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Faculty of Civil Engineering

Department of Construction Management and Economics

Implementation of BIM Systems for Energy Analysis and Optimization in Buildings

Master's Thesis

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III. Assignment receipt

The student acknowledges that the master’s thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the master’s thesis, the author must state the names of consultants and include a list of references.

Date of assignment receipt — Student’s signature

Declaration of authorship

I honestly declare that the presented Master's thesis was developed independently based on my own knowledge and using information sources listed in the chapter of bibliographical references. I also wish to confirm the following:

- This work was done fully while in candidature for an academic degree at the corresponding university.
- The thesis and its chapters clarifies in a clear way what was elaborated by myself, and what by others with names mentioned.
- I have acknowledged all main sources of help.

Prague, 6th January 2019

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Matej Koyš

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Abstract

This master's thesis was developed on a theoretical basis to raise awareness about BIM in the building industry and to give an idea of the innovations that could potentially enhance energy management and architectural design in the Czech Republic. It starts with a research within both areas and describes a relatively new user-friendly approach to implement energy consumption reducing measures already in the early design stage. In the middle stage, I will introduce studies and research on certified reliable tools currently used by companies the most.

The main problem focuses on a simple simulation that acquaints the reader with the built-in analysis tool in Revit and checks the accuracy of the used software to verify its reliability for future design and development purposes. For the simulation, a referential building will be used – in this scenario a family house (a former university project with elaborated architectural study, partial project documentation including an EPC).

The outcome of the given experiment is a comparison of the results and used calculation methods, defining their differences and setting recommendation for improvement from the user perspective.

Key words: Energy analysis; BIM; Autodesk Revit; Built-in energy tool; Analysis from the user-perspective.

Abstrakt

Tato diplomová práce byla vytvořena na teoretické bázi pro zvýšení povědomí o BIM ve stavebnictví a poskytnutí představy o inovacích, které by mohly potenciálně posílit energetický management a architektonický design v České republice. Začíná výzkumem v obou oblastech a popisuje relativně nový, uživatelsky přívětivý přístup k implementaci opatření ke snížení spotřeby energie již v počáteční fázi návrhu. Ve středním stádiu představím studie a výzkum certifikovaných spolehlivých nástrojů, které v současné době společnosti nejčastěji používají.

Hlavní problém se zaměřuje na jednoduchou simulaci, která čtenáře obeznámí s integrovaným analytickým nástrojem v aplikaci Revit a vyhodnotí přesnost použitého softwaru pro ověření jeho spolehlivosti pro budoucí účely návrhu a vývoje. Pro simulaci byla použita referenční budova - v tomto případě rodinný dům (bývalý univerzitní projekt s vypracovanou architektonickou studií, částečná projektová dokumentace včetně PENB).

Výsledkem daného experimentu je srovnání výsledků a použitých výpočtových metod, definování jejich rozdílů a stanovení doporučení pro zlepšení z pohledu uživatele.

Klíčová slova: Energetická analýza; BIM; Autodesk Revit; Vestavěný energetický nástroj; Analýza z perspektivy uživatele.

List of abbreviations

AEC	Architecture, Engineering and Construction
BIM	Building Information Modelling
BPA	Building Performance Analysis
CM	Carbon Management
CTS	Conduction Time Series method
EA	Energy Audit
EAP	Energy Agreements Programme
EM	Energy Management
EMS	Energy Management System
EPA	Energy Performance Analysis
EPC	Energy Performance Certificate (in Czech: *PENB*)
EUI	Energy Use Intensity [kBTU/sf or MJ/m^2]
gbXML	Green Building Extensible Markup Language
HBM	Heat Balance Method
HVAC	Heating Ventilation and Air-Conditioning
IDP	Integrated Design Process
IFC	Industry Foundation Class
LOD	Level of Development
PES	Potential Energy Savings
PRF	Periodic Response Factor
REM	Rapid Energy Modelling
RTS	Radiant Time Series method
SME	Small and Medium Enterprises
SW	Software
XML	Extensible Markup Language

Table of contents

1. Introduction

The following chapter describes the context and trigger of the determined subject and it's background. It also sets objectives and goals of the experimental phase and specifies elaboration methods.

1.1 Project context

The main purpose of this work is to contribute to the development of BIM systems and their implementation within the Czech Republic and other countries where this important concept was lacking attention in several environments so far and in energy management as well.

The above-mentioned aim is just one side of the context though. Crucial to mention is the fact that cost savings in the energy efficiency of a building can be achieved already during the design stage of a project and they even may be of significant range. Various simulations and technical features working with real physical parameters implemented in the design software of today may enhance the possibilities and insight of an architect or project engineer to implement energy reducing measures already in the early stages. These measures are representing the message of energy management working on a principle of constant improvement.

1.2 Thesis background

A very common trend of nowadays' history is to simplify things. The design of buildings is no exception. Let's use it as an example to explain it – the design of a house comprises not only architectural composition, materials, technical equipment, the combination and collaboration of all kind of elements, dimensioning, construction costs, scheduling, planning and legislation. Nowadays the world also has to think about it's carbon footprint, emissions, used energy sources, raising energy prices and life cycle costs of the end user. The certification of buildings in terms of energy and rising requirements also contributes to the development of architects so they become more acquainted in this area, what comprehends also learning and implementing measures to achieve savings.

The aim of the industry is definitely to simplify the work of architects and all affected parties by decreasing the amount of various software and by merging some of the above-mentioned functionalities into one user-friendly environment that will be accessible for all involved participants including technicians, structural engineers, facility managers or possibly also the end users in a certain range.

A comprehensive design process in architectural practice is being enhanced by energy and thermal simulations, improved visual representations and supported by collaboration via digital media between the different parties involved in a project. (Aksamija, 2012). Of course, this would not be possible without the right tool, which is Building Information Modeling (BIM). It enables immediate results and scenarios, where it is possible to see insufficiencies and future problems that can be avoided much earlier. This way it's also possible to comply with the raising demand on various and difficult structures by minimizing the high probability of mistakes. In the role of engineers, it becomes also important for those to learn and implement it into their daily life, so they can focus on other important client needs.

1.3 Objectives and scope

The thesis is comprised of two main parts. One of these parts tackles the research in key areas for the experiment such as energy management and it's regulation, legislation, implementation and technology used for the development, design and realization of buildings. The research part also includes a brief review of the history of BIM, it's scope, functionalities, common usage, software types and supporting systems, as well as the implementation of BIM in the Czech Republic.

In the second half, the work focuses on the experimental stage where it challenges the accuracy of particular energy management functionalities of one of the biggest representatives or for some people the flag ship of BIM at all – Autodesk Revit. It will test the internal energy analysis tool and further the compatibility with external software for energy analyses via compatible export formats while focusing on their interoperability.

The key objective is to test and elaborate a comparison of the results of the chosen methods and diverse software that is specialized in the same analyzed areas. This way it will be possible to provide feedback or ideas for further development of a new project approach in the area of civil engineering and energy efficiency design in the Czech Republic.

1.4 Elaboration methods

The initial stage is the preparation of a referential building for analysis. This involves setting the appropriate and correct parameters of materials, the corresponding location, HVAC system, orientation, bonding of elements etc. In this scenario, it is necessary to count with additional adjustments due to the conversion from a different software.

If everything is set, the experiment can start by running an analysis in two selected versions of Revit (2016 and 2018) where the approaches exhibit noticeable differences. I will compare these approaches and their results with the outputs of other SW outputs in various areas such as heating and cooling demand, wind loses or solar gains etc.

2. Literature review on Energy Management

Before making any form of execution, it is necessary to undergo a study of basic principles, theory, methods and tools for achieving energy efficiency. For this reason, the thesis focuses in this chapter on the most common tools – energy audits and energy performance certificates. The subchapters are supplemented by the impact of BIM on these tools.

2.1 About Energy Management in general

Energy management (EM) became nowadays almost an essential when it comes to efficient operation of companies but also regular households. Even though for long-term success in achieving reasonable energy savings it might be already a necessity, it's often being neglected despite a large potential of cost reducing.

A huge motivation could be increasing pressure from rising energy prices, new restrictions coming from the government caused by climate changes, but also an image improvement by customers or stakeholders in case of companies. It seems that the investors are becoming more aware of this and usually the largest and most modern projects fulfil really good energy standards. Of course the implementation of energy management needs to be designed to the nature of each organization, household, resp. their buildings and the owners. The effort spent on EM should be in proportion to the needs and gained benefits. To achieve the most from EM the main objectives should be *integrated and proactive energy procurement, energy efficiency* and the *usage of renewable energy*.

Energy management systems (EMS) are a great way of achieving certain standards and are used by many companies. It's possible to certify an EMS to an internationally recognized standard, they can choose from various examples. The main one is BS EN 16001:2009 Energy Management Systems, which's structure is similar to the ISO 14001 Environmental Management Standard. It's main idea lies in providing a framework and enabling systematic approach for continuous improvement. In 2011 the default standards were replaced by ISO 50001 Energy Management Systems. In other cases to ensure an efficient energy usage companies can transfer this responsibility by hiring an *energy manager*. [3]

A different chapter is the technology itself. While each building is unique, thermophysical formulas and computational principles normally don't change. Instead they are simultaneously simplified via user-friendly software what might enlighten laic private developers pursuing their projects.

Since the beginning of human life on Earth human needs are continuously developing and this led to continuous progress. The durability of all materials in order to resist climate changes increases with every year as well as all implementing procedures related to EM, from the initial and executional phase until the last check-up. It's an infinite process, a cycle of continuous planning, followed by the steps taken to achieve the promising outcome through work, which needs to be checked. Afterwards an evaluation of the attained results determines further decision taking and handling. This whole process is well known as the PDCA diagram described below.

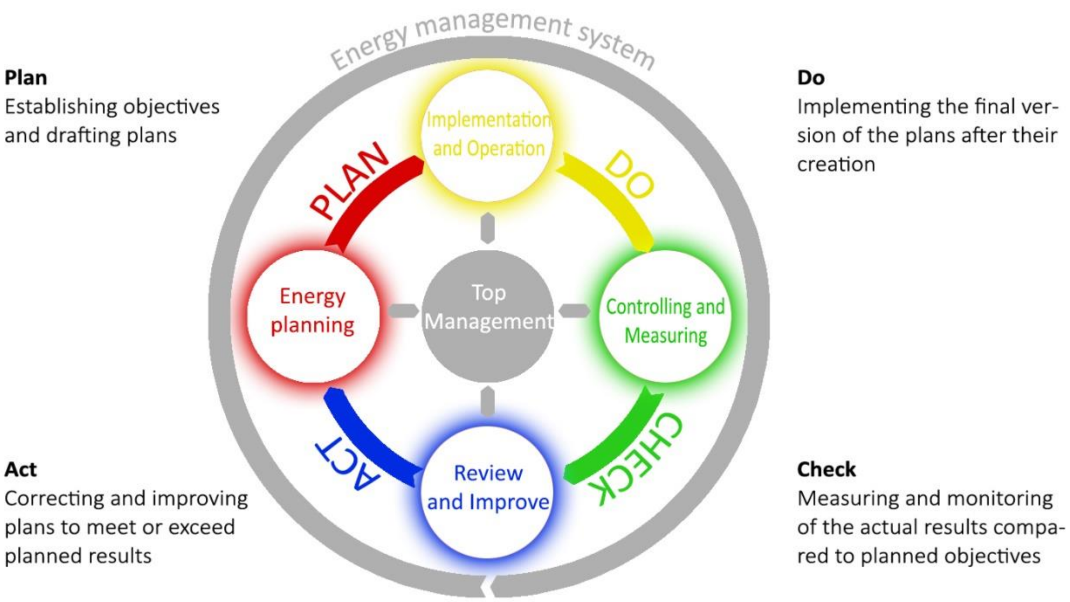

Figure 1: The PDCA diagram [3]

This unique tool became an operating principle of ISO management standards. Applying it may result in enhanced energy management for corporate efficiency. Apart from EM it's being also used e.g. in projects, processes or products in diverse areas by their managements for their continual improvement. It's also known as the "Deming cycle" or "Shewhart cycle", named by the main two developers of this concept.

