	0.15
Pitched roof	0.200	0.34
Ceiling to unheated cellar	0.168	0.16
Windows	1.280	-
Doors	1.260	-
Garage door	1.220	-
P 06_1		
Outside wall	0.245	0.15
Flat roof	0.101	0.36
Ceiling to unheated cellar	0.168	0.16
Windows	1.270	-
Doors	1.300	-
Garage door	1.100	-
P 06_2		
Outside wall	0.245	0.15
Flat roof	0.101	0.36
Ceiling to outside air	0.129	0.20
Ceiling to unheated cellar	0.168	0.16
Windows	1.280	-
Doors	1.280	-
P 06_3		
Outside wall	0.245	0.15
Flat roof	0.101	0.36
Ceiling to ground	0.154	0.15
Ceiling to unheated cellar	0.168	0.16
Windows	1.300	-
Doors	1.250	-
Garage door	1.100	-
P 07		
Outside wall	0.191	0.20
Flat roof	0.190	0.18
Pitched roof	0.200	0.34
Ceiling to ground	0.210	0.15
Ceiling to unheated cellar	0.172	0.16
Windows	1.280	-
Doors	0.846	-
P 08		
Outside wall	0.245	0.15
Pitched roof	0.200	0.34
Attic Floor	0.198	0.17
Ceiling to unheated cellar	0.168	0.16
Windows	1.340	-
Doors	1.100	-

P 12		
Outside wall	0.245	0.15
Flat roof	0.148	0.24
Ceiling to unheated cellar	0.168	0.16
Windows	1.280	-
Doors	1.200	-
P 13		
Outside wall	0.238	0.15
Pitched roof	0.175	0.20
Ceiling to ground	0.224	0.15
Ceiling to outside air	0.154	0.15
Windows	1.280	-
Doors	1.400	-
P 14		
Outside wall	0.306	0.12
Pitched roof	0.20	0.20
Ceiling to ground	0.222	0.15
Ceiling to outside air	0.154	0.15
Windows	1.400	-
Doors	1.220	-
P 15		
Outside wall	0.300	0.12
Pitched roof	0.200	0.20
Ceiling to ground	0.242	0.12
Windows	1.280	-
Doors	1.320	-

For the purpose of this thesis, some other parameters were kept constant for all the buildings. Lighting and equipment loads for all the building are the same; since all the buildings are small scope residential buildings, it is assumed that they are naturally ventilated. Shading coefficients, measure of solar energy transmittance through windows, g-value, was kept constant for all the glazing in the building sample and amounts 0.6. For simplification purposes, shading devices were not taken into account, neither the obstruction of surrounding buildings. Since most of the buildings are small scale single or multi-family houses, it is highly unlikely that they can be located in the highly dense urban area.

The reference temperature applied in the simulation is -13°C for outside air temperature, and heated room temperature 20°C. For the reference location values for heating days and for heating degree days amount 211d and 3400Kd respectively. The objective of this step would be obtaining energy certificate for every building from the analyzed sample. The results that would be used for further analyses would be expressed in terms of performance indicator, heating demand [$kWh.m^{-2}.a^{-1}$].

3.5 Descriptive building variables

Building design variables capture either geometric or non-geometric (semantic) information of the building. The semantic design variables (Table 9) are used to define various essential performance characteristics of a building, such as thermal, lighting or acoustical. They can also be used to identify occupational and functional characteristics of a building. Most semantic design variables can be defined in terms of numeric values (Mahdavi and Gurtekin 2001).

Table 9. Few examples of commonly used semantic design variables (Mahdavi and Gurtekin 2001)

Semantic design variables	*Unit*
U-value	$W \cdot m^{-2} \cdot K^{-1}$
Thermal Mass	$kg \cdot m^{-2}$
Shading Coefficient	-
Visible Transmittance	-
Internal Load	$W \cdot m^{-2}$
Air Change Rate	h^{-1}

Geometric design information is more difficult to express in terms of scalar values. Examples of some common building geometry indicators are the ratio of a building's length to its width (plan aspect ratio), the ratio of space's height to its depth, the floor-to-floor height and ratio of glazing area to the facade (or floor) area. Most of these indicators are rather limited in their scope and applicability. This implies the need for improved aggregate descriptors of building geometry (Mahdavi and Gurtekin 2001).

Figure 4 shows an attempt to capture geometric and semantic design variables in one diagram. They are categorized in those two main groups, with a few indicators that capture both geometric and thermal properties of the building envelope, and they represent the intersection of those two sets. For geometric variables, some attributes of build form are captured, such as the shape of build form, or type of building, type of roof, attic or basement floor and some similar properties that cannot be expressed as scalar values, because they are only descriptive attributes of a building.

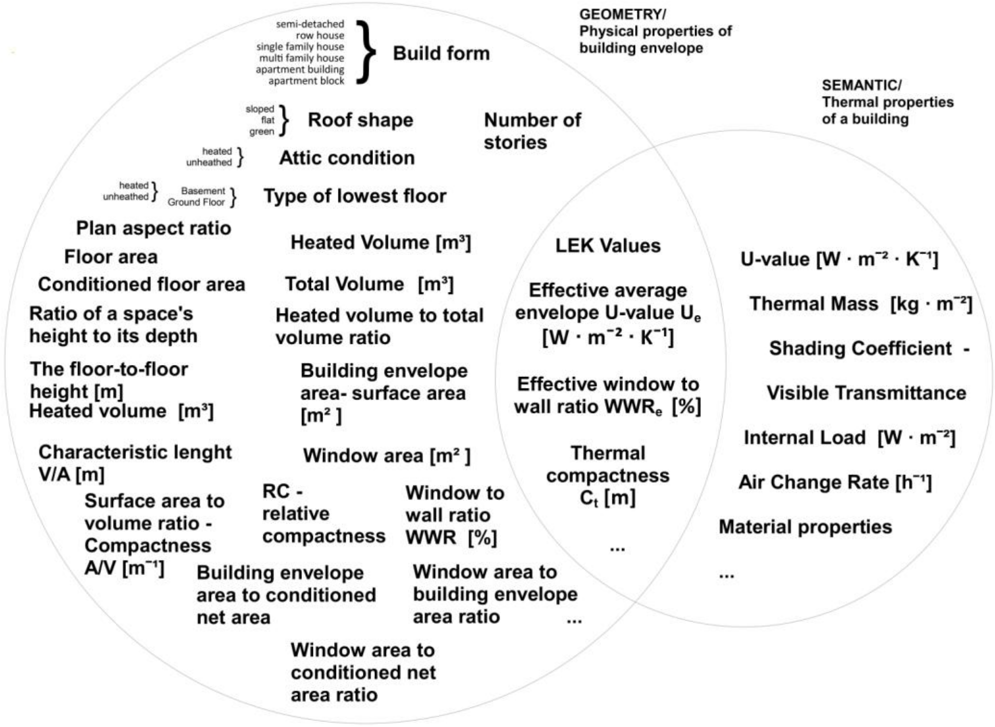


Figure 4. Geometric and semantic properties of a building

According to EN 15217 definition; *Building envelope* is total area of all parts of a building which surround conditioned rooms, and through which the thermal energy is transmitted into / out of the outside environment or into /out non-conditioned rooms, while *Building* is defined as complete building including the building envelope and all building installations for which energy is used to condition the indoor climate, drinking water and lighting, and other uses related to the use of the building.

For the purposes of this thesis, design variables that are analyzed and annotated as significant are finally separated in following categories shown in Table 10.

"In principle, one can think of many different descriptors of building geometry. An important question is, however, if a proposed indicator is of perceptual relevance. A designer may be told that increasing or decreasing the value of a design variable would affect the performance of a building in this or that way. But this information would be of little use if the designer cannot relate the numeric values of the variable to some intuitively accessible feature of the design" (Mahdavi and Gurtekin 2002, p.295).

Table 10. Building design variables

Physical Properties of building envelope	
A_f	Footprint area [m^2]
A_{cn}	Conditioned floor area [m^2]
A_{roof}	Roof Area [m^2]
A_{wall}	Wall Area [m^2]
A_w	Window Area [m^2]
A_s	Building Envelope area or building surface area [m^2]
A_{st}	Whole Building Envelope area (Total Surface area) [m^2]
V	Gross Volume [m^3] - Gross volume of heated space or simply heated volume
V_t	Total volume [m^3] - Volume of a whole building, heated and unheated spaces
Form factors	
C	Compactness (German "Kompaktheit") or Surface Area to Volume ratio [m^{-1}]
RC	Relative Compactness
l_c	Characteristic Length [m]
V/A_{wall}	Volume to Wall area Ratio [m^{-1}]
V/A_f	Volume to Footprint Area Ratio [m^{-1}]
Properties of transparent elements of building envelope	
WWR [%]	Window to Wall ratio
WWR_e [%]	Effective Window to Wall ratio
Relational variables	
A_s/A_{cn}	Building envelope area to Conditioned net floor area ratio
A_w/A_{cn}	Window area to Conditioned net floor area ratio
A_w/A_s	Window area to Building envelope area ratio
S_{roof}/S_{wall}	Roof Area to Wall Area Ratio
A_f/A_{wall}	Footprint area to Wall area Ratio
A_w/A_f	Window to footprint area Ratio
A_s/A_f	Envelope area to footprint area Ratio
Thermal Properties	
U	Mean area weighed envelope U-value [W.m^{-2}.K^{-1}]
LEK	LEK Value ("Linien europäischer Kriterien", ÖNORM B8110 and H 5055)
U_e	Effective average envelope U-value [W.m^{-2}.K^{-1}]
C_t	Thermal compactness [m]
A_e	Effective envelope area [m^2]

The purpose of the variables given in the table above is to test and compare their relevance and impact on the building's performance, and how do they correlate to buildings performance and to each other, and if there is a way to prescribe, describe or predict their influence on buildings performance. Some of the variables are self-explanatory and easy to derive, while some on the other hand demand some calculations. The common feature for all of them is that they do not demand thermal simulation or any kind of complicated software calculations.

Physical properties of building enclosure are relatively easy to obtain and they are generally the areas of parts of a building envelope or whole envelope and some volumetric characteristics.

The most important and most used ones are *Gross volume*, which is defined by EN 15217 as Sum of the gross volume contents of all conditioned rooms of a building/building part, through which a heat balance with a certain room temperature is created.

Heated gross floor area according to ÖNORM B 1800 is defined as the sum of the base areas of all the outer dimensions that determine basic floor plan of a building.

Most common used indicators of buildings geometry are compactness and characteristic length. *Shape factor or 'Kompaltheit'* of building shapes describes the relation between a total surface area and building's volume, $C=A_s/V$. The other common used indicator is *"Characteristic Length",*

$$l_c = V \cdot A^{-1} \text{ [m]} \qquad (3)$$

which is simply the ratio of a building's volume (V) to its envelope area (A_s) (Mahdavi et al. 1996).

One important ongoing effort within the framework of the research was to develop improved aggregate descriptors of building geometry. The design variable *"Relative Compactness"* is one of the preliminary results of this effort. It utilizes the relation between a building's volume and total surface (enclosure) area (Mahdavi and Gurtekin 2002).

Mahdavi and Gurtekin (2002) derived the *Relative Compactness* of a shape by comparing its volume to surface area ratio to that of the most compact shape with the same volume. The most compact shape in geometry is the sphere. Therefore, when the volume to surface area ratio of another shape is compared with the one of a sphere, the following relationship can be established:

$$RC \cong 4.84 \cdot V^{2/3} \cdot A^{-1}{}_{sphere} \qquad (4)$$

Even though sphere is the most compact shape, it is perhaps not the ideal reference, as most buildings have orthogonal polyhedronal shapes. Using cube (the most compact polyhedron) as the reference shape, we obtain:

$$RC = 6 \cdot V^{2/3} \cdot A^{-1}{}_{cube} \qquad (5)$$

RC is purely shape-dependent, in contrast to conventional compactness indicators and has been used in previous studies for the purposes of predicting energy demand and influence of buildings shape on the same.

The most commonly used descriptive indicator in prescriptive standards regarding transparent elements of the building envelope is *window to wall ratio* (WWR). The window-to-wall ratio is the measure of the percentage area determined by dividing the building's total glazed area by its exterior envelope wall area. WWR is an important variable affecting energy performance in a building. Window area will have impacts on the building's heating, cooling, and lighting, as well as relating it to the natural environment in terms of access to daylight, ventilation and views.

Since the window properties are highly dependent on climate and radiation, and design variables mentioned above do not capture the building orientation and climate conditions good enough, in one study Ghiassi et al. (2015) has introduced a new variable, namely effective window to wall radio.

Effective window to wall ratio (Equation 6), defined as the average window to external wall ratio, corrected for orientation, shading and g-value (Ghiassi et al. 2015).

$$WWR_e=(\Sigma(WWR_i \cdot A_{wi} \cdot f_{oi} \cdot g_i \cdot SVF_i))/(\Sigma A_{wi}) \qquad (6)$$

WWR_e: Effective window to wall ratio

WWR: Window to wall ratio of the building

A_{wi}: Area of the external wall facing a certain orientation (12 orientations were considered)

f_{oi}: Correction factor for the orientation (with a maximum of 1 for the south and a minimum of 0.5 for north oriented windows)

g_i: g-value of window

SVF_i: Value of the Sky View Factor on a point on the ground close to the building's facade. This value is used as an approximation of the shading factor, to account for the impact of the surrounding obstructions in reducing solar gains (Ghiassi et al. 2015).

To fit the purpose of this thesis, the equation above has been simplified, since the g-value for all the buildings in the sample is the same, and SVF has been taken to be the same for all the building, so at the end effective window to wall ratio has been calculated based on the following equation:

$$WWR_e=(\Sigma(WWR_i \cdot A_{wi} \cdot f_{oi}))/(\Sigma A_{wi}) \qquad (7).$$

Values for correction factor f_{oi} , have been taken over from the authors of the study mentioned above, calculated according to the monthly solar radiation values given for various orientation in the ÖNORM B 8110-5: 2011.

Relational variables were chosen for this study based on some previous similar studies that were inspecting influence of some of them on aspects of building performance, thermal comfort etc. Some building standards also include some of them. Since the ratio is a relationship between two numbers indicating how many times the first number contains the second (Penny Cyclopedia, p. 307) and in this case between variables of the same unit, these ratios are dimensionless quantities.

All the variables introduced above only capture building geometry or some aspect of build form, but do not include any of the thermal properties. Therefore the following variables try to capture some of the thermal properties of the building envelope and built form.

The most common used is U-value, an indicator that found its place in almost all building standards. U-value is a measure of the heat transfer in a building component construction and describes how well a building element conducts heat or the rate of transfer of heat (in watts) through one square meter of a structure divided by the difference in temperature across the structure. The U-value analyzed in this thesis is the mean area weighted U-value of the elements of the thermally relevant building envelope enclosures, weighted by the area of the respective building components. Therefore, since this variable does not capture the condition of surrounding environment, a new indicator has been introduced in previously mention study of Ghiassi et al. 2015, namely the effective average envelope U-value.

Effective average envelope U-value (Equation 8), defined as the average U-value of heat emitting building enclosures weighted by the area of the respective building components and corrected for adjacency relationships (Ghiassi et al. 2015).

$$U_e = (\Sigma(U_i \bullet A_i \bullet f_i))/(\Sigma A_i) \quad (8)$$

U_e: Effective average envelope U-value

U_i: U-value of a building component based on OIB guidelines (OIB 2015)

A_i: Area of heat emitting building components

f_i: Temperature correction factor based on the position of the heat emitting enclosure relative to ground, outdoor space and adjacent unheated spaces (ÖNORM B 8110-6). Some of the correction factors applied in this research are given in table 11.

Table 11. Temperature correction factor (ÖNORM B 8110-6)

Building component	f (temperature correction factor)
Outside wall	1.0
Wall to unheated space	0.5
Wall to unheated barn	0.5
Ceiling to unheated cellar	0.5
Ceiling to ground	0.5
Flat roof	1.0
Windows	1.0
Attic Floor	0.9
Basement Wall	0.6

From the above formula, A_e Effective envelope area has been derived, which is the sum of areas of heat emitting building enclosures corrected for adjacency relationships.

$$A_e = \Sigma(A_i \cdot f_i) \qquad (9)$$

The same indicator was used for deriving C_t - *Thermal compactness*. Thermal compactness (Equation 10), defined as the ratio of heated volume to thermally effective envelope area, which is the sum of areas of heat emitting building elements, corrected for adjacencies (Ghiassi et al. 2015).

$$C_t=V/(\Sigma A_i \cdot f_i) \qquad (10)$$

Final indicator from the group of thermal properties variables is LEK value. Some efforts in the European context-have aimed at establishing rational and simple to-use standards for the overall heat transfer coefficient of the building envelope. The LEK value ("Linien europäischer Kriterien", ÖNORM B8110 and H 5055) characterizes the heat protection of the building and establishes a relationship between the characteristic length ($l_c = V \cdot A^{-1}$) of a building and the mean heat transfer coefficient of the building envelope based on the equation:

$$LEK = 300 \cdot (U / (2 + l_c)) \qquad (11)$$

The LEK value is a measure of the thermal quality of a building, but is rarely used because of some weaknesses. The weakness of this assessment criterion is that ventilation losses, internal and solar gains are not taken into account. For this reason, the meaningfulness is limited, but for the purpose of this study, the indicator would be put to the test.

3.6 Statistical analysis and data evaluation

In this final step of the method, all the collected data would be statistically analyzed with SPSS. SPSS is the acronym of Statistical Package for the Social Science. SPSS is a comprehensive system for analyzing data. SPSS can take data from almost any type of file and use them to generate tabulated reports, charts, and plots of distributions and trends, descriptive statistics, and complex statistical analysis. SPSS is one of the most popular statistical packages which can perform highly complex data manipulation and analysis with simple instructions. For the purpose of this thesis, the following fields of statistical analyses would be examined:

- Descriptive statistics — Frequencies,
- Pearson's Correlation (continuous data, parametric statistics), and
- Numeral outcome prediction — Multiple linear regression.

Descriptive statistics are statistics that quantitatively describe or summarize features of a collection of information. Some measures that are commonly used to describe a data set and would be used in the further analysis are measures of central tendency and measures of variability or dispersion. Measures of central tendency include the mean, median and mode, while measures of variability include the standard deviation (or variance), the minimum and maximum values of the variables (Trochim 2006).

The Pearson product-moment correlation coefficient (Pearson's correlation, for short) is a measure of the strength and direction of association that exists between two variables measured on at least an interval scale.

A Pearson's correlation attempts to draw a line of best fit through the data of two variables, and the Pearson's correlation coefficient, r, indicates how far away all these data points are to this line of best fit (i. e. how well the data points fit this new model/line of best fit).

Some of the assumptions have to be met when calculating Pearson's correlation:

- two variables should be measured on an interval or ratio level; they have to be continuous;
- there needs to be a linear relation between the two variables;
- there should be no significant outliers. Outliers are simply single data point within the data that do not follow the usual pattern;
- variables should be approximately normally distributed.

For the purpose of this thesis, all the design variables will be tested in correspondence to each other, and how do they correlate to performance indicator, heating demand.

Based on best fitting design variables, the ones that are shown to have the most impact on performance indicator, the heating demand of the building, regression analysis will be carried out. This step would test the possibility for prediction of heating demand based on some of the analyzed variables. That should be done via the method of regression analysis.

In statistical modeling, regression analysis is a statistical process for estimating the relationships among variables. It includes many techniques for modeling and analyzing several variables when the focus is on the relationship between a dependent variable and one or more independent variables (or 'predictors').

"In statistics, linear regression is an approach to modeling the relationship between a scalar dependent variable y and one or more explanatory variables (or independent variables) denoted X. The case of one explanatory variable is called simple linear regression. For more than one explanatory variable, the process is called multiple linear regression" (Freedman 2009, p. 26).

If the goal is a prediction, or forecasting, or error reduction, linear regression can be used to fit a predictive model to an observed data set of *y* and *X* values. After developing such a model, if an additional value of X is then given without its accompanying value of *y*, the fitted model can be used to make a prediction of the value of *y*. As *X* variable, or independent predictors variable, building design indicators should be tested one by one. As a dependent variable, or outcome variable, whose value is expected to be predicted, heading demand would be used.

Based on R^2 values, and fitted R-value, as well as the significance level p, the best fitting model would be chosen. That should be done by finding set, of most probably two variables, and based on the line of best fit; the regression equation would be derived. Some additional steps would be done in order to analyze the consistency and credibility of the outcome of this step. Variables would be examined for the possible errors, the integrity of linearity and constant variance, and lack of multicollinearity among predictor variables.

This equation should give the possibility to predict the heating demand of a building using only values of chosen variables for a certain building. This simplified method could have the possibility to help predict thermal behavior of the building, leaving out the complicated and time-consuming method of energy certification.

After finding the valid set of variables, next step would be going back to analyzed sample and with emphasis on the chosen variables; the more cases for each building would be created. That should be done by changing input parameters of each building, creating for each of them around 4 to 5 different case scenarios. This would provide more variance of the sample, and therefore more data and information that are necessary for final remarks and at the same time, more certainty of acquired results.

The method of energy certification would be used again for newly created cases. Heating demand indicator would be looked upon and analyzed and set against those changed input parameters.

The data obtained in this step would help understand the thermal quality of the sample and how increasing and decreasing values of design variables affects the performance of the building. The final goal is to create a simple prescriptive index, based on analyzed sample, using results of both energy certificates and multiple regression equation; with a table of different values for chosen most significant variables. This index should serve as a guideline for energy efficient design of a building in early stages of design. Furthermore, the index would provide information, which simple set of values for design variables, gives a certain level of heating demand energy scale. Following this prescriptive index would lead to an energy efficient design of a building, with information on expected building's thermal performance, and would spare time and costs related to the method of building performance simulation.

4 RESULTS

4.1 Overview

All buildings from the sample were analyzed and obtained data were evaluated. Results of this research are presented in following four chapters. The first section contains results for annual heating demand HWB (Heizwärmebedarf) obtained from energy certificates for each building. Annual heating demand as the performance indicator would be taken as a benchmark for quality of thermal design of the scrutinized building sample. The second part presents an evaluation of correlation of each design variable with calculated heating demand. Consequently, the data obtained in previous two steps were used to create a regression equation, which gives an opportunity to estimate the heating demand using a set of independent variables. Furthermore, the building sample has been extended for few more case scenarios for each building, leading to finally 76 cases of originally 15 buildings sample. Energy certificates for all the cases were obtained, using the outcome of the calculation method of energy certificates as a valid benchmark to create the index of prescriptive building design variables. Based on the calculated heating demand with the help of heating demand values estimated from regression equation calculation, enough data has been assembled to predict the energy efficiency category of a design for different values of input design variables.

4.2 Predicted annual heating demand

According to the method explained in chapter 3.4, an energy certificate is acquired and annual heating demand HWB (Heizwärmebedarf) has been used as the outcome and a representative indicator of a performance-based approach.

Figure 5 shows predicted annual demand for heating for each of the analyzed buildings. As shown in Figure 5, the value of lowest heating demand amounts 30.30 $kWh.m^{-2}.a^{-1}$, while highest demand accounts for 74.74 $kWh.m^{-2}.a^{-1}$. The average value for all buildings is 52.89 $kWh.m^{-2}.a^{-1}$ with a standard deviation of 12.85.

On an efficiency scale ranking of the buildings in compliance with OIB-Guideline 6, building fall into B ($HWB_{BGF,SK} \leq 50$ $kWh.m^{-2}.a^{-1}$) and C ($HWB_{BGF,SK} \leq 100$ $kWh.m^{-2}.a^{-1}$) category of energy label. It is noticeable that not all buildings comply with OIB-Guideline 6 requirement for maximum permitted annual heating demand off 54.4 $kWh.m^{-2}.a^{-1}$.