Considering the EM in context, you can imagine that this whole field is in relation and also a principal element of a bigger notion known as Carbon Management (CM) – the management of a buildings greenhouse gas emissions (GHG), which falls into an even bigger category called Environmental Management. There are several sources of GHG such as leakage of refrigerant processes, methane from landfill chemical emissions etc. The biggest contributor however remains carbon dioxide from energy use and that's the reason why EM is an essential part of the two bigger scopes. [12]

To establish a functioning and efficient EMS it's necessary to build an *energy policy and a strategy*. It is possible to view an energy policy as a written statement confirming, that the company commits to manage energy and carbon emissions. Usually you can find there:

- *An endorsement from senior management – preferably the CEO or equivalent;*
- *The company energy/carbon vision and aspirations, with specific objectives;*

- *A commitment to ensuring the integration of energy management in all relevant decision making;*
- *A commitment to ensure that sufficient resources are in place to meet policy objectives;*
- *A commitment to meeting the training and development needs of energy management staff and to raise the energy awareness of all staff;*
- *A commitment to develop and maintain an up-to-date energy strategy and/or action plan to meet the objectives of the energy policy;*
- *A commitment to a regular and formal review.* [12]

Key areas of an energy strategy (applicable for the majority of companies):

1. *Organizing energy management;*
2. *Regulatory compliance and incentives;*
3. *Investment;*
4. *Procurement;*
5. *Metering, monitoring and targeting;*
6. *Opportunities identification;*
7. *Organizational culture;*
8. *Communications.* [12]

2.2 Energy audits

2.2.1 Definition

The Energy Audit (EA) may be interpreted as a periodical long-term process of examination and an analysis of the whole energy system of a building, which serves as a tool for ensuring efficient usage of energy.

It comprises a constant study based on surveys to identify usage in buildings or energy plants, where the main goal is to find new saving opportunities. Basic requirement are proper audit methods and equipment used by an energy manager providing him necessary information of the energy flow indicators.

Key part of an energy audit is the proposal of energy saving procedures, which include a technical and economic analysis of the project looking also for ways to conserve energy.

Energy balances in energy audits

There is a difference between the balances in EA and the real thermodynamic values where some of them can be obtained by measurement only, what might be a disadvantage or error. This leads to the creation of even more errors by further calculations. [1]

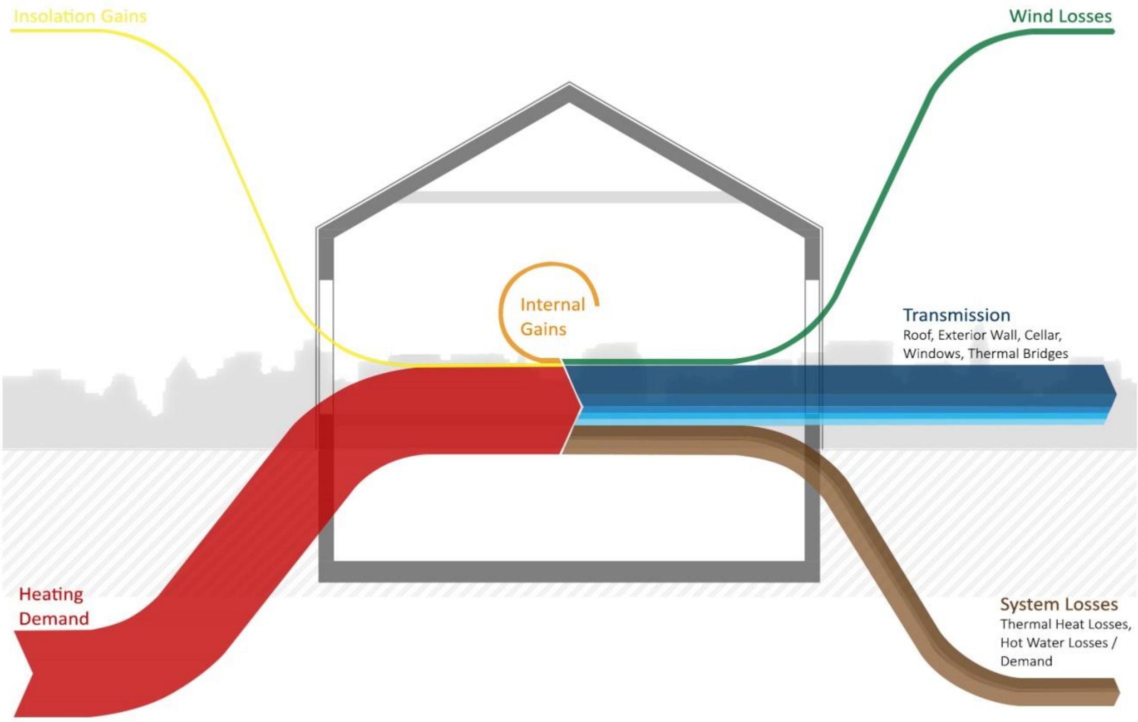

Figure 2: Sankey diagram of a family house proving the 1st law of thermodynamics [7]

Significant cost savings can be very often achieved by simple low cost arrangements:

- *An energy fare change;*
- *The rescheduling of production activities to use the benefit of preferential energy prices defined by time;*
- *The adjustment of existing controls of a plant to match the actual requirements;*
- *The implementation of efficient maintenance policies where the responsible employees are encouraged not to use energy wasteful way of work;*
- *Purchase of small capital items e.g. thermostats and time switches.* [1]

Following equipment might be used for data analysis based on the physical entities:

- *Electricity – Electrical analyser;*
- *Mass flow – Anemometer (turbine, Pitot);*
- *Temperature – Thermometer;*
- *Humidity – Humidity meter;*
- *Flue gases composition – O2, CO2, CO analyzer;*
- *Luminance – Lux meter;*
- *Total dissolved solids – TDS meter.* [1]

2.2.2 Implementation of Energy Audits

According to the Czech decree n. 480/2012 Coll. section 9 art. 1 physical and corporate entities are obliged to compile an energy audit for their buildings or energetic services, in case the total value of the energy consumption is equal or higher than 35000 GJ (9722 MWh) per year as a sum of all objects belonging to the owner. Concerned are only buildings with the consumption of 700 GJ (194MWh) per year. For organizational branches of the country the total value of all belonging objects is laid down by 1500 GJ (417 MWh) per year. [6]

Methods of executing the EA and its individual parts[1]

A. <u>The title sheet</u> – contains the subjects of the EA, as well as the date of execution, the name/s and last name/s of the energy specialist, authorization number and EA registration number from the record of activities.

B. <u>The identification data</u> – include mainly information about the owner of the EA subject e.g. name/s, identification n., company/personal permanent address etc. Also a part of the data concerns the EA subject, e.g. name, address and placement.

C. <u>The description of the current state</u> of the subject of the energy audit contains:
   - the characteristics of the main activities of the energy audit subject, but also a description of the technical installations, systems and buildings which are subject of the EA and a site plan;
   - energy inputs over the previous 3 years, including average values, which are obtained from accounting documents;
   - own energy sources whose (basic technical characteristics are listed in Annex 3 Decree 480/2012); part of this data is annual balance of energy production from own energy sources;
   - energy distribution; the requested data is determined for the main pipelines with the following information: the type, the length, the capacity, the diameter, the design, the age and the technical condition, the thickness and condition of the heat insulation.

   For all power distribution systems the energy distribution schemes need to be presented, the evaluation is based on their status and equipment measurement;
   - significant energy consuming appliances with mentioning the type, energy input, annual operating hours and the mode of regulation;
   - the thermal and technical characteristics of buildings;
   - information about the energy management system according to ISO 50001.

D. <u>The evaluation of the current state</u> of the subject of the energy audit includes:

[1] Particular structure taken from Czech decree n. 480/2012, EA structures may vary between countries.

- assessing the energy use efficiency in energy sources, heat and cold distribution and in major energy consumers;
- evaluation of thermal and technical properties of building structures;
- evaluation of the level of energy management system;
- the total energy balance.

E. Proposals of measures to increase the efficiency of energy use contain the name and description of the measures, annual energy savings in MWh/year and a comparison of the savings to the previous state before implementation. Important to mention are also the costs of the planned realization and the average new monthly costs in comparison with the monthly costs before applying the new measures.

F. Variants from the proposal of individual measures – at least 2 variants from each proposed measure need to be planned. Each variant consists of the description (see previous point E.), an economic evaluation of the proposed variants and the adjusted annual energetic balance of the proposed variants.

G. Selection of the optimal variant will be executed according to the results of the economic evaluation in regard to the amount of energy savings in MWh/year and the ecological evaluation (or the dotation program criteria).

H. The recommendation of the energy specialist authorized to process the energy audit comprises the optimal variant description, annual energy savings after realization, realization costs, the average planned monthly operational costs, the adjusted economical energetic balance for the optimal variant, it's economic and ecological statement and the proposal of an appropriate energy management concept. [6]

The energy audit can be categorized into two types:

1. Namely walk-through or preliminary audit
   - Needed visit to a plant;
   - The outcome is a report based on observation during the visit and historical data.
2. Detail audit
   - Processed for the energy savings proposal recommended in the walk-through or preliminary audit. It provides detailed data on the inputs and energy flows + technical solution options with economic analysis. A feasibility study is required. [1]

2.2.3 Goals of the energy audit

The main difference between the above-mentioned two types of audits is that whereas the walk-through audit focuses on establishing the quantity and cost of each form of energy in a facility, the detail audit realizes the energy savings proposals for the preliminary or walk-through option. The second option also provides detailed data on energy inputs to and flows within a facility while analyzing the economic impact of the proposed solutions so the factory management can decide about implementation and priorities. [1]

Main goals of the EA:

- Clear identification of types and costs of energy use;
- Understanding how, where and when energy is being used or wasted;
- Finding and inspecting more cost-effective ways of energy use;
- Economy analysis of those new alternatives + determination and application of the most efficient one to the particular company or industry.

2.2.4 Requirements

Pre-site inspection data requirements:

- Billing data of the energy and water consumption from the past 12 months (or more years preferably);
- Production data from the past 12 months at least;
- Basic building description and configuration information containing at least the conditioned floor area (blueprints, bill of materials etc.);
- Characteristics of the main equipment;
- Information about building schedule and occupancy, functional organization;
- Specification of building purposes by area, e.g. computer facilities, library, cafeteria, offices etc.;
- Any other available energy assessment data incl. demand profiles, inventories etc.;
- Degree-day data applicable to the site location (it's recommended to obtain data from a local weather station - valuable information for cost saving calculations). [1]

2.2.5 Comparison of Energy Audits and Energy Performance Certificates

Another good tool for analyzing and creating cost and energy efficient measures is the Energy Performance Certificate regulated by the Directive 2002/91/EC. The main goal of EPC is the creation of recommendations, which demonstrate the improvement potential from the energy efficiency point of view. One of the purposes of these recommendations are renovation activities for increasing energy efficiency, especially on existing buildings.
The EPC provides main information about the quality of a building based on energy demand and performance.

The recommendations in the EPC may be either "standard" or "tailor-made", providing measures as the new U-values of elements, the kind of heating/AC system including their capacity and specific requirements (e.g. space needed for pellets by new heating systems).

The EPC could be also used for a rough estimate on the renovation measure costs where an energy audit would be necessary. However, beside very simple cases they do not replace a more detailed energy audit as a basis for their implementation.