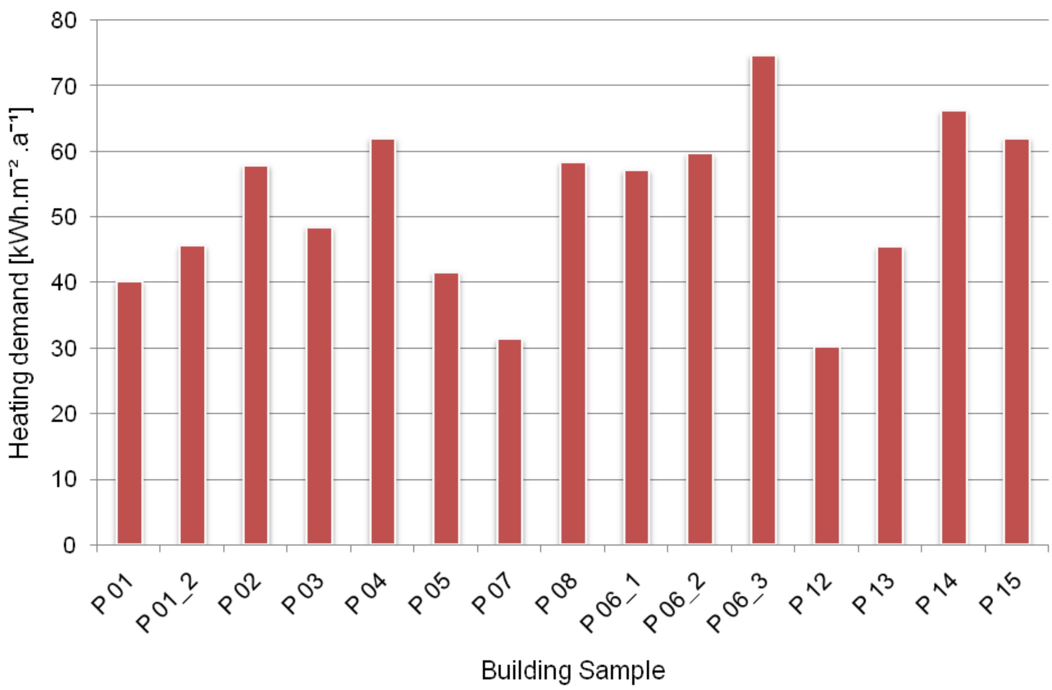


Figure 5. Annual heating demand

4.3 Descriptive design variables

The following chapter will analyze the most significant design variables explained in chapter 3.5 for every building and compare their influence on previously calculated annual heating demand. The correlation Pearson's coefficients will be looked upon, and depending on the outcome, the possibility of creating a regression model will be taken into consideration. Regression model created from the data of analyzed sample could help estimate the heating demand if the step of energy certificate of energy simulation would be left out.

Variables analyzed in the first step are some of the physical properties of the building envelope. These variables are significant indicators of buildings' size, parts of buildings area and volume, but since they are dependent on building's size, they cannot be compared to each other in a proper manner and therefore these variables alone do not have a great predictable power. However, they are an important step towards defining key variables, which are derived from some of them.

Since most indicators are limited in their applicability and not all of the variables mentioned in previous chapters are of a perceptual relevance for the purpose of this study, Table 12 shows a list of variables that are meaningful and most significant for this research.

Table 12. Legend of analyzed variables

A_s/V	*Shape factor or 'Kompaltheit' of building shapes describes the relation between a total surface area and building's volume.*
RC	*Relative Compactness of a shape as a comparison between its volume to surface area ratio to that of the cure with the same volume.*
l_c	*Characteristic length is simply the ratio of a building's volume (V) to its envelope area (A_s)*
V/A_{wall}	*Volume to Wall area Ratio*
V/A_f	*Volume to Footprint Area Ratio*
WWR	*Window to Wall ratio*
WWR_e	*Effective Window to Wall ratio as the average window to external wall ratio, corrected for orientation.*
U-Value	*Mean area weighted U-value of the thermal envelope, weighted by the area of the respective building components.*
U_e	*Effective average envelope U-value defined as the average U-value of heat emitting building enclosures weighted by the area of the respective building components and corrected for adjacency relationships*
LEK	*The heat protection of the building that establishes a relationship between the characteristic length of a building and the mean heat transfer coefficient of the building envelope.*
C_t	*Thermal compactness defined as the ratio of heated volume to thermally effective envelope area, which is the sum of areas of heat emitting building elements, corrected for adjacencies.*

Form factors are most commonly used building design indicators for predicting building's heating energy demand, and they have found their place in many building codes and standards. Their influence on annual heating demand has been analyzed within the sample.

Correlation between building's shape factor or also noted as a surface area to volume ratio and heating demand (Figure 6) is relatively high, with an R^2 of 0.62 and adjusted R^2 of 0.592. This value means that based on our sample 62% or adjusted value 59% of a sample can be explained by this regression model, which has fairly high predictable power. The standard error of estimation is 8.22, these value shows the average distance of data points from the fitted regression line, while Pearson's coefficient stands by 0.788 with a p-value of 0.000. Based on the sample it can be noticed that the more compact the building, the lower the calculated heating demand. More compact buildings result in lower compactness value; therefore this is a strong positive linear relationship.

On contrary to few research studies done on the impact of relative compactness on heading demand (Pessenlehner and Mahdavi 2004, Ourghi et al. 2007, AlAnzi 2009) this study showed a very little correlation between those two variables (Figure 7).

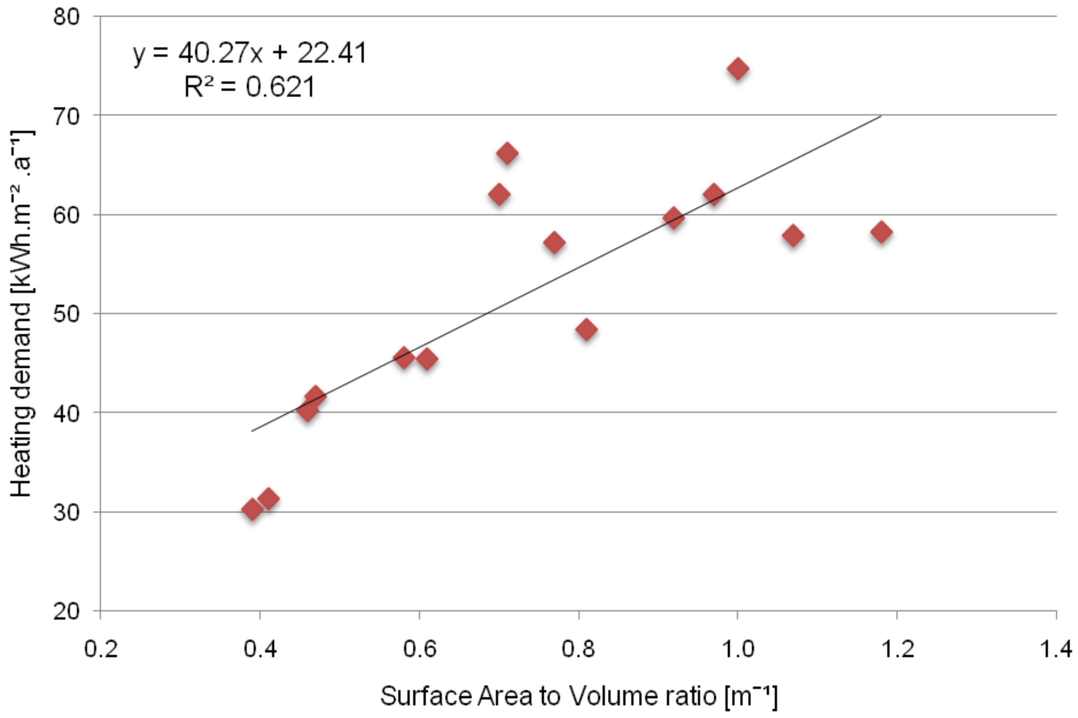


Figure 6. Calculated heating demand as a function of ratio between Surface Area and Volume

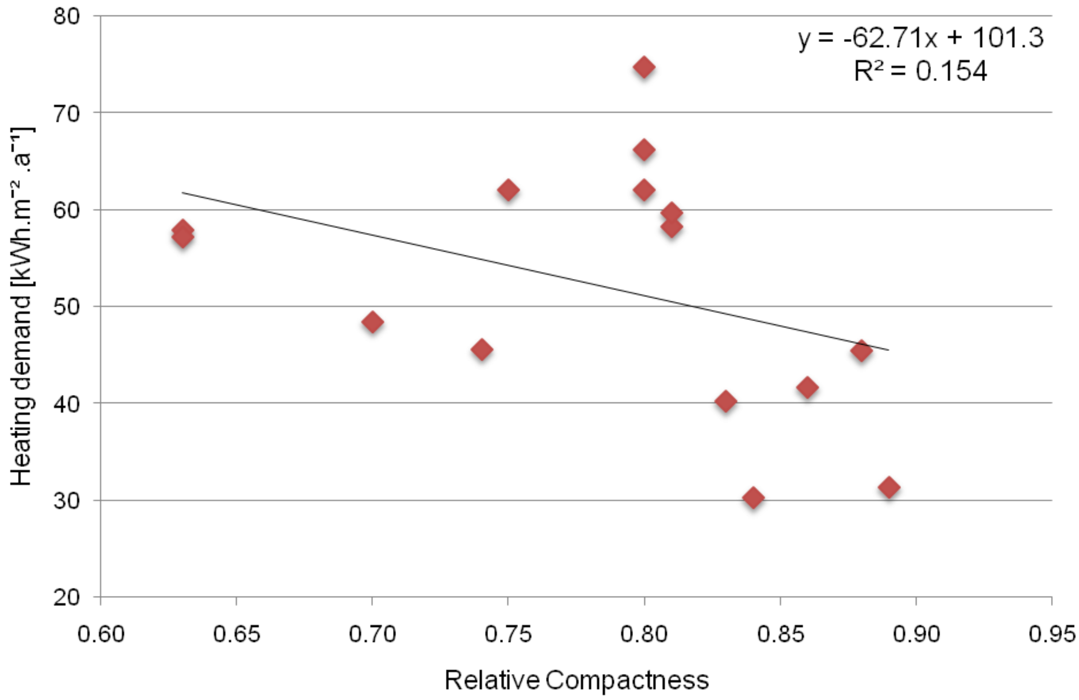


Figure 7. Calculated heating demand as a function of Relative compactness

The R^2 value is only 0.154, and Pearson's coefficient -0.376 with a p-value that is not statically significant. The most probable reason for this outcome could be not enough variance within the sample. The average value of RC in analyzed buildings is 0.78, with minimum and maximum values of 0.63 and 0.89 respectably. All the value fall into the category of compact to highly compact building shapes.

Characteristic length is often used indicator in buildings standards, including OIB-Guideline 6 which gives a simple formula for calculating heating demand. Figure 8 shows a correlation in the analyzed sample between characteristic length l_c and annual heating demand. The value of R^2 is 0.75 with fitted R value 0.727 and Pearson's coefficient of -0.864 with p-value 0.000, meaning that correlation is statistically significant. The correlation is fairly high negative or downhill correlation, and as expected from correlation with compactness, buildings with a larger value for characteristic length result in lower heating load.

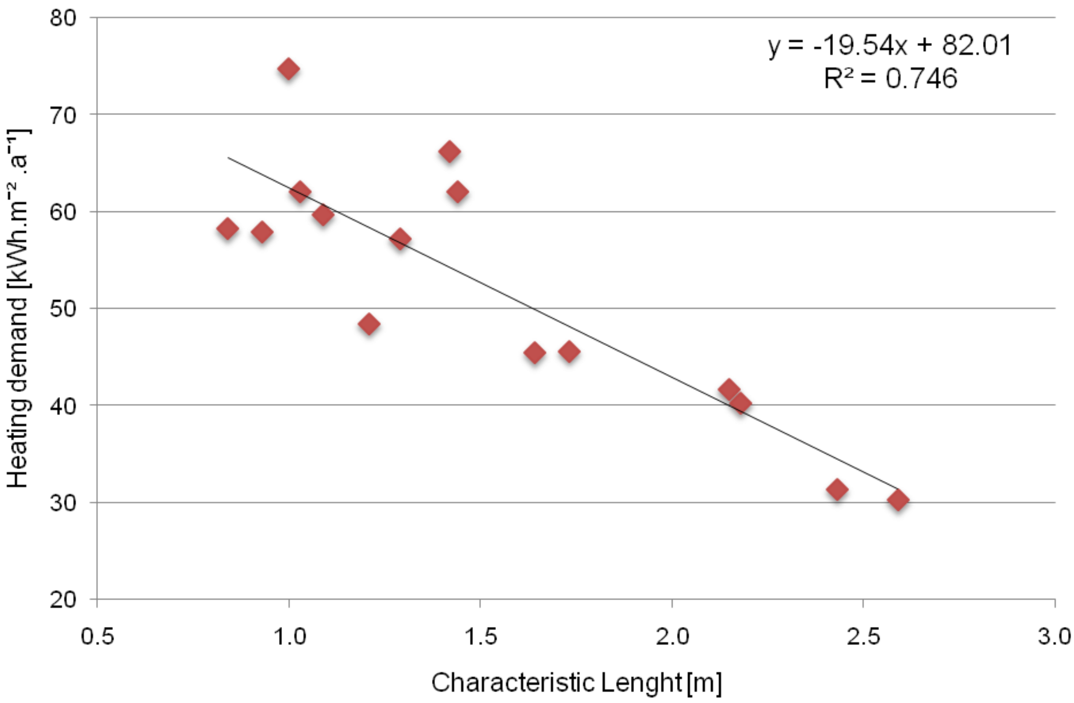


Figure 8. Calculated heating demand as a function of Characteristic Length

Volume to wall area ratio (Figure 9) and volume to footprint area ratio (Figure 10) showed a strong correlation, with R^2 values of 0.766 and 0.512 respectably. Both variables show strong negative correlation with Pearson's coefficients of 0.865 and 0.715, both statistically significant on 0.01 level.

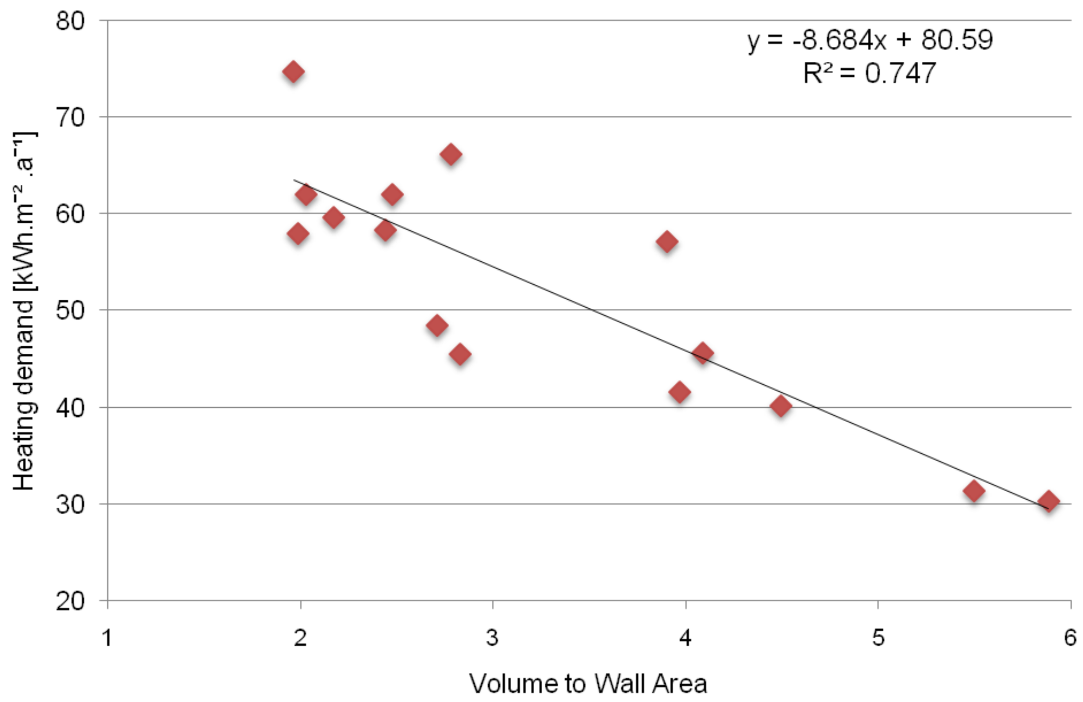


Figure 9. Calculated heating demand as a function of ratio between volume and wall area

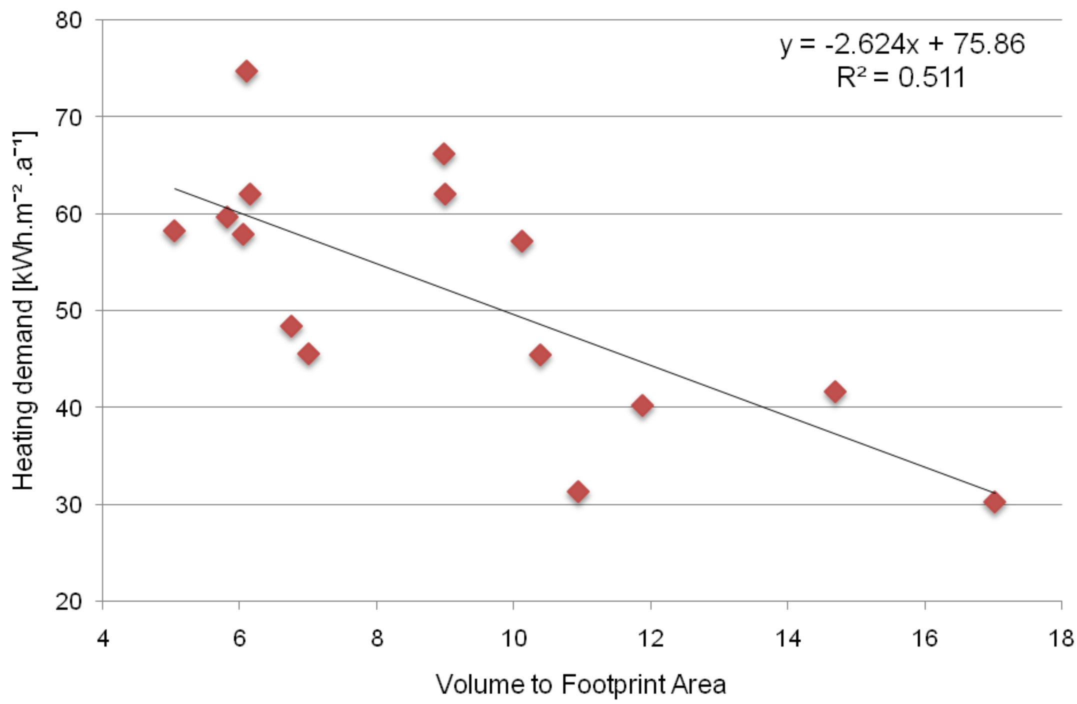


Figure 10. Calculated heating demand as a function of the ratio between volume and footprint area

In terms of properties of transparent elements of building envelope WWR, window to wall ratio, didn't express expected correlation. WWR values for given sample are a minimum of 10% and a maximum of 39%. All the values account for low values of

WWR, and since there is no much dissimilarity within the values, that could be accepted as a possible explanation for such a low correlation. While R^2 value for WWR (Figure 11) reports 0.102, the R^2 value for effective window to wall ratio (Figure 12) reports 0.05 which is almost zero correlation.

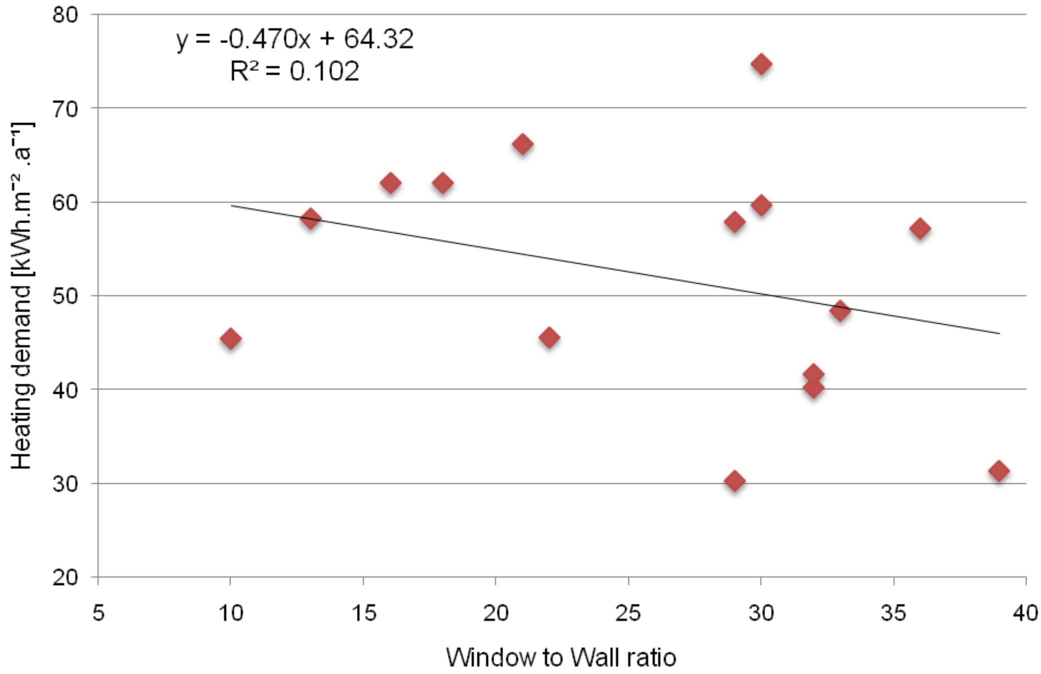


Figure 11. Calculated heating demand as a function of WWR

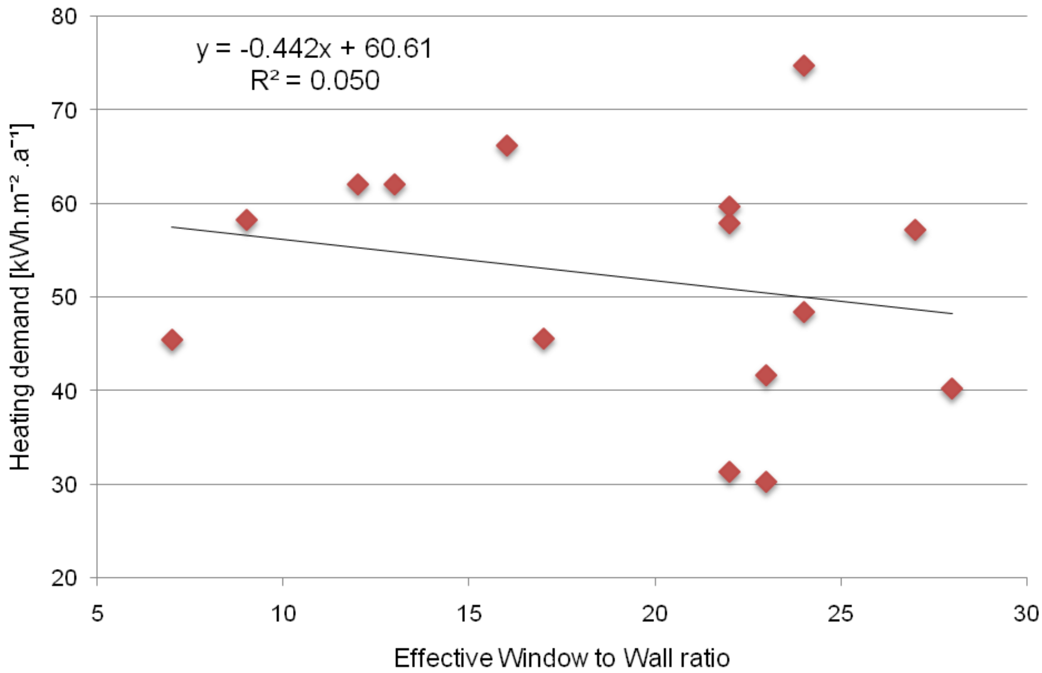


Figure 12. Calculated heating demand as a function of WWR_e

Mean area weighed U-value of the building envelope (Figure 13), as the most important indicator of the thermal quality of the building, did not report expected correlation in analyzed sample. The value of R^2 appears to be 0.024, which stands for almost zero correlation. Similar correlations close to zero were noted for effective average envelope U-value (Figure 14). This paradox can easily be explained as an aftermath of not enough variance in analyzed values. In this stage of the work, only one case scenario for each building's U-value was examined, and therefore U-value alone did not show high correlation, meaning that this variable should be analyzed in correspondence with some other indicators. All buildings comply with a really good thermal quality properties and low U-values prescribed by OIB-Guideline 6:2015. The lowest mean area weighted heat transfer coefficient holds the value of 0.259 $W.m^{-2}.K^{-1}$ while highest U-value stands by 0.442 $W.m^{-2}.K^{-1}$.