2.2.6 Comparison of the energy audit within European countries

At the beginning it's important to mention the main targets of all European countries, which are generally known as the 20-20-20 targets. In other words it means *achieving 20% of energy supply from renewable sources, a reduction of greenhouse gas emissions of at least 20% as compared to 1990 levels, and an increase of energy efficiency by 20% as compared to a baseline projection*. [11]

For the sake of supporting these targets the EU introduced the Energy Efficiency Directive (EED) in December 2012, which had to be transposed into Member State legislation in 2014. The directive also imparts importance to the EA and energy management schemes in the improvement in sector of the end-user (as mentioned in Article 8 of the EED). It concludes that the *Member States shall establish transparent and non discriminatory minimum criteria for energy audits*. These Member States shall also develop programs to encourage small and medium enterprises (SMEs) to undergo energy audits, as well as bring to the attention of the SMEs concrete examples of how energy management systems could improve their businesses. They also shall raise awareness about the benefits of these audits among households via appropriate program development and advice services; another obligation of these states is to ensure that enterprises that are not SMEs are dependent on upon an energy audit carried out by accredited experts in a cost effective and independent manner. *Energy audits may stand alone or be part of a broader environmental audit.* [11]

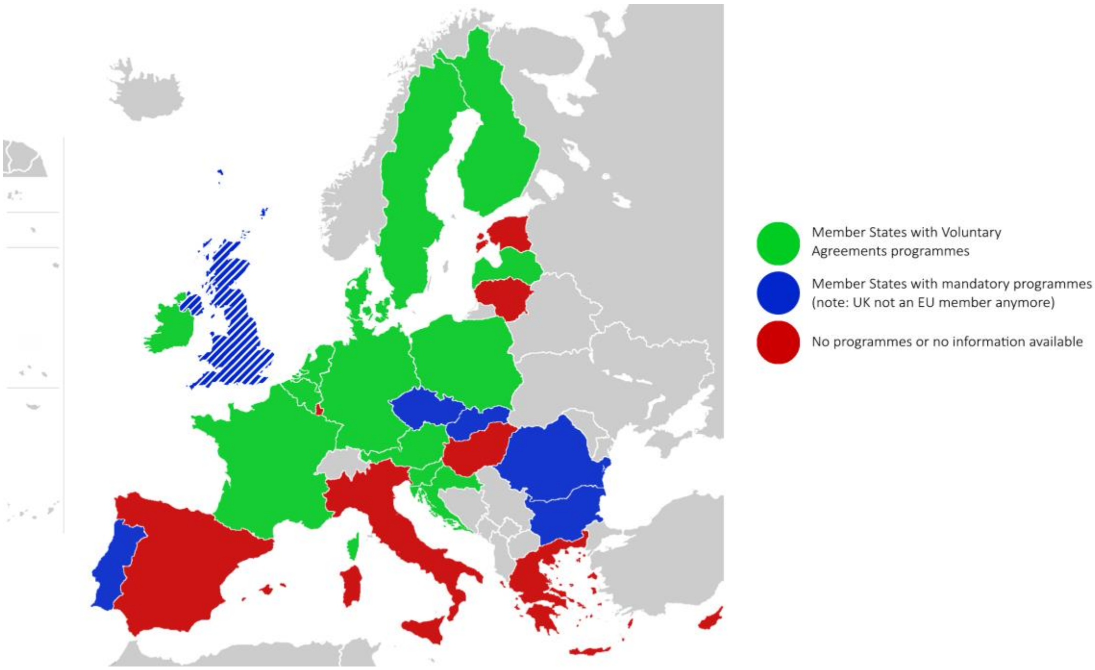

Figure 3: Types of current EA programmes in the EU 28 [14]

Since there are 28 Member States in the European Union, I will simplify the study and chose 4 particular countries for comparison, where three countries represented best practices with Voluntary Agreements programmes and one country (here Czech Republic) with best practices from the members with mandatory programmes of the EA.

Energy audit in Ireland

The main responsible organization in Ireland is the Sustainable Agency of Ireland (SEAI) which promotes several support programmes for it's industry with substantial success. In close cooperation with the Large Industry Energy Network (LIEN), a voluntary grouping of companies, which are working together on the development and maintenance of solid energy management within the country. The commitment by being part of LIEN: *to develop an energy management programme, to set energy targets, undertake an annual energy audit and produce an annual statement of energy*. Companies can become members of LIEN if their annual energy costs are more than 1 mil. € or if they are members of the Energy Agreements Programme (EAP), which is a subset of LIEN.

The EAP was launched in May 2016 and is a voluntary programme for companies with high energy consumption, which commit to implement an EMS according the standard ISO 50001 within 12 months after the confirmed and signed agreement with SEAI which creates the methods to achieving higher energy savings in their activities. As a part and advantage of the cooperation, SEAI provides financial support, advise and assistance in networking. SEAI also executes a gap analysis to inspect insufficiencies and proposes solutions to achieve certification of the companies under supervision of the National Accreditation Body.

For each EAP member, SEAI allocates an Agreement Support Manager (ASM) that is helping them to meet their commitments with the EAP and provides other forms of support as well. The ASM may provide technical support in areas they are familiarized, depending on the sector.

In Ireland is also an SME Support Centre with advice services, mentoring and training in energy management (adjusted for this type of businesses). The SMEs can benefit from specific user-friendly tools in form of templates for cost saving calculations, but also an application called Energy Map that helps by the creation of an action plan step by step. Companies can avoid the cost of certification by creating their Energy Management Action Plan and following and tracing it's 20 steps. [14]

Energy audit in Germany

At a federal level, there are two programme types promoting the energy audit in Germany. The first one is the German Promotional Bank, which started promoting the EA for SMEs in 2008. It was aimed for companies which have less than 250 employees and was based on the attribution of grants covering the costs up to 80% for the initial audit (taking 2 days) and 60% for the detailed audit (taking 10 days). *This program has been successfully working since the beginning with about 5000 audits per year, with roughly two to three energy efficiency measures being adopted per audit.* It is also possible to benefit from the KfW soft loan program for the financing of energy efficiency investments.

The second program at a federal level is the "BAFA Vor-Ort Beratung" (meaning "Consulting on-place" in translation) existent since 1998. The program consists of an EA dedicated to house owners, where a subsidy is being given depending on the size of the house. The program is focusing on residential buildings and an on-site inspection has to be done. The requirements on reports are minimal. *After the audit the information is collected centrally at the Bundesamt für Wirtschaft und Ausfuhrkontrolle (BAFA).*

The requirement on auditors are similar by both programmes. The basic requirements are *a degree in engineering or be authorized to issue energy performance certificates plus further professional training and years of experience in the energy field.* They also have to watch out on independence and being neutral e.g. towards energy utilities in case they may not be hired or take provisions from them. [14]

Energy audit in Belgium

In Belgium each region develops their own incentives and policies in terms of energy management and efficiency, there is no responsible energy agency on a federal level. E.g. in the industry the energy policy is focusing on *voluntary agreements between industry and the regional governments of Flanders and Wallonia.* The agreements in Flanders are set by a "benchmark" and signed by companies with an annual consumption of 0.5PJ. In Wallonia there are voluntary Branch Agreements signed by 13 sector associations with proven efficiency improvement over years.

A big milestone was the establishment of the Benchmarking Covenant, which led to the participation of major industries from all industrial sectors and transformed the regional sector in one of the most efficient in the world. By signing the covenant industries commit to the "best international standard". An advantage is, that the industries have less measures to take with CO2 reduction or energy efficiency.

For medium-sized companies with an annual consumption between 0.1-0.5PJ there is the Auditing Covenant, which is another voluntary agreement. The commitment is the performance of an energy audit and implement respective measures.

The Walloon region prospers from the success of the Branch Agreements. Made on a voluntary basis between the government and different industrial sectors. *In what concerns the financing of energy audits the Walloon Region Energy has developed the AMURE* *programme that gives companies a subsidy to carry out an energy audit in their facilities.* It serves as an empowerment for the companies to evaluate the viability of investments and create a plan to improve energy efficiency. After signing the contract, the audit report has to be submitted within 1 year. *The amount of the subsidy is 50% of the audit cost excluding VAT.* [14]

Energy audit in the Czech Republic

Since 2001 the Czech Republic benefits from the introduction of the EAs in both sectors, private and public. The EA is considered as a key instrument for energy efficiency measures. The exact procedures and implementation are already described in chapter 2.2 of this document.

In case of a higher energy consumption than specified by the legislation, the obligation for the EA development had to be fulfilled within 3 years since the respective law came into effect (here by the end of 2004). *For public sector institutions, there were provided grants for energy auditing under condition that recommended measures would be really implemented.*

A general format provides limited definition of the quality control of energy audits and auditors take responsibility for it's correctness. Also, *since 2013 each auditor must upload basic information on any Energy Audit completed into a national register kept by the Ministry.* [14]

2.2.7 Energy auditing by ASHRAE – BIM based auditing

ASHRAE (also known as American Society of Heating, Refrigerating and Air-Conditioning Engineers) is one of the main providers of energy auditing services in the world. Its establishment is characterized as the merging *in 1959 of the American Society of Heating and Air-Conditioning Engineers (ASHAE) founded in 1894 and The American Society of Refrigerating Engineers (ASRE) founded in 1904.* [21]

In general, approximately 86% of building construction expenditures result from existing building. This means that it would be necessary to address audits in existing buildings to achieve an overall net zero standard. The difficulty lies in the lack of industry standardization of audit methods and the need of common vocabulary. ASHRAE released two publications on energy auditing, the first edition came out 2004 under the name *Procedures for Commercial Building Energy.* In 2011 it was adjusted to *Procedures for Commercial Building Energy Audits*, upgraded by a lot more "how to" advice sections, lifecycle cost approaches, excel templates, checklists, summary of measurement approaches, but also the importance of team building and human factors etc. [19]

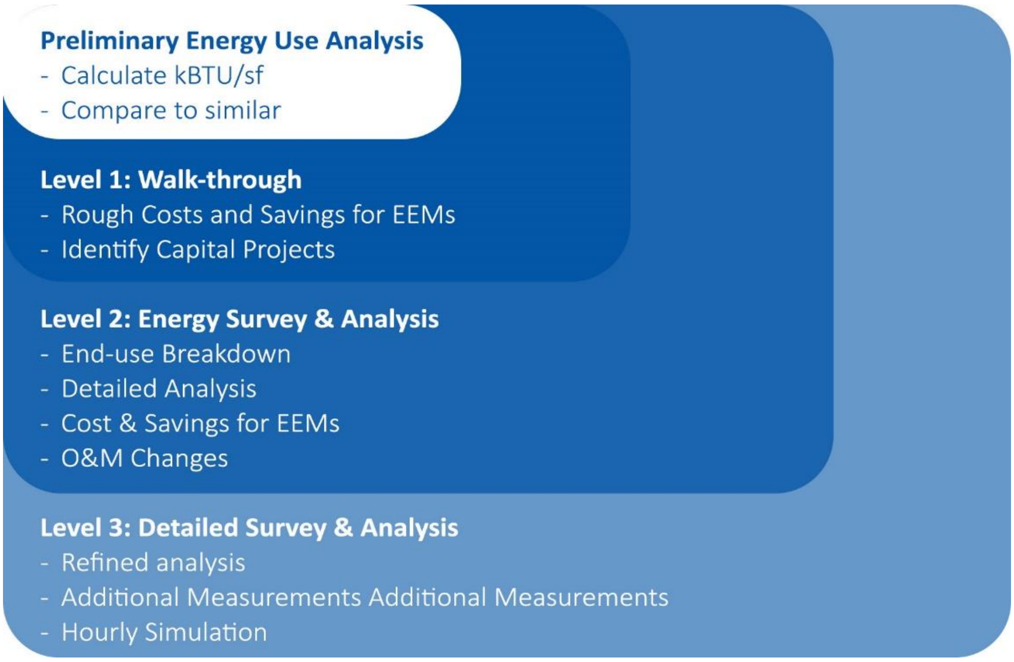

Figure 4: Auditing levels used by ASHRAE [19]