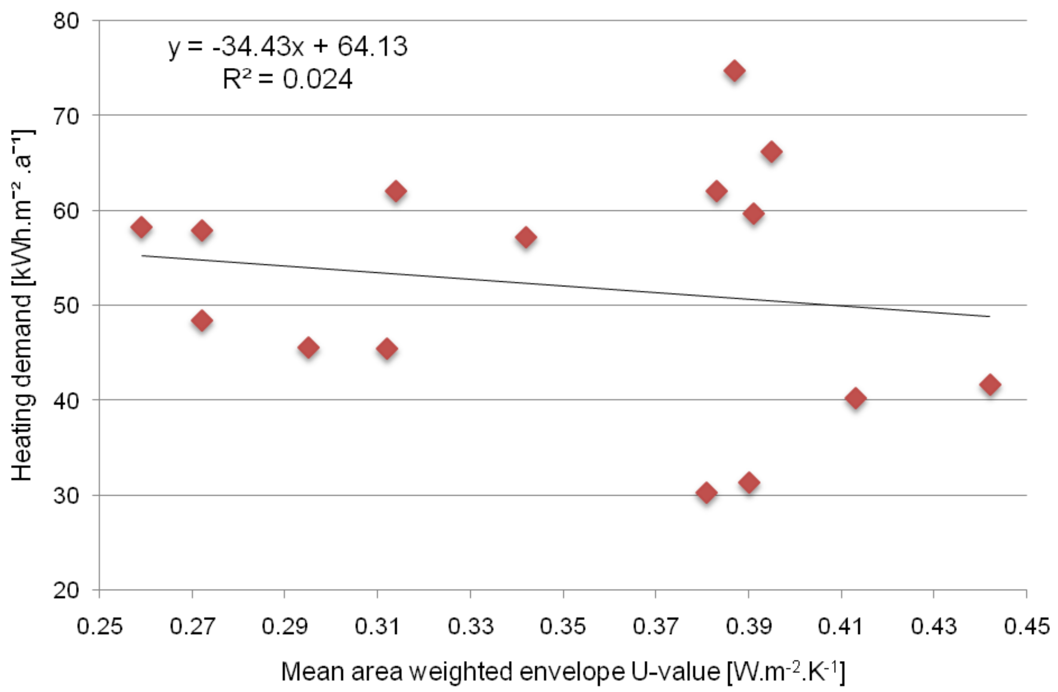


Figure 13. Calculated heating demand as a function of mean area weighted U-value of building envelope

On the other hand, LEK value (Figure 15), as an indicator of thermal quality, showed a much better correlation in given sample. LEK value as a relationship between the characteristic length l_c and U-value has better predictor potential than U-value alone. R value is 0.711 with a significance level of 0.003, while R^2 value reports 0.505. Generally applies that energy saving houses have LEK values below 30, low-energy houses below 20, passive houses below 10. Lowest LEK value from analyzed buildings totals 24, while highest value totals 39. Building with lowest heating demand had LEK value of 25, and highest LEK value of 39 belongs to the building with highest heating demand. It is clear that the correlation between annual heating demand and LEK values is strong linear correlation and implies the lower the LEK value the lower the heating demand.

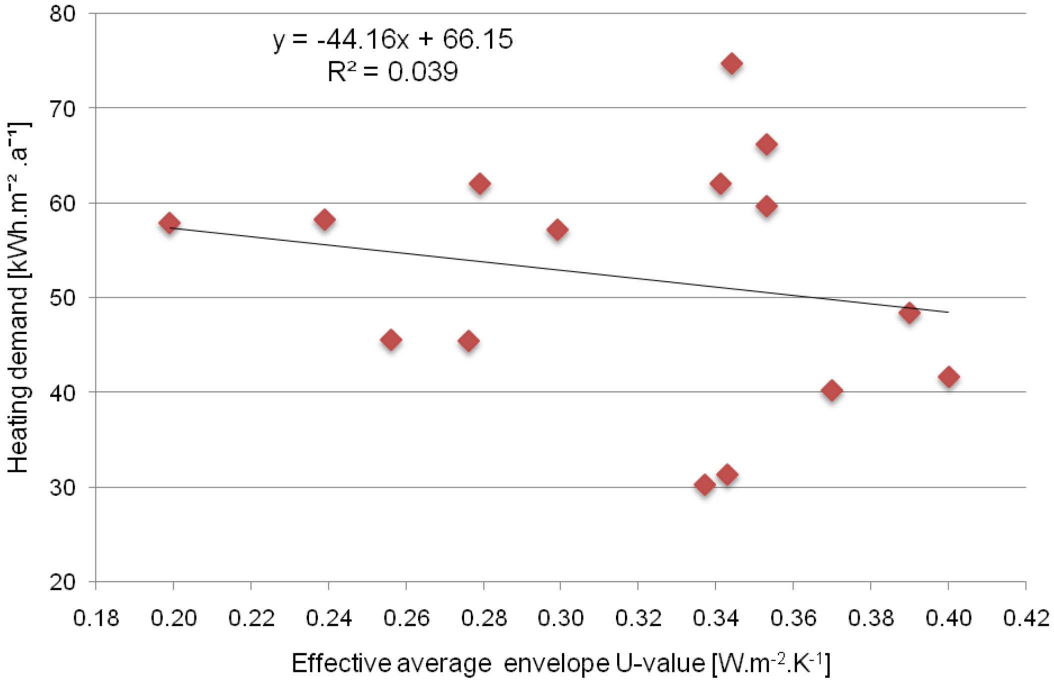


Figure 14. Calculated heating demand as a function of effective average envelope U-value

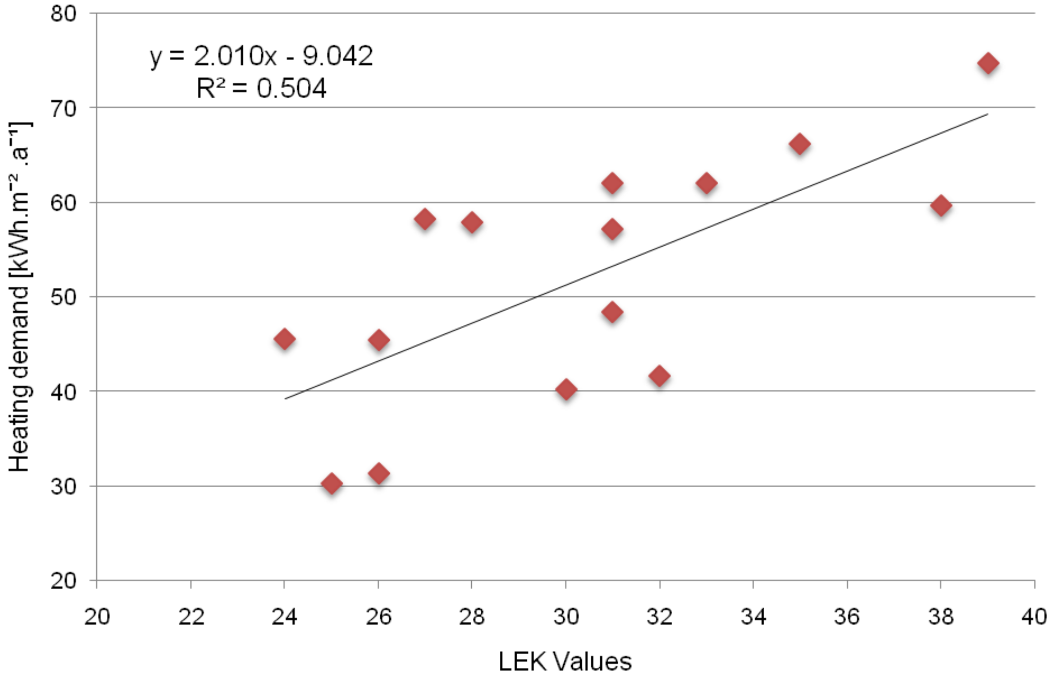


Figure 15. Calculated heating demand as a function of LEK values

Furthermore, thermal compactness (Figure 16) shows the highest correlation with the annual heating demand of all the variables, a bit higher than characteristic length. Thermal compactness can also be noted as effective characteristic length, where l_c stands for the ratio of a building's volume to its envelope area, so effective characteristic length can be defined as the ratio of buildings volume to envelope area corrected for adjacencies. The indicator has high predictable power with a statistically significant R value of 0.871 and R^2 value of 0.758 with mean absolute percentage deviation of 6.57.

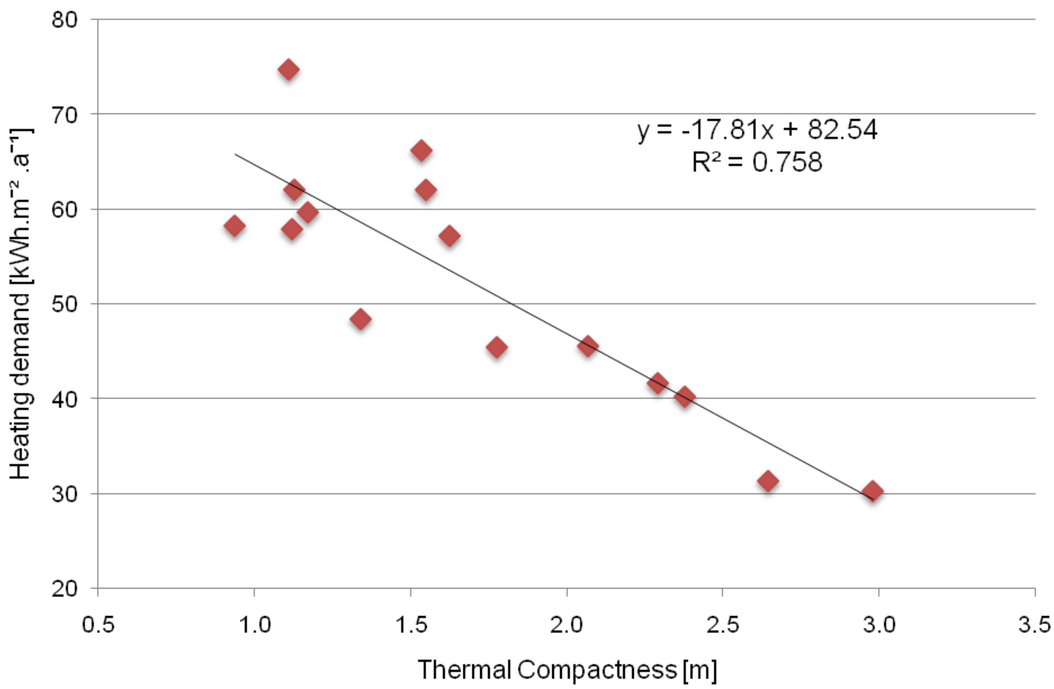


Figure 16. Calculated heating demand as a function of thermal compactness

4.4 Multiple regression model for simplified prediction of the heating energy demand

Prescriptive building energy codes often set minimum requirements concerning thermal properties of building components. To account for the prediction of the energy use in stages before thermal simulation takes place, some energy-related standards and studies make use of simple numeric indicators to predict buildings energy demand. Typically, such indicators are derived based on the relationship between the volume of a built form and the surface area of its enclosure. The indicators are then used along with information on the thermal transmittance of the building enclosure elements to evaluate the degree to which a building design meets the relevant minimum thermal requirements (Pessenlehner and Mahdavi 2003).

According to the analysis of all design variables done in the previous chapter and based on their influence on building performance, a small set of test variables was selected. Important mark in this step was excluding the possibility of multicollinearity between chosen variables. Multicollinearity refers in this case to a situation in which two or more explanatory variables are highly correlated, meaning that one can be linearly predicted from the others with a substantial degree of accuracy. Examples of such variables are characteristic length and compactness, they both define similar form property, and therefore both of them cannot be taken into a same set of variables.

Analysis inspected above shown highest correlation to building performance for compactness, characteristic length, l_c (but for test purpose, only one of them would be validated) and LEK value. On the other hand, WWR and average U-value didn't show that much of a correlation, but from previous practice and experience, their impact on thermal quality has been validated. All of the prescriptive standards, such as ASHRAE 90.1 and the International Energy Conservation Code (IECC), prescribe maximum permitted values for these two variables so they will both be evaluated. Although LEK value is a relationship between characteristic length and heat transfer coefficient, the variable did not show signs of multicollinearity in the statistical test with none of the two variables, so it was also taken into consideration for regression analyses.

Based on regression analysis, a correlation is found to provide the best curve fit between the calculated annual building energy use for heating and the two parameters: *characteristic length l_c and mean area weighed envelope U-value.* The correlation equation (Equation (12)) can be utilized during the preliminary design phase to assess the impact of building shape and thermal characteristic of the envelope on the energy efficiency of small-scale residential buildings.

The objective of multiple regression analysis is to predict the single dependent variable Y (heating demand) by a set of independent variables Xi (shape factor, WWR, U-value etc.). Compared to neural networks, multiple regression analysis could be an easier and more practical solution to different problems which are following a constant pattern. When having a large database of values, the regression techniques could be applied with success and with good results on the correlation between the model and the analyzed data set.

Developing a correlation method, it is essential to generate a large database by doing many parametric studies and then create a simple equation by using regression analysis. Analyzed sample does not have a large enough number of variations, but this approach has great potential with large data sets.

With two independent variables the prediction of Y is expressed by the following equation:

$$Y' = b_0 + b_1X_1 + b_2X_2 \qquad (12).$$

Y' is predicted variable, heating demand, and X_1 and X_2 are our predictor variables mean area weighted U-value as X_1 and characteristic length l_c as X_2 . Table 13 shows coefficient of our fitted model,

Table 13. Optimal weights in the regression model

Coefficients[a]

	Unstandardized Coefficients		Standardized Coefficients		
	Regression coefficient B	Standard Error	Beta	T	Sig.
(Constant)	54.107	7.019		7.709	0.000
Mean U-Value	106.568	23.724	0.482	4.492	0.001
l_c	-25.668	2.427	-1.135	-10.577	0.000

a. Dependent Variable: Heating Demand

and the regression equation appears as:

$$Y' = 54.107 + 106.568\ X_1 - 25.668\ X_2 \qquad (13).$$

Table 14 shows that regression model has an R^2 value of 0.905, meaning that 90% of the data is explained by the model. A significance level of the model is significant on 0.05 level with Sigma value for the model being 0.000. The standard error of estimate is a measure of error of prediction, and for this model, it accounts for 4.27.

Table 14. Correlation coefficients

Model Summary[b]

R	R Square	Adjusted R Square	Std. Error of Estimate
0.952[a]	0.905	0.890	4.274

a. Predictors: (Coefficient, Constant), l_c, mean area weighted U-Value
b. Dependent Variable: Heating Demand

The residuals from a fitted model are the differences between the responses observed at each combination values of the explanatory variables and the corresponding prediction of the response computed using the regression function. Figure 17 shows residuals of fitted model, which form almost a straight line.

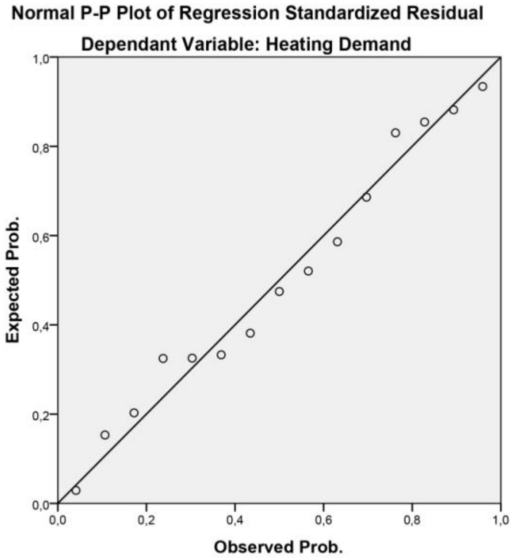


Figure 17. Normal probability plot of regression standardized residuals

To test the credibility of the fitted model, the R^2 value has been checked (Figure 18) within the model and further standard error of deviation has been looked upon.

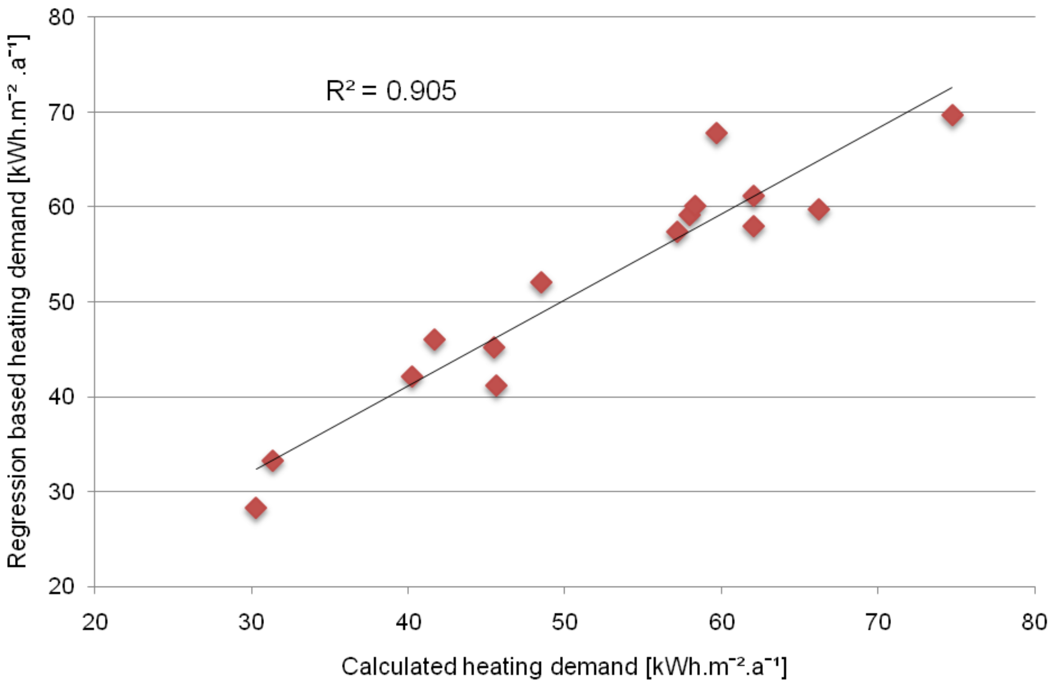


Figure 18. Regression based heating demand, as a function of calculated heating demand

Figure 19 shows the relative deviation of individual simulation results for heating demand from the corresponding predictions based on linear regression. Deviations lie between -10% and 14%, with an absolute average error of 6%.

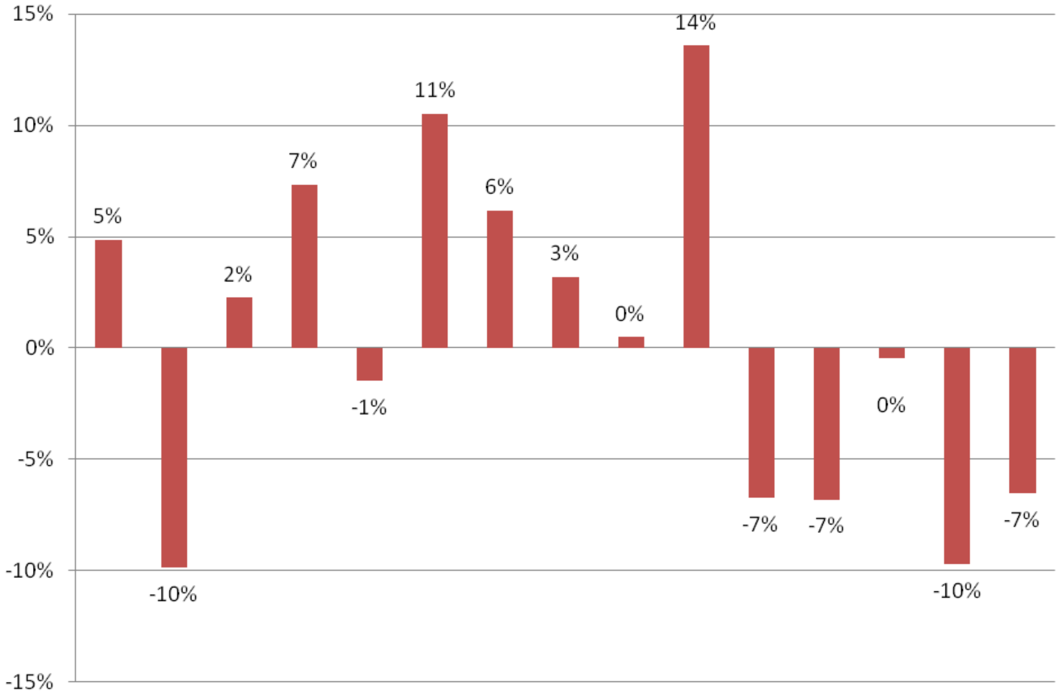


Figure 19. Deviation of regression based heating demand, as a function of calculated heating demand

4.5 Prescriptive index for energy efficient building design

The following chapter will deal with a simple method of interpreting the outcome and overlap level of the two approaches explained in previous two chapters, the calculation method of energy certificate on one side, and on the other side a chosen set of variables.

Regression analyses showed that best fitting model consists of following two variables: characteristic length and mean area weighed envelope U-value. Some energy codes and previous studies have already shown the importance of these indicators, and therefore their utilization for the further purposes of this study has been justified. In order to create enough quantity of data, new case scenarios for each building have been created. In these cases, the emphasis is on those two accepted variables and creating the more variance as possible for each of them.

Values for characteristic length in building sample vary from 0.84 m for lowest and 2.59 m for the highest value. Mean area weighed envelope U-value in base case scenarios varies between 0.442 and 0.259 $W.m^{-2}.K^{-1}$. Given that all buildings fall into B ($HWB_{BGF,SK}$ ≤ 50 $kWh.m^{-2}.a^{-1}$) and C ($HWB_{BGF,SK}$ ≤ 100 $kWh.m^{-2}.a^{-1}$) category of energy label, the goal would be creating more variability in heating demand and creating more energy efficiency labels. Consequently, for each building, few new case scenarios were created. That has been conducted by changing thermal properties of building components, specifically lowering the values for heat transfer coefficient of different building elements, changing the material properties, changing the thickness of insulation and other layers. For each case scenario, characteristic length was kept constant, while each case has lower mean area weighted U-value than the previous case. Therefore, around 60 new cases have been derived for the sample of 15 buildings, having 76 cases altogether.

For every single case, an energy certificate has been calculated, and heating demand as performance indicator has been extracted, providing more variety on efficiency scale ranking. Figure 20 shows values for calculated heating demand.

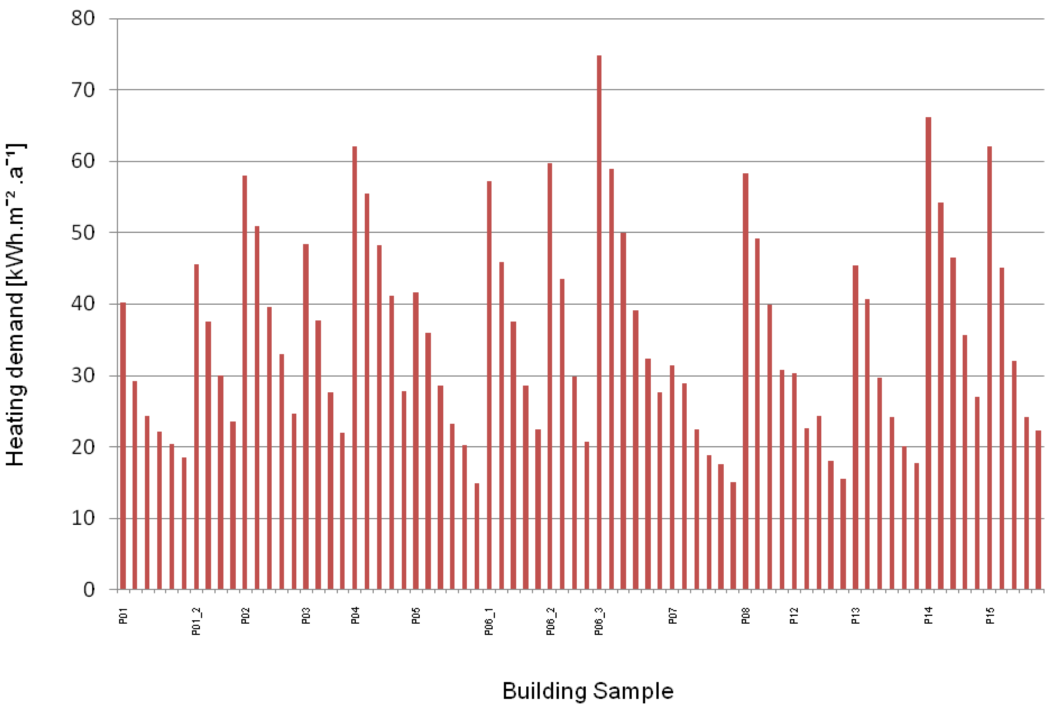


Figure 20. Annual heating demand

For each base case, new case scenarios are shown right next to the base case ones, with each one of them showing lower value for heating demand. As expected from previous studies and general wisdom; for each building where characteristic length was kept constant, results show the lower the mean area weighed envelope U-value, the lower the heating demand. In the newly analyzed sample, the value of lowest heating demand amounts 14.88 $kWh.m^{-2}.a^{-1}$, while highest demand stayed

74.74 $kWh.m^{-2}.a^{-1}$ as before. The goal was to create new better energy scale by improving thermal properties of the building envelope.

The final stage of analyzes consists of examining which values for given variables give desired level of energy efficiency. Taking into account calculated data and with the help of regression equation, around 240 different scenarios have been examined and the prescriptive index has been derived based on the thermal behavior of analyzed sample.

On an efficiency scale ranking from the buildings in complying with OIB-Guideline 6, building fall into C ($HWB_{BGF,SK}$ ≤ 100 $kWh.m^{-2}.a^{-1}$), B ($HWB_{BGF,SK}$ ≤ 50 $kWh.m^{-2}$ $.a^{-1}$), A ($HWB_{BGF,SK}$ ≤ 25 $kWh.m^{-2}$ $.a^{-1}$), A+ ($HWB_{BGF,SK}$ ≤ 15 $kWh.m^{-2}$ $.a^{-1}$) and A++ ($HWB_{BGF,SK}$ ≤ 10 $kWh.m^{-2}$ $.a^{-1}$) category of energy label.