Building size	Audit Level Required
5,000-49,999 sf	ASHRAE Level 1 - Walk-through Analysis
50,000+ sf	ASHRAE Level 2 - Energy Survey / Engineering Analysis

Table 1: Example of audit level requirements based on building size [19]

Level summary: *(overview of the EA main parts by ASHRAE and their presence in levels)* [19]

Process	Level: 1	2	3
Conduct Preliminary Energy Analysis (PEA)	●	●	●
Conduct walk-through survey	●	●	●
Identify low-cost/no cost recommendations	●	●	●
Identify capital improvements	●	●	●
Review M&E design, condition and O&M practices		●	●
Measure key parameters		●	●
Analyze capital measures (savings & costs including interaction)		●	●
Meet with owner/operators to review recommendations		●	●
Conduct additional testing/monitoring			●
Perform detailed system modeling			●
Provided schematic layouts for recommendations			●

Report	Level: 1	2	3
Estimate savings from utility rate change	●	●	●
Compare EUI to that of similar sites	●	●	●
Summarize utility data	●	●	●

Estimate savings if EUI met target	●	●	●
Estimate low/cost / no-cost savings		●	●
Perform detailed end-use breakdown		●	●
Estimate capital project costs and savings		●	●
Complete building description and equipment inventory		●	●
General description of considered measures		●	●
Recommended M&V method		●	●
Financial analysis of recommended EEMs		●	●
Detailed description of recommended measures			●
Detailed EEM cost estimates			●

2.2.8 Rapid Energy Modelling vs. Energy Audits – An experiment

One of the biggest challenges in the discovery and implementation of energy efficiency measures in the evolution stages of a building is to *get to an energy analysis result cheap and fast enough*. In this section, you will find an experimental study from 2014 made by ACEEE comparing two main approaches in terms of energy analysis. One approach with minimal data input requirements + intelligent assumptions and defaults, followed by generating an instant energy analysis to identify key results and the important areas for improvement, compared to the standard approach for energy auditing tested on 23 referential buildings.

As a smart person once said, *"all models are wrong, but some are useful"* (George E.P. Box). Of course, modelling tools are being improved on a constant and long-term basis by enhancing the input options for a more precise outcome but still these results are inaccurate. Skilled users are able deal with these variations and to produce quality models but the challenge remains in *scalability, consistency and repeatability*.

Rapid Energy Modelling (REM) is a way of generating energy models almost instantly, based on *automated assumptions and range analysis* focusing on what matters the most in a building. It serves mainly to make designers aware of important questions to answer first, before focusing on other dependent areas. These questions help to identify a building's problems and to resolve them in the right order.

Unfortunately, due to the lack of quality of the energy data and poor access to information, facility and efficiency managers have difficulties managing their building energy footprints and prioritizing energy retrofit budgets effectively. ASHRAE's method consists in creating level audits using more comprehensive energy-auditing techniques is generally known to be too costly and time-intensive. Other typical approaches for energy assessment are considered to be expensive and time consuming as well. *Typical approaches for rapidly assessing and benchmarking energy use and evaluating proposed energy retrofit measures often fail to acknowledge the complexity of buildings or identify* *key building performance factors that influence energy use and the effectiveness of retrofit decisions.* REM is not only proposed as an alternative to energy audits, but also to less expensive benchmarking approaches as e.g. Energy Star or CBECS, which do not propose saving opportunities nor offer building-specific detail. [2]

These challenges were addressed to the company Autodesk, which created a first version of Rapid Energy Modelling – a fusion of Building Information Modelling and conceptual energy analysis. The goal of this experiment was to investigate the theory that REM is a method that is viable and scalable enough *to rapidly generate consistent, repeatable, useful and cost-effective estimates of energy consumption*. REM was used for the demonstration project over a one-year period for 23 buildings of the Department of Defense (DoD) of the United States in 5 climate zones with a mix of heating and cooling.

The inputs for the energy model were derived using satellite and aerial imagery and responses to the energy questionnaire, and focused on rapid baseline characterization of the building geometry, operations and systems. The REM model also doesn't consider e.g. different space utilizations (e.g. office and lab are considered as one building type) and it also doesn't utilize floorplans or precisely modelled interior walls, instead it rather opts for a space zoning simplification and a maximum width of the perimeter to minimize errors due to the missing partitions (like ASHRAE). Accurate modelling of interior spaces is considered as cost-ineffective and time consuming. Despite these facts, *the REM results provide a rational baseline of information from which to make asset management decisions.* Also, a subset of 5 of the selected buildings was further processed with design alternative possibilities of REM SW to estimate the potential energy savings using *Energy Conservation Measures (ECM)*.

The results

The REM workflow processed reasonably accurate results for estimating overall *Energy Use Intensity (EUI)* for the tested DoD buildings. Overall, the *Mean Absolute Percentage Error (MAPE)* for the modeled electric results (incl. all 23 buildings) was 18.12% compared to the real measured data. Natural gas results for these buildings resulted in the MAPE of 41.80%, but the REM results get close to the CBECS natural gas values, so *results may point to underlying material or operational characteristics of the buildings that differ significantly from normal buildings, which usually points to an opportunity to improve the building rather than the model.*

The various building types comprised 13 offices (across 7 army, navy and air force locations), 5 barracks and 5 special use buildings (e.g. fire station, gym, cafeteria, school, auto facility). The 13 offices (in size of 4800-281732 sf) were also part of a core analysis, resulting in a reasonably accurate MAPE of 14.20%.

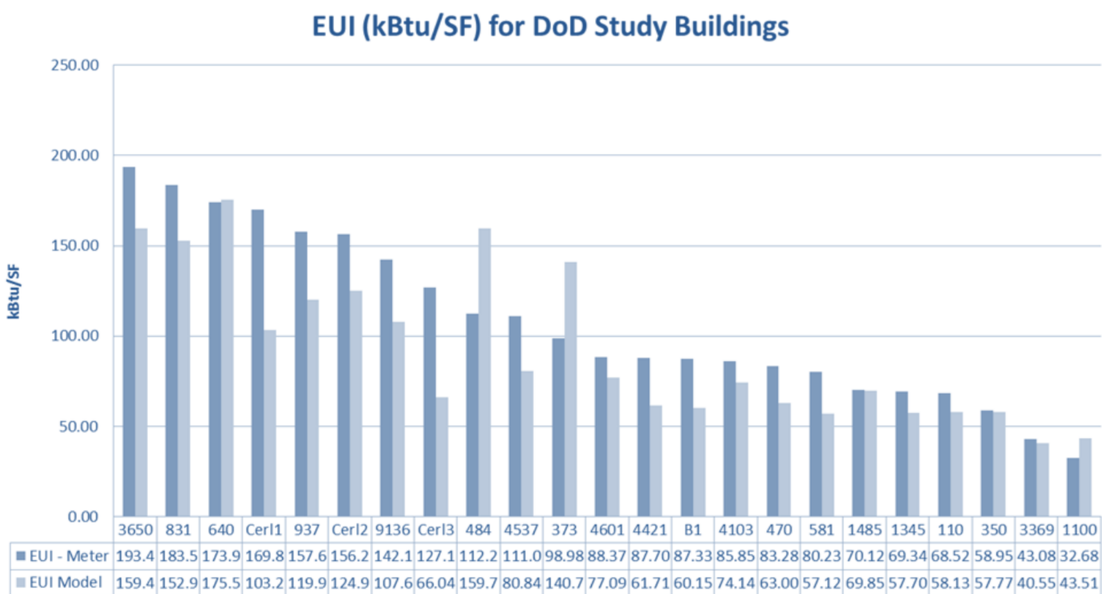

Figure 5: Summary of the results for all 23 analyzed buildings [2]

Statistics	Electric	Natural gas	EUI
Mean Absolute Percentage Error	18.12%	41.80%	22.44%

Table 2: Summary of the experiment data of the analyzed buildings [2]

These benefits of REM mean this process can be more cost effective than conducting typical Level 2 audits. With more individuals doing energy assessments, the number of buildings studied can also increase. Although the technology is new, the energy performance analysis process utilizes familiar SW to facility managers (e.g. Google Earth, CAD/BIM etc.).

REM is a method that has *the potential to help scale energy assessments across the building portfolio, determine which buildings in the portfolio present the best opportunity for retrofits, quickly evaluate relative benefits of energy conservation measures through auto-simulation of potential energy savings, and contribute to energy and cost savings for the DoD.* It also allows *facility managers and energy managers to quickly create building models based on limited information, rapidly assess which buildings are using the most energy, and generate reports.*

Important to mention also is that thanks to the *potential energy savings (PES)* chart and automatic range analysis the personnel and all affected users can easily and quickly track the sensitivity of the building to changes in parameters, and the relative energy cost value of modifications to HVAC, roof, walls, windows, lighting, equipment, etc. *REM results can also help energy managers to make informed decisions about which buildings can benefit most from energy retrofits, and may be the most practical to meter and audit in more detail.* [2]

2.3 Energy Performance Certificates

2.3.1 Terms and definition

The Energy performance certificate (EPC) serves to evaluate the energy performance of a building - quantifies all energy consumed in the standardized operation of the rated building and (similar to the appliance's energy label) classifies the building into the appropriate class in the A-G range. The card assesses all the energy needed to operate the building, i.e. heating energy, hot water preparation, cooling, air conditioning and air conditioning, and energy for lighting. The EPC can be created for any building or its integral part.

For instance in the Czech Republic as from of January 1, 2009, *the builder, owner of a building or association of unit owners under Act No. 406/2000 Coll., on energy management, as amended, is obliged to ensure that the energy performance of the building is met and evidenced.* This obligation is more precisely specified from 1 January 2013. The card is valid for 10 years from the date of its execution or until a major change has been made to the completed building for which it was processed. The card can be created only by an energy specialist, which is authorized by the Ministry of Industry and Trade to process the card.

Taking still the example from the Czech Republic, the EPC consists of two parts, namely graphical representation and protocol. Further information can be found in Act No. 406/2000 Coll., On Energy Management and in Decree No. 78/2013 on the Energy Performance of Buildings, as amended. [13]

2.3.2 Comparison of the EPC procedures within European countries

The Energy Performance Certificates (EPC), an integral part of the EPBD, *are an important instrument that should contribute to enhance the energy performance of buildings*. The main aim of the EPCs is to serve as an information tool for building owners, occupiers and the property actors when a building or building unit is sold or rented. *Therefore, EPCs may be a powerful market tool to create demand for energy efficiency in buildings by targeting such improvements as a decision-making criterion in real estate transactions, and by providing recommendations for the cost-effective or cost-optimal upgrading of the energy performance.*

Even though this is not specifically required by the EPBD, 24 Member States and Norway have to date established centralized EPC registers. These measures have been undertaken in the context of monitoring and quality controls of the energy certification processes (i.e. random sampling).

The implementation of the EPC schemes at a Member States (MS) level is still ongoing and struggles with challenges such as public acceptance and market-uptake. *The EPC schemes are not fully implemented in all Member States nor sufficiently enforced yet. Therefore, the quality, credibility and usefulness of the EPCs vary greatly among the Member States, and there is still a need to further support and set guidelines for the implementation of the EPC schemes at the national level.* The potential to change the status quo lies in the effective implementation of the new requirements of the EPBD recast (2010/91/EU), such as establishing a well-functioning system for independent control of EPCs and enforcement of penalties for non-compliance. [10]

Based on the current status of EPC implementation across Europe, the following recommendations can be made:

A. To consistently improve the enforcement of the EPC schemes in Member States and strengthen the monitoring of their compliance both at Member State and European levels.