Table 15 shows which combination of values for characteristic length and heat transfer coefficient, for reference Vienna climate data, would give the desired category of energy efficiency mentioned above. On one axis the values for characteristic length are plotted, ranging from 0.8 till 3.5 m. Although, single and multi-family houses can rarely have a characteristic length of more than 2, the value of around 3 is realistic for big scale residential buildings. Another axis represents values for mean area weighted envelope U-value, with the lowest value of 0.1 $W.m^{-2}.K^{-1}$ and highest 0.7 $W.m^{-2}.K^{-1}$.

The derived index is easy to follow for designers, and for buildings that do not undergo the step of energy simulations, gives an overview which category of energy label the building would potentially have.

Table 15. Prescriptive index with energy labels (Reference climate Vienna, Austria)

Mean area weighted envelope U - value [$W.m^{-2}.K^{-1}$]	Characteristic Lenght [m]																											
-	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3.0	3.1	3.2	3.3	3.4	3.5
0.70	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	B	B	B	B	B	B	B	B
0.60	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	B	B	B	B	B	B	B	B
0.50	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	B	B	B	B	B	B	B	B
0.49	C	C	C	C	C	C	C	C	C	C	C	C	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	A
0.48	C	C	C	C	C	C	C	C	C	C	C	C	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	A
0.47	C	C	C	C	C	C	C	C	C	C	C	C	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	A
0.46	C	C	C	C	C	C	C	C	C	C	C	C	B	B	B	B	B	B	B	B	B	B	B	A	A	A	A	A+
0.45	C	C	C	C	C	C	C	C	C	C	C	C	B	B	B	B	B	B	B	B	B	B	B	A	A	A	A	A+
0.44	C	C	C	C	C	C	C	C	C	C	C	C	B	B	B	B	B	B	B	B	B	B	B	A	A	A	A	A+
0.43	C	C	C	C	C	C	C	C	C	C	C	C	B	B	B	B	B	B	B	B	B	B	B	A	A	A	A	A+
0.42	C	C	C	C	C	C	C	C	C	C	C	C	B	B	B	B	B	B	B	B	B	B	B	A	A	A	A	A+
0.41	C	C	C	C	C	C	C	C	C	C	C	C	B	B	B	B	B	B	B	B	B	B	B	A	A	A	A	A+
0.40	C	C	C	C	C	C	C	C	C	C	C	C	B	B	B	B	B	B	B	B	B	B	B	A	A	A	A	A+
0.39	C	C	C	C	C	C	C	C	C	C	C	C	B	B	B	B	B	B	A	A	A	A	A	A+	A+	A+	A+	A+
0.38	C	C	C	C	C	C	C	C	C	C	C	C	B	B	B	B	B	B	A	A	A	A	A	A+	A+	A+	A+	A+
0.37	C	C	C	C	C	C	C	C	C	C	C	C	B	B	B	B	B	B	A	A	A	A	A	A+	A+	A+	A+	A+
0.36	C	C	C	C	C	C	C	C	C	C	C	C	B	B	B	B	B	B	A	A	A	A	A	A+	A+	A+	A+	A+
0.35	C	C	C	C	C	C	C	C	C	C	C	C	B	B	B	B	B	B	A	A	A	A	A	A+	A+	A+	A+	A+
0.34	C	C	C	C	C	C	C	C	C	C	C	C	B	B	B	B	B	B	A	A	A	A	A	A+	A+	A+	A+	A+
0.33	C	C	C	C	C	C	C	C	C	C	C	C	B	B	B	B	B	B	A	A	A	A	A	A+	A+	A+	A+	A+
0.32	C	C	C	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	A	A	A+	A+	A+	A+	A+	A+	A+	A+
0.31	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	A	A	A	A	A+	A+	A+	A+	A+	A+	A+	A+	A+
0.30	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	A	A	A	A	A+	A+	A+	A++	A++	A++	A++	A++	A++
0.29	B	B	B	B	B	B	B	B	B	B	B	B	B	A	A	A	A	A	A	A+	A+	A+	A++	A++	A++	A++	A++	A++
0.28	B	B	B	B	B	B	B	B	B	B	B	B	B	A	A	A	A	A	A	A+	A+	A+	A++	A++	A++	A++	A++	A++
0.27	B	B	B	B	B	B	B	B	B	B	B	B	B	A	A	A	A	A	A	A+	A+	A+	A++	A++	A++	A++	A++	A++
0.26	B	B	B	B	B	B	B	B	B	B	B	B	B	A	A	A	A	A	A	A+	A+	A+	A++	A++	A++	A++	A++	A++
0.25	B	B	B	B	B	B	B	B	B	B	B	B	B	A	A	A	A	A	A	A+	A+	A+	A++	A++	A++	A++	A++	A++
0.24	B	B	B	B	B	B	B	B	B	B	B	B	B	A	A	A+	A+	A+	A+	A+	A+	A+	A++	A++	A++	A++	A++	A++
0.23	B	B	B	B	B	B	B	B	B	B	B	B	B	A	A	A+	A+	A+	A+	A+	A+	A+	A++	A++	A++	A++	A++	A++
0.22	B	B	B	B	B	B	B	B	B	B	B	B	B	A	A	A+	A+	A+	A+	A+	A+	A+	A++	A++	A++	A++	A++	A++
0.21	B	B	B	B	B	B	B	B	B	B	B	B	B	A	A	A+	A+	A+	A+	A+	A+	A+	A++	A++	A++	A++	A++	A++
0.20	B	B	B	B	B	B	B	B	A	A	A	A	A	A	A	A+	A+	A+	A+	A+	A+	A+	A++	A++	A++	A++	A++	A++
0.19	B	B	B	A	A	A	A	A	A	A	A	A	A	A	A	A+	A+	A+	A+	A++	A++	A++	A++	A++	A++	A++	A++	A++
0.18	B	B	B	A	A	A	A	A	A	A	A	A	A	A	A	A+	A+	A+	A+	A++	A++	A++	A++	A++	A++	A++	A++	A++
0.17	B	B	B	A	A	A	A	A	A	A	A	A	A+	A+	A+	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++
0.16	B	B	B	A	A	A	A	A	A	A	A	A	A+	A+	A+	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++
0.15	B	B	B	A	A	A	A	A	A	A	A	A	A+	A+	A+	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++
0.14	B	B	A	A	A	A	A	A	A	A	A	A	A+	A+	A+	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++
0.13	B	B	A	A	A	A	A	A	A	A	A	A	A+	A+	A+	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++
0.12	B	B	A	A	A	A	A	A	A	A	A	A	A+	A+	A+	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++
0.11	B	B	A	A	A	A	A	A	A	A	A	A	A+	A+	A+	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++
0.10	B	B	A	A	A	A	A	A	A	A	A	A	A+	A+	A+	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++	A++

5 DISCUSSION

5.1 Overview of investigated key design parameters

The main goal of this work was to evaluate the outcome of calculation method and method of prescribing a set of descriptive building indicators in early stages of design. Energy efficiency requirements in building codes can ensure that the energy efficiency measures are taken into account from the very beginning, i.e. already at the building's design phase.

Currently, much attention is being paid to finding methods and approaches that make the thermal performance of building more predictable. This is due to the increasing requirements for sustainability and planning for the Service Life of buildings. Rigorous studies of the role of the building materials as an instrument for making the thermal performance more effective and predictable have been carried out. Such studies tend often to investigate the thermal performance of building as a function of building materials, independent of building form and other architectural factors. Studies of this sort are particularly concerned with the degree of thermal efficiency of the building, as based fundamentally on materials thermo-physical property and dimensional characteristics of building components. Although the role and the significance of the shape of building envelope have been studied upon, there is a lack of systematic investigation of such building aspect (Behsh 2002).

From general experience and previous studies, it is established that architectural design variables which most influence the energy performance of a building are the envelope materials, shape and window areas. As these start to be defined in the early design stages, designers require simple tools to obtain information about the energy performance of the building for the design variations being considered at this phase.

Since performance requirements differ drastically between countries and total sample set was tested based on Austrian regulation of reaching desired building performance, not all the buildings satisfy that desired performance. Overall, the predicted annual heating demand for all of the buildings does not exceed C category or energy label ($HWB_{BGF,\ SK} \leq 100$ kWh.m^{-2}.a^{-1}), with highest heating demand grasping 74.74 kWh.m^{-2} .a^{-1}. Based on that, we can conclude that buildings comply with good principles of general design, taking into account that no energy evaluation has been done in early stages of design.

Table 16 shows some values derived from analyzed sample of residential buildings, which can be used as a guideline to energy efficient design in early stages of design process, taking into consideration only building's descriptive indicator characteristic length, l_c [m] and thermal property of the building envelope, namely mean area weighted U-value [$W.m^{-2}.K^{-1}$]. For each variable for maximum permitted value, a related energy efficiency category is assigned. Energy efficiency categories range from A++ to C category, in compliance with OIB-Guideline 6 categories of energy label. Residential buildings that satisfy these prescriptive requirements can comply with good thermal quality, although guidelines like this one can be a bit rigid and limit the designer's freedom, this guideline seem to give a lot of freedom in building design, while it limits requirements for only the two above mentioned indicators.

Table 16. Prescribed requirements for characteristic length and U-value

Energy label category	l_c [m]	U-value [$W.m^{-2}.K^{-1}$]
A++	3.00 - 3.50	max 0.30
	2.70 - 2.99	max 0.19
	2.20 - 2.69	max 0.17
A+	3.50	0.40 - 0.49
	3.00 - 3.49	0.40 - 0.46
	2.60 - 2.99	0.33 - 0.39
	2.50 - 2.70	0.32
	2.20 - 2.59	0.24 - 0.31
	2.00 - 2.19	0.18 - 0.30
	1.90 - 2.00	0.18 - 0.20
	1.60 - 1.99	max 0.20
	1.00 - 1.59	max 0.19
	0.90 - 1.00	max 0.14
A	3.50	0.47 - 0.49
	3.00 - 3.49	0.40 - 0.46
	2.60 - 2.99	0.33 - 0.39
	2.50 - 2.70	0.32
	2.20 - 2.59	0.24 - 0.31
	2.00 - 2.19	0.18 - 0.30
	1.90 - 2.00	0.18 - 0.20
	1.60 - 1.99	max 0.20
	1.00 - 1.59	max 0.19
	0.90 - 1.00	max 0.14
B	2.80 - 3.50	0.50 - 0.70
	2.00 - 3.49	0.47 - 0.50
	2.00 - 3.00	0.40 - 0.47
	2.00 - 2.50	0.32 - 0.4
	2.00 - 2.20	0.30 - 0.31
	1.10 - 2.20	0.21 - 0.31
	1.10 - 1.50	0.20 - 0.32
	0.80 - 1.09	max 0.31
C	2.00 - 2.70	0.50 - 0.70
	1.00 - 1.99	0.33 - 0.70
	0.80 - 1.09	0.32 - 0.70

As it can be seen from Tables 15 and 16, not all values for characteristic length can reach highest energy efficiency levels. The best performing buildings are the ones with l_c of 2 m and higher. Since characteristic length is a ratio between buildings volume and surface area, high number implies minimum heat gain/loss. The greater the surface of envelope area is the more heat gain/loss through it. Buildings with tiny spikes and lots of changes in footprints have a very large surface area for a given volume and therefore they have higher heating demands. From the analyzed sample, the best performing buildings are the ones with high value for characteristic length and low mean U-value. Only those buildings can comply with A++ and A+ levels of energy efficiently. Based on property mentioned above, building with really high value for l_c can reach high energy efficiency levels even with lower mean area weighted U-value. On the other hand, buildings which have the small volume to surface area ratio, have to comply with really high-efficiency requirement for thermal properties of the building envelope (low U-value) to reach high energy efficiency class.

The index mentioned above takes into account only two previously mentioned design variables and can be considered as a simplified prescriptive approach. However, buildings analyzed in this study comply with some other requirements of universal good design, and their influence on heating demand and on the outcome of the whole study should not be neglected. Therefore, comparison with the outcome and with previous studies will be discussed as follows.

From the analyzed sample, as well as from numerous studies done in this field, can be concluded that there is a strong correlation between the shape coefficient and energy demand.

Allen's rule: A race of warm-blooded species in a cold climate typically has shorter protruding body parts (nose, ears, tail, and legs) relative to body size than another race of the same species in a warm climate. Joel Asaph Allen, American zoologist and ornithologist 1877 Source: A Dictionary of Zoology, 1999, Michael Allaby.