B. To strengthen the role of EPCs in the context of national legislation, especially for renovation policies and programmes.

C. To introduce further quality assurance measures, especially during the early stages of the certification process, as follows*:*
   - The requirements for qualified and/or accredited experts strengthened and harmonized across Member States.
   - The certifier needs to be physically present onsite
   - Digital tools for quality checks of the EPC data should be used, such as plausibility check in the calculation software and/or the EPC registers.
   - There is a need for further enforcement and harmonization of the EPCs quality checks across Member States.

D. To provide guidance in the development of centralized EPC registries, not only to support the independent control system, but as a tool to map and monitor the national building stock.

E. To promote the effective use of the EPC data.

F. To create an independent evaluation of the effectiveness of the EPC scheme. [10]

The building sector plays a critical role in the European Commission's proposal for an energy saving target of 30% by 2030. The Energy Performance of Buildings Directive, introduced in 2002 (EPBD 2002/91/EC) and revised in 2010 (EPBD recast 2010/31/EU)9 , is *the key instrument to increase the energy performance of buildings across the European Union. The energy savings resulting potentially from (a proper) implementation of the EPBD are assessed to be at least 60 Mtoe by 2020. The European Commission has estimated that additional ambitious renovation policies can lead to up to 46% energy savings between 2021 and 2030.* [10]

EPC in the Czech Republic

In the Czech Republic, the responsible body for the implementation of the EPBD is the Ministry of Industry and Trade. Energy assessments of buildings indeed aren't something new in the Czech Republic since there has been a methodology for energy audits and certificates in place since 2001 for buildings with energy consumption higher than 1500 GJ per year.

EPCs are only required for new buildings and in the case of major renovation (an obligation linked to the building permit). The selected methodology bases on calculated rating, making use of reference buildings. The choice to issue EPCs only in case of new buildings or major renovations is not fully in line with EPBD requirements, since this leaves out most existing buildings. *Only new buildings and buildings that undergo major renovation should have an EPC issued to request a building permit.* In case the buildings are sold or let afterwards, the certificate should be presented at the moment of transaction. All other existing sites do not require an EPC at a moment of transaction. In public buildings the same rules apply, the EPC has to be presented when they are new or recently renovated.

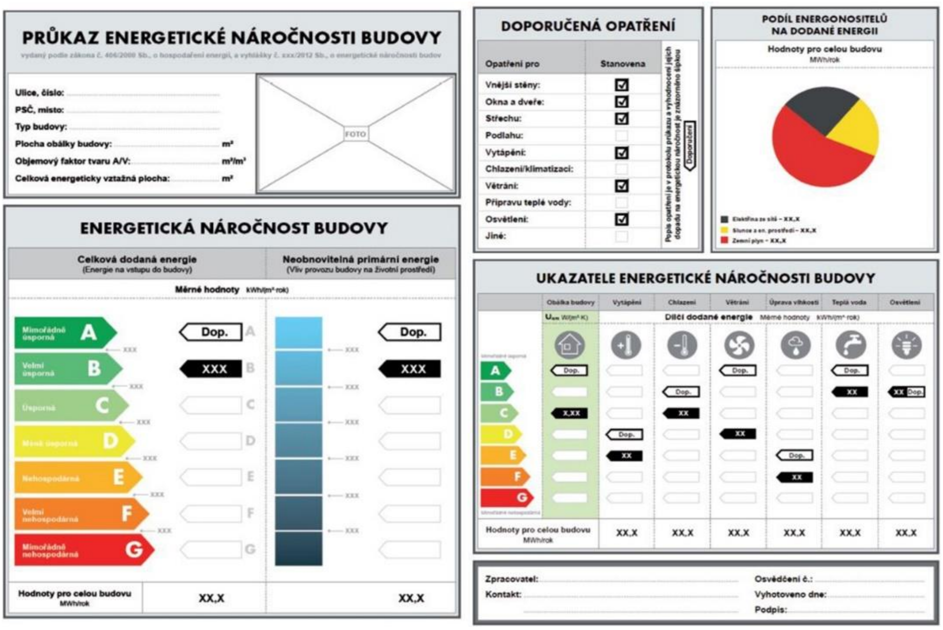

Figure 6: Example of an Energy performance certificate in the Czech Republic [9]

The data displayed on the EPCs is by the general public not viewed as very useful, since an EPC is usually issued for new buildings or buildings that undergo major renovation (as an instrument to check compliance with energy performance requirements). These buildings are therefore always in a 'good' energy class, and it is not very useful to recommend energy saving measures. So the main target group for the recommendations (existing buildings) is not affected.

Low governmental interest is a barrier for implementation, alongside the choice for a minimal implementation of EPCs (only for new and renovated buildings). The interference of market players/stakeholders with political preferences for implementation has played a role in the choice of assessment variables with regard to energy consumption. [13]

EPC in Germany

In Germany, the implementation of the EPBD lies in the responsibility of three ministries: the *Federal Ministry of Transport, Building and Urban Development,* the *Ministry of Economics and Technology* and the *Ministry of Environment, Natural Conservation and Nuclear Safety*. The Energy Performance Certification scheme is not new to Germany. Since 2002 energy certificates have been mandatory for new buildings and, in certain cases, for major refurbishments. With the EPBD implementation the EPCs received a new design (uniform for new and existing buildings), but certificates issued under the old scheme remained valid.

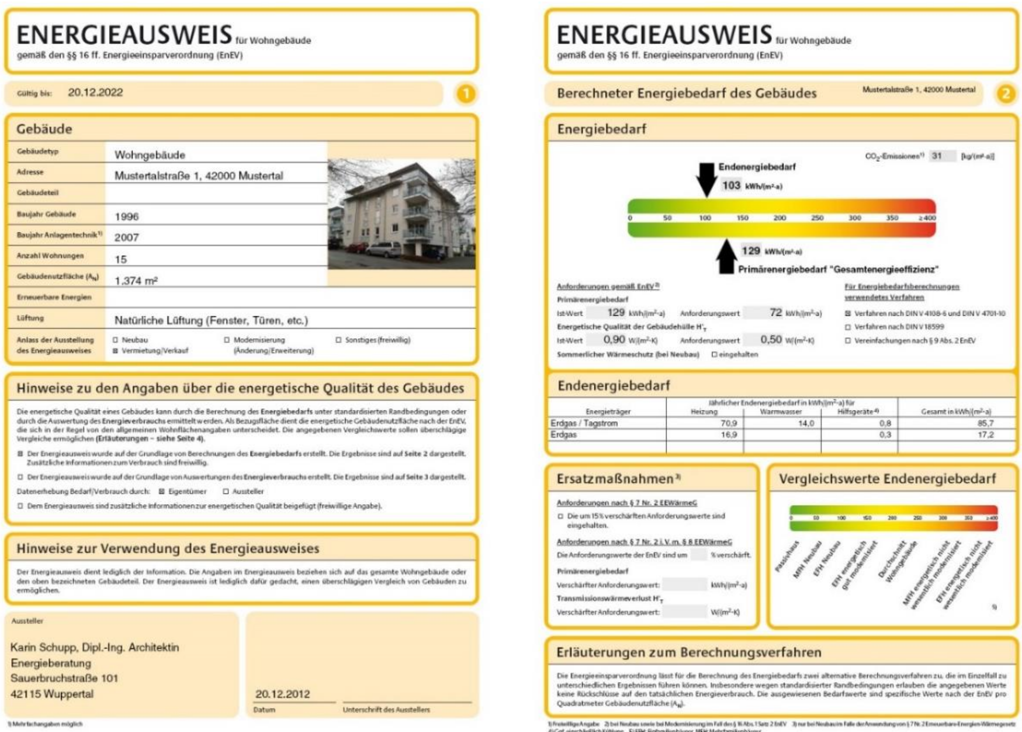

Figure 7: Example of an Energy performance certificate in Germany
(for residential buildings) [8]

In specific situations the dwelling user/owner can choose between a low quality and cheap certificate based on measured rating, and a higher quality and more expensive certificate based on calculated energy demand. The lower quality version is often chosen at the time of transaction to comply with the law. It is not exactly known how common practice the EPCs are at the time of transaction, since registration does not exist.

The low quality certificate has little useful information for the building owner and therefor does not stimulate energy efficiency very effectively. The quality of the certificate is a discussion point. *The German Energy Agency DENA* has started its own database with available energy experts who have the authority to issue a EPC based on the calculating rating which has DENA quality seal.

Some barriers experienced are: *the low quality of the operational label version, some unclearness and changes in regulations, incentives not working properly* and *a lack of coordination and communication in the decisive process of developing the scheme*. For the future an amendment of the energy performance requirements for buildings is planned. An update of the legislation is expected in 2011/2012. [13]

EPC in Ireland

In Ireland, the implementation of the EPBD is the responsibility of the *Department of Environment, Heritage and Local Government* and the *Department of Communications, Marine and Natural Resources*. The EPBD was adopted in Irish law in 2006. Sustainable Energy Ireland (national energy authority) is responsible for developing and administering the EPC scheme. After a process of public consultation, the 'Action Plan for Implementation of the EPBD in Ireland' was published in August 2006. This Action Plan sets the outline of the proposed tasks, responsibilities and timeframe for full EPBD implementation in a workable and cost-effective manner. In Ireland the EPC is called a Building Energy Rating (BER). For new buildings it became mandatory in January 2007, for non-residential. The Buildings Performance Institute Europe (BPIE) buildings and public buildings in January 2008 and for existing residential buildings in the event of sale or rent in January 2009. The chosen assessment method is calculated rating.

Around 300 EPCs are issued in Ireland each day. Public acceptance is positively influenced by the public consultation round. In the development of the EPC scheme Sustainable Energy Ireland paid specific attention to balancing issues like practicality, costs, clarity and consistency because this was considered vital to the market reputation and effectiveness of the scheme. EPCs are issued by specially trained EPC "BER assessors", who are building professionals with relevant background, registered by Sustainable Energy Ireland. [13]

2.3.3 The potential impact of BIM on the Energy Performance Certificate

As in many professions, also in the creation of Energy Performance Certificates there is a necessity to use simplified approaches, default values (e.g. for HVAC systems, boilers, plumbing etc.). Nowadays, the world is moving closer to higher standards such as nZEB where these information becomes less and less evident. Unfortunately, detailed calculations require a lot of input data and additional calculation tools. There is also no evidence of effective compliance or enforcement in the most countries.

The areas that could potentially be improved using BIM in relation to the fulfillment and enforcement of the EPC are:

- Specific data analysis tools *(e.g. EPC simulations, acoustics, fire, manufacturing control software…)* enable the optimization and technical control of the building design stage *(an approximate "speller check")*;
- Less additional effort for the modeler in terms of gathering EPC (and other) input data, they are added by databases to particular objects and components in the model;
- Setting up databases with locally available products plays an important role and should include necessary EPC data in compatible formats with data analysis tools. Also important is to comply with European legislation for EPC such as CEN TC 442;

  An example of this data might be e.g. the following (in this example the data needed for EPC for sustainable summer comfort issues, the majority of the data available from the BIM model directly):

  - *Solar shading;*
  - *Thermal mass;*
  - *Multi-zoning;*
  - *Ventilative cooling;*
  - *Cool roof products;*
  - *Control strategies.*

- BIM enables to have a bigger set of relevant "extra input data":
  BIM models may be very detailed offering functions such as *organization of spaces, composition of building components, building nodes*. In practice this means that the users will have *access to a wide range of input data without the need for a lot of extra "input data work" in the EPC context*. They need to find back this data, which requires definitions, explicit names and addresses *("semantics")*. Of course, this needs to be organized from the whole beginning of the modelling process. It is important to manage these "semantics" in the model to find back and to have all the necessary data for a certain type of data analysis, e.g. EPC calculations;

- A chance to simplify particular calculation aspects – as mentioned in the point above, the potential of BIM is in a larger set of relevant input data. *This might e.g. allow to assess the 2- and 3-dimensional heat flows by a direct calculation, without the need for extra work by the EPC rapporteurs*;

- A chance to have more refined assessment procedures – a good example: the evaluation of *the risk of overheating and/or the need for active cooling*. The ideal conditions for such an experiment are *at room level and by using dynamic simulations*. Without using BIM the biggest difficulty is *the need for a detailed model of the building and/or it's installations*. BIM would simplify this process significantly;

- A chance for an effective enforcement without the need of governmental actions to be involved. *Simulation proofs on "AS BUILT" models (LOD 500)*;

- Challenges – the main challenge lies in the certification of these simulation tools and in the harmonization of country codes with extensions for different countries / regions;

- BIM connected to EIM (Environmental Information Models) *can be a support for Urban Building Physics and more.* [20]

As mentioned already in the previous chapters, with evolution things tend to be optimized and simplified for the end-user by using more-sophisticated technology. As a great example you can view a smart phone – embodies various functions that used to be individual particular items such as a camera, GPS, phone, MP3 player or a PC web browser. If somebody would come up with the idea to combine all these functions into one small device fitting into a pocket approximately 20 years ago, people would probably view it as "crazy".

But if you think of it, the same you have with BIM at this moment. Also trying to simplify or to unite several key areas of the construction industry such as architectural design, acoustics, air conditioning, lightning, electricity, water appliances, fire aspects or not to forget energy performance and much more.

3. Review of Building Information Modelling

In addition to the previous chapter, I will now try to find ways to understand the role and application of BIM systems in energy management and the connection between them. This chapter explains mandatory tools and procedures related to the project.

3.1 About BIM

<u>Building Information Modeling</u> *(also known as Building Information Management, abbreviated as BIM)* is an environment that enables generating and managing data of a range of various structures (buildings) throughout their whole life-cycles. BIM is changing the way projects are developed and built. In today’s competitive world, it becomes necessary to acquire new skills in new innovative technology such as BIM and to prepare future generations for this change as well.

Nowadays, there is huge and growing interest within the <u>Architecture, Engineering and Construction (AEC)</u> industry. As also the general public may know already, BIM is a parametric modelling process strongly associated with visual presentation and geometric modelling enriched with a lot of information. One of the main benefits is the immediate 3D processing from a 2D entry level by drawing simple lines with defined properties. However, there is much more to BIM than visualizations and generated documentation only though. *Although is still at an early stage of development and implementation, the BIM is one of the most promising technologies for the integration of teams working on the same project.* [16][18]

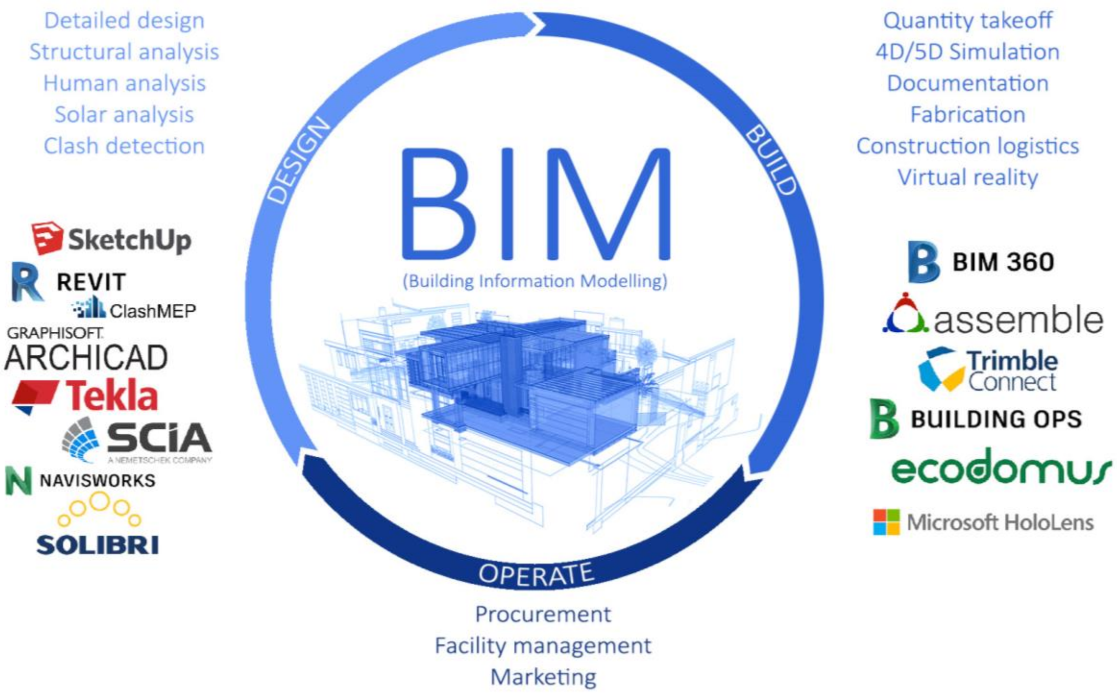

Figure 8: General scheme of the BIM environment with corresponding software examples [23][24][25]

Recently is BIM being used by many companies mainly in the construction industry for achieving savings in terms of building efficiency and for improving the accuracy and coordination of documentation. For creating such models, it's important that the user acquires knowledge in identifying data involved in each phase of the project. *The implementation of this concept involves multiple actors from different sectors of the AEC industry.* Also due to the rising pressure in civil engineering to save time and cost it is almost inevitable to adopt to tools like BIM. [18]

3.1.1 A brief history of BIM

BIM's history can be traced back to the 1970' to the time when the concept of BIM was mentioned by Charles M. Eastman, professor at the Georgia Institute of Technology. Nevertheless, it reached the peak just during it's last decade after becoming involved in the EU law. *The Member States may require the use of specific electronic tools* closely related to building information electronic modelling. For these cases, alternative ways of access have to be provided by the contractors, until these types of tools become generally available. [16]

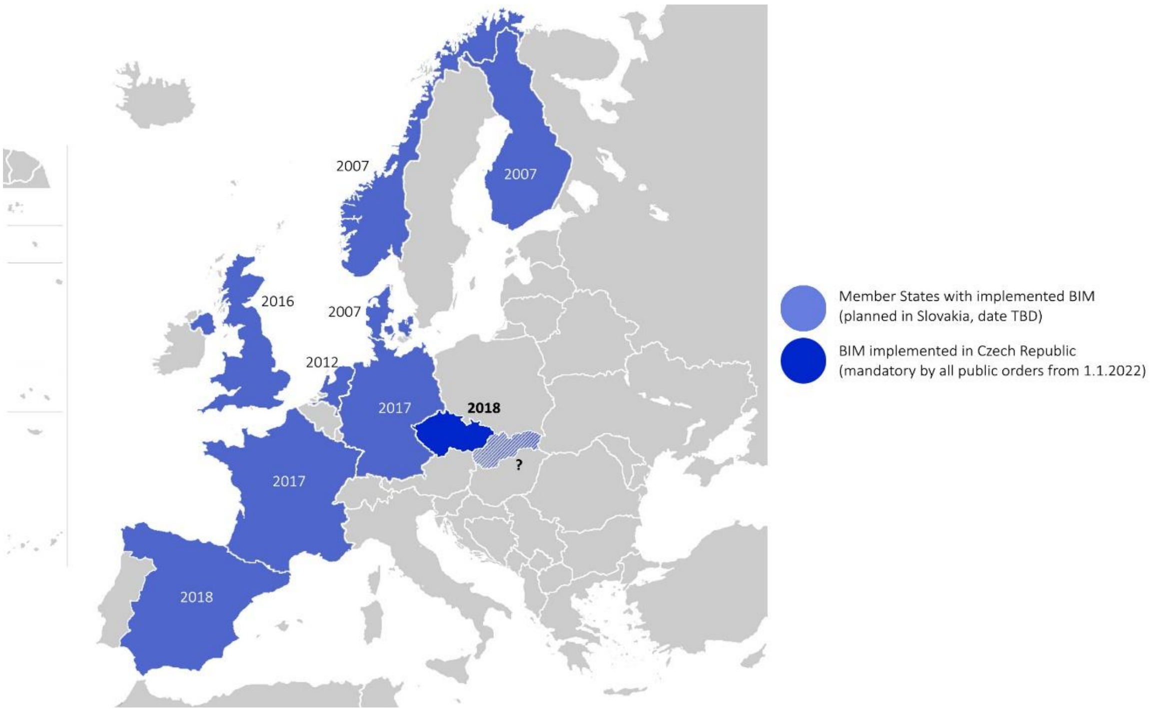

Figure 9: Countries where BIM became a part of construction acts, as recommended by the European Commission [16]

The conceptual foundations of BIM reach to the earliest days of computing to the year 1962 when Douglas C. Englebart forecasted an unfavorable vision of the future of architects in his publication *Augmenting Human Intellect,* described in the following words:

"… the architect next begins to enter a series of specifications and data–a six-inch slab floor, twelve-inch concrete walls eight feet high within the excavation, and so on. When he has finished, the revised scene appears on the screen. A structure is taking shape. He examines it, adjusts it… These lists grow into an evermore-detailed, interlinked structure, which represents the maturing thought behind the actual design."[26]

Mr. Englebart proposed *object based design, parametric manipulation and a relational database* that actually became reality several years after his prediction. Of course, the history provides a long list of design researchers that left a huge impact in this area which are e.g. *Herbert Simon, Nicholas Negroponte* and *Ian McHarg who was developing a parallel track with Geographic Information Systems (GIS).*

The first visualizations range besides the SAGE interface to the *Sketchpad* program developed by *Ivan Sutherland* that was one of the first computational programs appearing as the representation of geometry. Two main approaches that displayed and recorded shape information that started to appear in the 1970s and 1980s were *constructive solid geometry (CSG)* and *boundary representation (brep)*. The CSG uses primitive shapes that can be combined subtracted to create the image of more complex objects.

One of the first software for creating functioning building databases was the Building Description System (BDS). It described individual library elements, which can be retrieved and added to models. It used a graphical user interface with orthographic and perspective views. It also provided a database allowing the user to retrieve data by category, e.g. material type and supplier. When speaking about BDS it is important to mention the resonant name of its designer, which was Charles Eastman. He *was trained as an architect at Berkeley and went on to work in computer science at Carnegie Melon University. Eastman continues as expert in BIM technology and Professor at the Georgia Tech School of Architecture.*

Mr. Eastman declared that constructional drawings were inefficient and were the reason for surpluses of one object that used to be projected at several scales. He was also pointed criticism against printed drawings because of their decay over time.

He also concluded that his BDS will reduce the design costs by more than 50%. In the end was BDS just an experiment written on an PDP-10 computer before the age of classic personal computers and most architects did not even have the chance to try this software. It is also unclear if there is any official project that was realized by using BDS. However, this changed with Mr. Eastman's next project called Graphical Language for Interactive Design (GLIDE) which was created in 1977 and performed a majority of the characteristics of modern BIM.

Following this example, there were several other systems developed in England during the early 80's which drove this trend and were applied to construction projects. Some examples are GDS, EdCAAD or RUCAPS, where the last one was developed in 1986 and it was even used for temporal phasing of the construction processes of the London Heathrow Airport's Terminal 3. Another landmark in the development of BIM is the foundation of the Center for Integrated Facility Engineering (CIFE) in 1988.

In 1993, Lawrence Berkeley National Lab developed a famous example of a simulation tool with the name Building Design Advisor, which provided feedback and proposed solutions. It was one of the first to provide information about how objects perform after specifying given parameters such as *project orientation, geometry, material properties or building systems*.