The thermal envelope area is the area that separates between the conditioned and unconditioned areas or alternatively, the indoor and the outdoor environment. As a result, the heat losses through the thermal envelope account for large percentage of the total final energy use of a building in cold climates. Buildings with a higher shape factor are less compact and therefore have a larger thermal envelope area in proportion to their volume and therefore larger heat losses (Danielski et al. 2012).

Designing new residential buildings with lower shape factor will result in lower specific heat demand. Shape factor A/V has an important function in German Energy Saving Ordinance 2009 (EnEV 2009), which sets the requirements for the total primary energy demand of the buildings by the shape factor. Shape factor is used as a guideline in the educational material for passive house architects. The shape factor for a typical single-family house is 0.8 - 1.0 m^{-1}, and for a passive house is ≤ 0.8 m^{-1}.

In analyzed sample, the best performing buildings were the ones with compactness lower than 0.8 m^{-1}, and the best performing building has compactness of 0.4 m^{-1}.

Some previous studies (Pessenlehner and Mahdavi 2003, AlAnzi et al.2012) have found a solid association between RC and heating load. More compact shapes result in somewhat smaller heating loads, and they conclude that RC seems to capture geometry well, despite its negligence of the morphological variance of the sample. In analyzed sample, the correlation has not been established, but that can be due to fact that all buildings have similar value for RC and there are not so many discrepancies between calculated heating demands. On the other hand, the results of a detailed parametric analysis conducted by study of AlAnzi et al. 2012 indicate that the effect of building shape on total building energy use depends on primarily three factors, the relative compactness, RC, the window to wall ratio, WWR and glazing type defined by it solar heat gain coefficient, SHGC. For buildings with low window-to-wall ratios, it is found that the total energy use is inversely proportional to the building's relative compactness independent of its form. Concerning this finding and applying it to the analyzed sample, some correlation does occur. Building with high RC of around 0.8 and with WWR around 30% do seem to have lower calculated heating demand, but this observation does seem to show some aberrations within the whole sample.

In the study from Catalina et al. 2008, it has been established that the impact of the shape coefficient on energy demand also depends on the envelope heat transfer coefficient (or U-value) being the impact smaller for smaller values of the latter. In analyzed sample all the building comply with low values for U-value, resulting in good thermal quality, but occurrence stated above has not been noted.

The LEK value is a measure of the thermal quality of buildings, but is rarely used in building standards because of some weaknesses. The idea is to use different LEK-lines to prescribe the minimum thermal insulation requirements for various building types in different locations. The weakness of this assessment criterion is that ventilation losses, internal and solar gains are not taken into account. The LEK value has not gained a substantial distribution because it is difficult to understand in terms of a physical design of the building. For this reason, the meaningfulness is limited.

Although prescriptive by nature, LEK values can be used as a performance indicator to describe the thermal quality of buildings but because of the limitations, the use of some more common other energy characteristics in the whole Europe is recommended. Opposed to that general rules apply that energy saving houses have LEK values below 30, low-energy houses below 20, passive houses below 10. The study conducted for the purpose of this thesis did show a significant correlation with LEK value and heating demand, and buildings with LEK values lower than 30, do show lower heating demands, with best performing buildings having LEK value of around 15.

On the building scale, the architectural design variables which most influence the energy performance of a building are related to the envelope design: the envelope materials, through their thermo-physical and optical properties, the envelope shape and the window to wall area per cardinal direction (as consequence of the building orientation) (Oral and Yilmaz 2002).

Since all buildings satisfy prescribed values of the maximum permitted U-values, and do comply with relatively low heating loads, it can be concluded that U values play an important role in the thermal quality of the building. On the other hand, maximum permitted values differ from country to country and are strongly dependent on the climate. For the purpose of this study, Vienna location has been chosen, and therefore the U-values prescribed for Austria. If the buildings complied with U-values for a warmer climate, the calculated outcome would probably differ notably.

Window glazing is one of the weakest thermal control points in building interiors. In a standard family residence, 10–20% of all heat loss occurs through the windows (Roos and Karlsson 1994). Most prescriptive standards give values for maximum permitted WWR, it goes from 10%, 20% till 40%. All buildings in sample comply with that conventional wisdom. On the contrary to that conventional wisdom, Pessenlehner and Mahdavi 2003 state that, given low U value glazing systems, increased glazing area can reduce heating load, whereby increased transmission losses through the enclosure are more than compensated by increased solar heat gains.

A study conducted by Albatici and Passerini (2011) showed that when U_w value (window glazing U-value) is 1.4 $W.m^{-2}.K^{-1}$, an intermediate value of glazed area can be found that minimizes heating requirements. Moreover, if U_w is lower than 1.2 $W.m^{-2}.K^{-1}$, heating requirements are lower the greater the window area is. This means that besides windows area, thermal properties of glasses and of window frame are important as well as the orientation in order to exploit solar energy. In analyzed sample, sizing of fenestration elements were kept constant; however, lowering the U-value of glazing and of window frame resulted in lower heating demand. For each case scenario, decreasing the U_w resulted indeed in lower heating demand and in higher energy efficiency scale. Aside from low WWR ration, U-values of glazing for all the building do not exceed the maximum permitted value of 1.4

$W.m^{-2}.K^{-1}$, and they range from 1.3 $W.m^{-2}.K^{-1}$ till 0.6 $W.m^{-2}.K^{-1}$ for the best performing buildings. To capture the influence of orientation of glazing on the heating demand, the WWR_e indicator has been introduced. Due to the scope of this work this design variable has been simplified and therefore its applicability and significance have failed to meet the expected outcome. This can be due to dependency on the climate conditions, due to too much simplification or it can also mean that this variable alone does not show forecasted outcome because it cannot be isolated from other significant influential design decisions.

5.2 Possible sources of error

The applied calculation methodology is based on a very detailed and accurate assessment of the single terms of the building energy balance; for this reason, considerable number of input data is required in the calculation. It is essential to quantify the influence of such data on the final results; at the same time, it is necessary to determine these data in an accurate way.

On the other hand, building performance simulation results have some errors. This can happen due to many reasons. Furthermore, measured energy consumption often differs from the simulated one. Based on that, errors from calculation methods in this study are not excluded. Errors could occur within the energy certificate calculation process as well as in the initial stage of creating buildings geometry. Numerous studies have been conducted in the field of exporting and importing different type of files within all the used simulation software.

For the purpose of this study, and due to the fact that this field of research is exceptionally broad, some simplifications had to be established. Namely, the influence of solar radiation and solar gains were neglected, as well as significant internal loads. The obstructions of surrounding have been overlooked as well, and the influence of shading devices.

For all the building in the sample only one orientation has been considered, which leaves a lot of space for further research, on investigation how would the same building with same properties behave under different orientations.

Although, most prescriptive based standards set requirements for cooling systems, mechanical ventilation, service water, lighting etc. those building components are disregarded for the simplification purposes. Principally that was done due to the fact that the main aim of this research was on inspecting descriptive variables of building's physical properties.

6 CONCLUSION

The aim of this thesis was to present and examine the option of alternative prescriptive approach towards energy efficiency in buildings. Buildings that comply with some prescribed values of descriptive design variables in early stages of design, where no thermal simulation has been executed, can comply with the high level of thermal quality. The set of single and multi-family houses designed according to the conventional wisdom of good design was thermally analyzed via the method of energy certification, which is currently valid for Vienna, Austria. The results show that buildings do have good thermal quality, and therefore all of these descriptive design variables were analyzed and their influence and correlation to the outcome of a good thermal quality was investigated. The results show that building's morphology and geometry have the most impact on building thermal quality, in first place characteristic length and its reciprocal value, building's shape factor or compactness. Buildings with highest values for characteristic length had the lowest values for heating demand.

Since all buildings satisfy requirements for the maximum permitted U-values according to OIB Guideline 6, and do comply with relatively low heating loads, it was concluded that U-values play an important role in the thermal quality of the building. Further analyzes on the impact of thermal quality of building envelope (U-values) showed that for same building, lowering the mean area weighted U-value had a huge impact on lowering the value of heating demand. These two variables mentioned above have been further investigated and the prescriptive index has been derived.

This index prescribes the values for the two variables; characteristic length and mean area weighted U-value, and gives the information about appropriate energy scale for each combination of values for these two inspected design variables. The energy scales in this index go from A++ category for best performing buildings, till C category of energy. Only buildings with high values for characteristic length can reach high levels on energy scale, with lower mean area weighted U-value. On the other hand, buildings which have lower values for characteristic length have to comply with really high requirements for thermal quality of the building envelope (low U-value) to reach high energy efficiency class. The values derived for this prescriptive index are based mostly on analyzed sample, as well as on conventional wisdom and previous studies and can be used as a guideline for design or for further research.

U-value and efficiency based codes, in particular for the prescriptive model, are generally the easiest to understand for developers. Standard constructions and installations can be given which fulfill the energy efficiency requirements, and buildings can be constructed without calculations or the use of computer models. The prescriptive method develops standard solutions which have been evaluated in pre-studies as cost efficient. Although, prescriptive methods can be a bit rigid and limit designer's freedom, the prescriptive index derived in this study serves more as an indicator, which combination of values for the two variables mentioned above, gives a certain level on energy scale and therefore it does not limit designer's choices to a large extent.

Basically, there are two different approaches for the prediction of energy performance of buildings: simplified and detailed simulation methods. Using the performance model requires computer-based models, a deeper understanding of some of the principles and higher costs of implementation. In the course of this work, one of the research questions was if the method has the ability to predict the thermal quality of the design, if the step of the detailed simulation, due to more cost and time efficiency, has been left out. Since buildings that meet prescriptive approach usually do not give any information regarding energy demand, as an additional step to prescriptive index, a simplified method to estimate the heating demand has been suggested and tested. Regression based equation has been generated, using the two mentioned variables, characteristic length and mean area weighed U-value, as predictor variables, to predict the single dependent variable, heating demand.

This simplified regression based approach gives results with a good level of accuracy for tested residential building and in comparison with dynamic simulation software, needs low calculus time and is easy to be used since the very first stage of the design process. Due to a relatively small sample size, some deviations from design variables could be expected and the outcome cannot be taken as totally valid, since it is not possible to provide equation suitable for each particular situation. Considering that values of the method change even if the physical properties of constructive elements change, results provided in this work should, therefore, be considered only as indications for future research.

The new building codes in developed countries are constantly introducing new regulation towards energy efficiency and therefore making calculation method more and more complex. These complexities are mainly due to ambitious and aggressive energy reduction goals in developed countries. On contrary to that, there are still a high number of countries without implemented building regulation, or at least not to that level as in developed countries. According to the Population Reference Bureau report from 2016, 84% of world's population lives in less developed countries. The performance-based approach may be the best approach toward energy efficiency but it is not possible to implement globally, and therefore there is a need for some simplified approaches that are more affordable.

Viewed in the historical perspective, prescriptive methods and related simplified evaluation tools were a necessity for design support and evaluation in the pre-computerization era. Given the current availability of powerful computer-aided simulation tools, predictive performance-based approaches could, in fact, render simplified tools obsolete (Mahdavi et al. 1996). However, as mentioned before, simplified tools can be more cost and time effective when applied in early stages of design for predictions of energy usage, as well as in developing countries where there are no regulations regarding energy efficiency or where these codes are not well implemented. Since the energy demand in developing countries is rapidly increasing, it is not possible to at once implement performance-based standards. Although prescriptive standards can be an alternative to energy efficiency, the simplified approaches could be a step in between transition from prescriptive to performance-based standards. Given these circumstances, it appears that, at least in the near future, computational simulation and simplified approaches probably will and should coexist.

This research is based only on small scale residential buildings of certain typology. More accurate results could be obtained if the sample was bigger and if some other building typologies were taken into account and analyzed. For the scope of this thesis, some simplification had to take place. No internal gains or loads from equipment were taken into account. The main aim of this work was to examine the design building variables, namely the physical properties of an envelope. For the further research these loads should be considered and analyzed in detail, and their influence on calculated heating demand should be compared. Another point of interest could be the influence of orientation of the buildings and orientation and sizes of fenestration. For analyzed sample, only one orientation was taken into account, which leaves a lot of space for experimenting in this field. On a bigger scale analysis shading devices and obstruction of surrounding could be examined more in detail.

The present study could be used as a suggestion for some simplified models and prescriptive based requirements in evaluating the quality of thermal design in early stages where no thermal simulation has taken place. This research field is really broad and methods like these could be applicable in developing countries where there are no performance-based standards, as well as no estimation of potential energy demand in buildings.

7 INDEX

7.1 List of Figures

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