Eventually, I have to mention two important geniuses, which programmed within the Soviet Block and contributed to nowadays BIM in a significant way, while the U.S. developed rapidly. And that are the names of the co-founder of Revit which is Leonid Raiz and founder of ArchiCad, known as Gábor Bojár. ArchiCad was developed 1982 in Budapest, Hungary by Mr. Bojár who *rebelled against the communism government and began a private company*. To be able to write the first lines of coding, he even pawned jewelry of his wife and smuggled Apple Computers through the Iron Curtain. The first release is known under the name Radar CH, which became later ArchiCad – the first BIM on a personal computer. Starting with a default similar to the BDS from Mr. Eastman, ArchiCad developed the most during the years 2007-2011 as a tool for residential and small commercial structures within Europe. Recently is ArchiCad one of the most used building design tools worldwide using a complicated programming environment called GDL (Geometric Description Language).

Not too much later, the Parametric Technology Corporation (PTC) founded in 1985 with Irwin Jungreis and Leonid Raiz, started in 1988 a project called Pro/ENGINEER using a *constraint based parametric modeling engine*. After gaining key knowledge from this project they both split and created an own company under the name *Charles River Software in Cambridge, MA*. Their main goal was to develop a software that is able to handle more complex projects than ArchiCad. After hiring a trained architect called David Conant who designed the first interface, in 2000 the company released the program Revit *(a made up word meant to imply revision and speed)*. It was written in C++ and *utilized a parametric change engine, made possible through object oriented programming*. In the year 2002, their company was purchased by Autodesk and started promoting it's object-based *Architectural Desktop* in a big way. *Revit revolutionized the world of Building Information Modeling by creating a platform that utilized a visual programming environment for creating parametric families and allowing for a time attribute to be added to a component to allow a 'fourth-dimension' of time associated to the model.* [26]

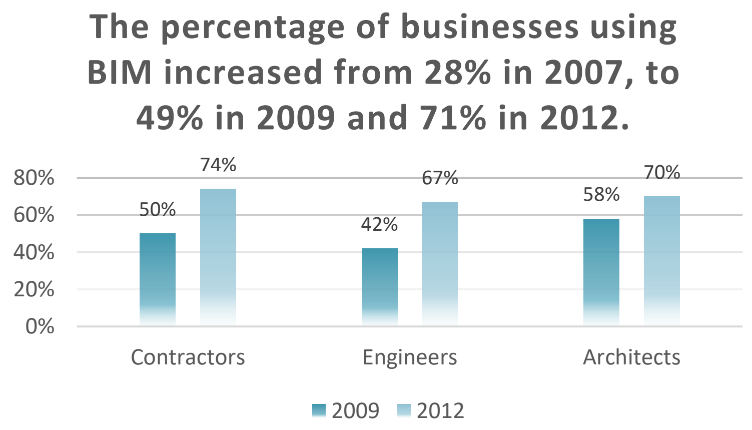

Table 2: Adoption of BIM by categories – comparison 2009/2012 [26][27]

3.1.2 BIM applied in construction projects

A good example where the use of BIM was tested in a construction project was a student dissertation from Paulo Neves, an MSc student at the Lisbon Technical University in Portugal. The publication is known under the title *Application of BIM technology in building design*.

The work reflects the differences between classic 2D/3D CAD generally used models and the parametric BIM approach with advanced modelling procedure allowing to obtain different data e.g. energy consumption, estimates and visualization. Similar as in the upcoming case study, the modelling effort in this dissertation was undertaken in Autodesk Revit as well. Concerning the BIM tools, all of them proved to be very useful while providing very similar results as the standard 2D/3D tools (e.g. CAD, SketchUp). *As a conclusion, the research work project confirmed the overall positive trend within the AEC industry regarding BIM adoption and its benefits.*

Furthermore, Mr. Neves confirms that modelling in Revit is intuitive but challenging at the same time. The fact of adding representations of elements into a building enables a more exact resembling of the finished building. A huge advantage is of course the instant rendering process after creating the model, whereas by the normal 2D approach an additional modelling would be necessary. This study shows also the possibility to use the conceptual analysis tool and the quantity and cost estimating which is a fundamental phase for contractors. BIM succeeded in showing the ability to measure quantity of materials.

The conclusion of this work says that after modelling the project in Revit and executing various analyses and tasks there is a remarkable difference from the traditional CAD approach. It represents a *step forward for any design or construction company willing to invest in training and SW.* [28]

3.1.3 Application in construction management

Case studies are good examples (and sometimes the only publicly accessible ones) that show certain progress or interesting analyses e.g. between new and old. For this reason, I will use another case study in this subchapter with the title *BIM applied to construction management* from a PhD candidate, Antonio Costa, studying within the field IT in construction at the Technical University of Lisbon in Portugal.

Mr. Costa's construction intends to demonstrate the ability of BIM software to create 4D model simulations and to interoperate with other planning software, e.g. Microsoft Project. To achieve this, an Autodesk Revit model was created including an IFC file at the end for the importation into Navisworks. Additionally, the construction schedule was imported from MS Project. Afterwards the links between the BIM model and the timeline were created. Since all objects are created parametrically, amendments are very easy to execute in BIM (all 2D drawings are corrected automatically). *Navisworks is used for integrating models from a variety of sources. It features excellent conflict detection and resolution and animation capabilities*. The SW created a direct link between the schedule and BIM model while each object was associated to an activity in the timeline. This enables the creation of a simulation of the construction process. [29]

3.2 Revit for Building Performance Analysis

A part of the history of Revit was already described in more detail in chapter 3.1.1. Generally, I can add that currently Revit is maybe the most common BIM software in terms of design and architecture in the world. In this subchapter the thesis will focus more on the functionalities in connection with a <u>Building Performance Analysis (BPA)</u>.

In general, it is known that a building consumes water, energy, electricity and produces carbon, waste and sewer. You can think of the BPA as a part or subset of the LEED Analysis (which is still a different level though). The BPA is more focusing on *Energy and Indoor Environmental Comfort.* Energy is being consumed by HVAC systems, domestic water systems, electrical lightning, various facilities, equipment and others.

Normally the HVAC engineer comes into place in the situation when the building is already set up by the architect, which decided about the site orientation and wall to window ratio, where e.g. the site orientation is normally a best guess from the architect to fit the site. Important to mention here is that *these ARE critical energy factors.* In the regular procedure, the HVAC engineer would think of the functional requirements, pick a mechanical system approach by maybe trying several ones and apply some rules-of-thumb to estimate the energy loads. This would be followed by an energy analysis in e.g. Energy Plus, DOE2 or another SW. This way the engineer would have to meet a certain energy demand that was already *set in stone.* For all this reasons (but even for more) Revit introduced a new approach this thesis will focus on. [30]

3.2.1 Insight 360

According to the specialists Joshua Benoist and Joel Harris from Autodesk, Insight 360 is their *answer to the "need"* of implementing IDP. Let's explain first what this means.

IDP stands for Integrated Design Process, which enables the democratization and sharing of decisions between stakeholders. This allowed e.g. the participation of the HVAC engineer directly at the beginning to share critical decisions, he no longer had to follow the architect. The old energy analysis tools were not able to provide this import functions such as site orientation, wall ratio, shading and other. It was necessary to insert these values into the application to get a single value out. SW like Trane Trace only generated huge reports with a lack of visual graphics and were limited by desktop computing.

From what the Autodesk specialists say, there was a "need" of a modern, mobile, collaborative and fast tool that grows with the LOD and delivers right data at the right time with minimal inputs in the early stage.

By implementing Insight 360, the idea was to remove the "single value" result option and to create *multiple design options* instead. You can imagine it by the idea of testing each degree of orientation and looking for the best values. To find the optimum, this would be very time and resource consuming/expensive.

Insight 360 uses DOE2.2 but can work with EnergyPlus as well. EnergyPlus was willing to release its C++ version to Autodesk, who volunteered in its conversion. DOE2.2 is significantly faster, it allows 360 total reports. They claim that Insight 360 is useful for architects and IDP teams early in the design life cycle. However, the engineers and owners appreciate the ability to further refine the analysis through gbXML. In fact though, Insight 360 is GBS (Green Building Studio). To be precise, *it's a skin on GBS that takes results of over 300 parametric simulations and computes an energy range from billions of combinations and helps us to understand what is important and what is not*. [30]

3.2.2 Calculation methods in Revit – The Radiant Time Series method

The main approach for calculating heating and cooling loads in the Autodesk software is the Radiant Time Series (RTS) method from ASHRAE. It calculates the needed consumption for all load components incl. lights, people, roofs, windows, appliances and other. You can imagine the procedure as the following:

1. Calculation of a 24h profile of heat gains for a *design day* (using the Conduction Time Series (CTS) method to compute the conduction time);
2. Splitting *heat gains into radiant and convective parts*;
3. Application of the corresponding *radiant time series to the radiant part of heat gains to account for time delay in conversion to cooling load*;

4. Counting the *convective part and the delayed radiant part of the heat gain to determine the cooling load for each hour for each component.*

As soon as the cooling loads for all components for each hour were calculated, the built in engine counts them together and determines the peak hour with the highest load to design later the air-conditioning (AC) system. It also *repeats this process for multiple design months to determine the month when the peak load occurs. Heat gain through exterior opaque surfaces is derived from the same elements of solar radiation and thermal gradient as that for fenestration areas.* [31]

The RTS method was first developed by ASHRAE as a *simplified companion to the rigorous heat balance procedure*, which was developed by Pedersen. This method was verified by a comparison of cooling loads predicted by RTS and cooling loads obtained by the *heat balance method*. The previous valid studies confirm the significance of this method, which is considered to be also an "*adiabatic zone assumption*", which demonstrated the validity of RTS for standard zone configurations. RTS can be used for first order estimates of cooling loads.

The study from ASHRAE from 2003 (see references) provides direct and indirect verification of the RTS method by experiments at extreme conditions (identified by Rees and others 1998), which are e.g. *a highly glazed space with no internal heat gains or infiltration*. By the heat balance and cooling loads there was an expected divergence. [17]

The calculation procedure

The RTS method is a two-stage procedure to calculate cooling loads (according Spittler and others 1997). At the beginning, the heat gains of the building space need to be calculated or estimated. These gains include the energy from *lights, equipment, human activity, conduction through the building envelope, convection from infiltration or ventilation and transmitted* or *absorbed solar gains*. The relation between the conductive heat gains and the relative magnitude is mentioned below:

$$f_r = \frac{R_c}{R_r + R_c} \tag{1}$$

$$f_c = 1 - f_r \tag{2}$$

f_r = *radiative fraction of conductive heat gain;*
f_c = *convective fraction of conductive heat gain;*
R_r = *radiation film resistance, ($ft^2 \cdot °F \cdot h$)/Btu; ([$m^2 \cdot °C$]/W);*
R_c = *convection film resistance, ($ft^2 \cdot °F \cdot h$)/Btu; ([$m^2 \cdot °C$]/W).*

Instead calculating detailed surface heat balances of convection and radiation, the RTS method rather *estimates their combined effect on exterior surfaces*. The calculation of the *conductive heat transfer* is based on the sol-air temperature defined by the following relation:

$$q_\theta = \sum_{f=0}^{23} Y_{p_f}(t_{e,\theta=f8} - t_{rc}) \tag{3}$$

q″ = *heat flux for the current hour, Btu/(h·ft²); (W/m²);*

Y_p = *air-to-air periodic response factors, Btu/(h·ft²·°F); (W/[m²·°C]);*

t_e = *sol-air temperature, °F (°C);*

t_{rc} = *constant room temperature, °F (°C);*

ϑ = *current hour; δ = time step.*

The equation uses Periodic Response Factors (PRF), which represent a set of pre-calculated values in order to be efficient in the environment of RTS. These values can be directly derived from a set of Conduction Transfer Functions (CTF) coefficients. The PRF developed by this process provide the same results as the CTF in case the *boundary conditions (sol-air temperatures) are steady periodic.* For the purposes of this thesis I will not further deconstruct the calculation methods for PRF. However, they are well described in a publication from Spitler and Fisher from 1999 (see references). [33]

The air-to-air PRF are *response factors for a one-dimensional, transient conduction problem with a steady periodic driving force*. As Equation 3 displays, *PRFs directly scale the contribution of previous fluxes (in the form of temperature gradients) to the current conductive heat flux.* This results in the PRF representing *the transient thermal response* of constructions, in this case a wall.

In the second stage of the calculation process, the heat gains are converted into cooling loads. *The radiative heat gains are multiplied by the Radiant Time Factors (RTFs) to obtain cooling loads.* An RTF is in other words *the response of the building space to a radiant pulse* and therefor it is dependent on material characteristics of the construction elements. However, the convective heat gains are not reliant on the construction materials and represent *instantaneous cooling loads*. For this reason, *the total hourly cooling loads are the summation of the hourly radiative and convective values*. [17]

Over-prediction of peak cooling loads in RTS

There is a difference between the RTS method and the Heat Balance Method (HBM) in the adiabatic zone assumption, *which is implicit* in RTS, matched with *the air-to-air conduction calculation* (according Rees 1998). The application of HBM to adiabatic zones generates the RTS. The over-prediction of cooling loads appears in a case where radiation raises the inside surfaces temperature above the outside surface temperature. Afterwards two processes follow: first, the raise of the inside temperature *increases the rate of inside convection* and therefor also the cooling load; second, the surface temperature change could *cause surface-to-surface conductive heat loss.* As you can see in Figure 10, the heat balance (which is based on surface temperature gradients – (T4-T3)) predicts a heat loss, the RTS method (based on the air temperature gradient – (T1-T2)) predicts a heat gain.

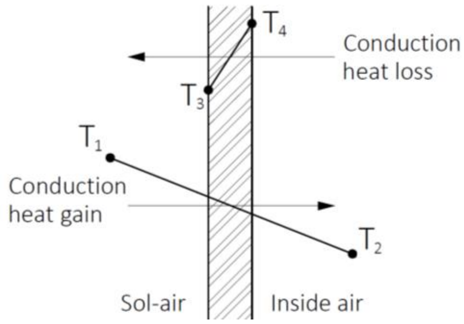

Figure 10: Opposing temperature gradients predicted by the HBM and RTS method [17]

The experimental procedure

Elliptical flow nozzles measure the volumetric flow rate in the air loop. The room inlet and outlet air temperatures are also measured using thermocouple grids located in the ducts. Following this fact, the cooling loads can be calculated based on this equation:

$$Q_\theta = m_\theta c_p (T_{out,\theta} - T_{in,\theta}) \quad (4)$$

In case of work with a modified model, it's important to count with *shortwave radiation heat loss through glazed surfaces.* This happens due to *shortwave radiation from internal gains, diffuse solar radiation* or *transmitted solar radiation from the floor.* First, the shortwave heat gain will be calculated:

$$Q_{sw,\theta} = Q_{r,beam,\theta} + Q_{diffuse,\theta} + Q_{sw,int,\theta} \quad (5)$$

$Q_{r,beam}$ = radiation reflected diffusely from the floor;
$Q_{diffuse}$ = transmitted diffuse solar radiation;
$Q_{sw,Int}$ = shortwave radiation from internal loads.

Under the premise that the *solar beam radiation* distribution is on the floor only and the diffuse solar radiation distribution happens uniformly on each interior surface, it can be calculated as the following:

$$Q_{r,beam,\theta} = s_{floor} \rho_{t,floor} Q_{beam,\theta} \quad (6)$$

s_{floor} = solar fraction;
$\rho_{t,floor}$ = shortwave reflectance of the floor;
Q_{beam} = beam radiation;
$Q_{diffuse}$ = diffuse radiation.

The *total heat loss of the shortwave radiation* through windows is in relation with the total shortwave heat gain in a specific space, as displayed here:

$$Q_{sw,loss,\theta} = Q_{sw,\theta} \sum_{k=0}^{\#windows} s_k \tau_{t,k} \tag{7}$$

s = solar fraction;
τ_t = transmittance of the windows.

Results

In the study from ASHRAE (see references [17]), typical heat gains were calculated for a design day with outside temperature 40°C and inside air boundary temperature 25°C. In the below table you can see the *individual heat gain contribution* to the total heat gain with a base configuration.

Component heat gain	Q^*_{infil}	Q^*_{cond}	Q^*_{solar}	$Q^*_{int.}$
Heat gain fraction	0.65%	31.85%	67.50%	0.00%

Table 3: Individual heat gain contribution [17]

A brief explanation of the components in the table:
Q^*_{infil} = *infiltration heat gain fraction;*
Q^*_{cond} = *air-to-air conductive heat gain fraction;*
Q^*_{solar} = *transmitted solar heat gain fraction;*
$Q^*_{int.}$ = *internal heat gain fraction.*

The heat gain fractions are calculated from Equation 8:

$$Q^* = \frac{\sum_{\theta-1}^{24} Q_\theta}{\sum_{\theta=1}^{24} Q_{tot,\theta}} \tag{8}$$

Q^* = *heat gain fraction;*
Q = *component heat gain, W or Btu/h;*
$Qtot$ = *total heat gain, W or Btu/h.*

The test building in the study showed that a significant part of the heat is contributed by solar gains, especially conductive heat gains. *Infiltration is insignificant, and internal gains are nonexistent.*

Modelling the thermal mass effect

The same study tested also two thermal massive test cells – one lightweight and one heavyweight cell. The heavyweight cell was created with walls from concrete blocks with brick overlay; roof and floor made from concrete as well. The lightweight cell was made from wood-framed walls with an *exterior insulated finish system (EIFS).* The PRF display different thermal responses of the building elements, as you can see in Figure 11.

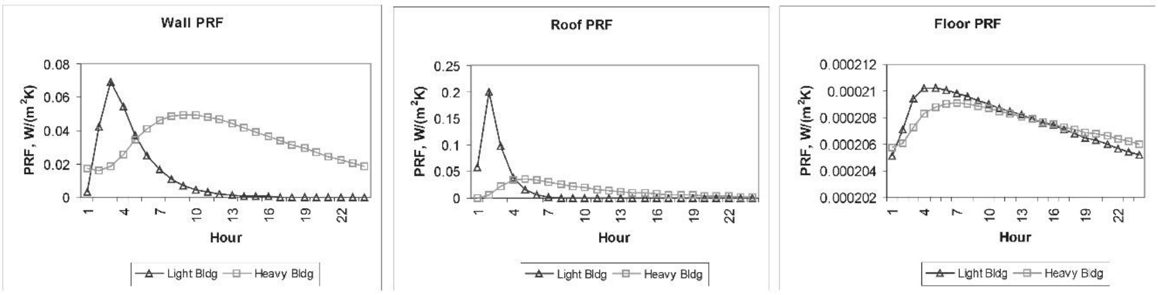

Figure 11: Periodic response factors for test buildings surfaces [17]

The *"fraction of peak load"* states the same cooling load profiles, which are expressed by the following equation:

$$Q_N = \frac{Q_{est} - Q_{min,exp}}{Q_{max,exp} - Q_{min,exp}} \% \qquad (9)$$

Q_N = normalized cooling load;
Q_{est} = estimated cooling load;
$Q_{min,exp}$ = minimum measured cooling loads;
$Q_{max,exp}$ = maximum measured cooling loads.

In the below figure you can identify the building thermal mass of the two test cells from above. The operational conditions where identical for both buildings in this experiment. As we can see from the *"load" plot, the thermal mass of the heavy building damps the peak load by 25% but shows no discernible shift in the peak hour*. [17]

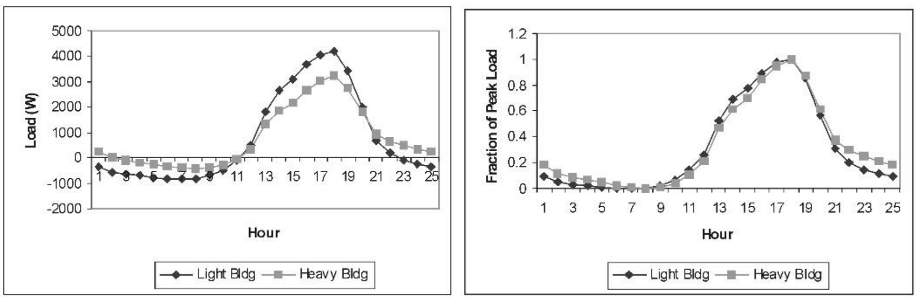

Figure 12: Comparison of thermal mass effects (lightweight and heavyweight cell) [17]

3.3 Data exchange formats in BIM for energy analysis

The importance of the conversion of a BIM model plays a key role in the accuracy of its following simulations. This chapter enlightens via a case study from the Technical University in Vienna the error rates of the conversion using the two most reliable formats for energy simulations for the two most used programs by architects – Revit and ArchiCAD.

3.3.1 Industry Foundation Classes

Industry Foundation Classes (IFC) are the official international standard for Building Information Modelling data exchange among various diverse software for multiple purposes within civil engineering and facility management. IFC is registered within the International Standardization Organization (ISO). The standard uses the following schemas:

- EXPRESS data specification language – *defined by ISO10303-11* and used to describe entities and relationships, also containing data verification rules in the data scheme;
- XML Schema definition language (XSD) – *defined in XML Schema W3C Recommendation.*

The company buildingSMART developed a standard for the information flow in an integrated project called Information Delivery Manual (IDM). The main goal of the IDM is to create efficient description of all relevant data for a specific task in the 3D BIM model in a way that it is accurately imported and processed by the respective software.

To exchange and share data according to the conceptual schema following exchange file formats were developed:

- Clear text encoding of the exchange structure – *defined in ISO 10303-21*,
- Extensible Markup Language (XML) – *defined in XML W3C Recommendation*.

Alternative exchange file formats may be used if they conform to the data schemas. [34]

3.3.2 Green Building XML

The Green Building XML (gbXML) data format developed in 1999 by Green Building Studio (GBS) was created mainly for analysis purposes for the data exchange between 3D-CAD/BIM and analysis applications. First acquisition by Autodesk was in 2008. Its main functionality is the retrieval of geometry and non-geometrical information from the model that is being saved in a text format under pre-defined notations. [35]

The information is divided into three different categories: *ShellGeometry*, *SpaceBoundary* and *Surface*. The software tools that generate gbXML do not always use all three in order to retrieve geometry. The majority of them applies ShellGeometry and SpaceBoundary *since in combination they represent geometry more accurately*. Some of them use only the Surface element to obtain the geometrical information. [22]

3.3.3 Interoperability and comparison of results using IFC and gbXML

The study of the colleagues from the Technical University of Vienna from the *Department of building science and building ecology* started the *process of generating, extracting, transforming* and *simulating building geometry for the purpose of BPA* defined by a set of actions to achieve a successful workflow. The individual operations were executed in sequential steps to design a workflow that provides a comparison data exchange formats in various stages of use. The scheme of the experiment is displayed in Figure 13. It starts with the creation of case study model in Revit/ArchiCAD, in both programs the building elements and spaces are identical. This is followed by the export via the IFC, resp. gbXML format. Afterwards the files were imported in the BPA tool – DesignBuilder resp. SBT-1. These tools create IDF-files that are eventually imported to EnergyPlus for simulation.

All the designed scenarios were simulated in EnergyPlus via a manual data input for the creation of reference models, followed by a comparison of the results. The data was analyzed and compared at certain levels with the original files to check the effects of the conversion, in case they occurred. [22]

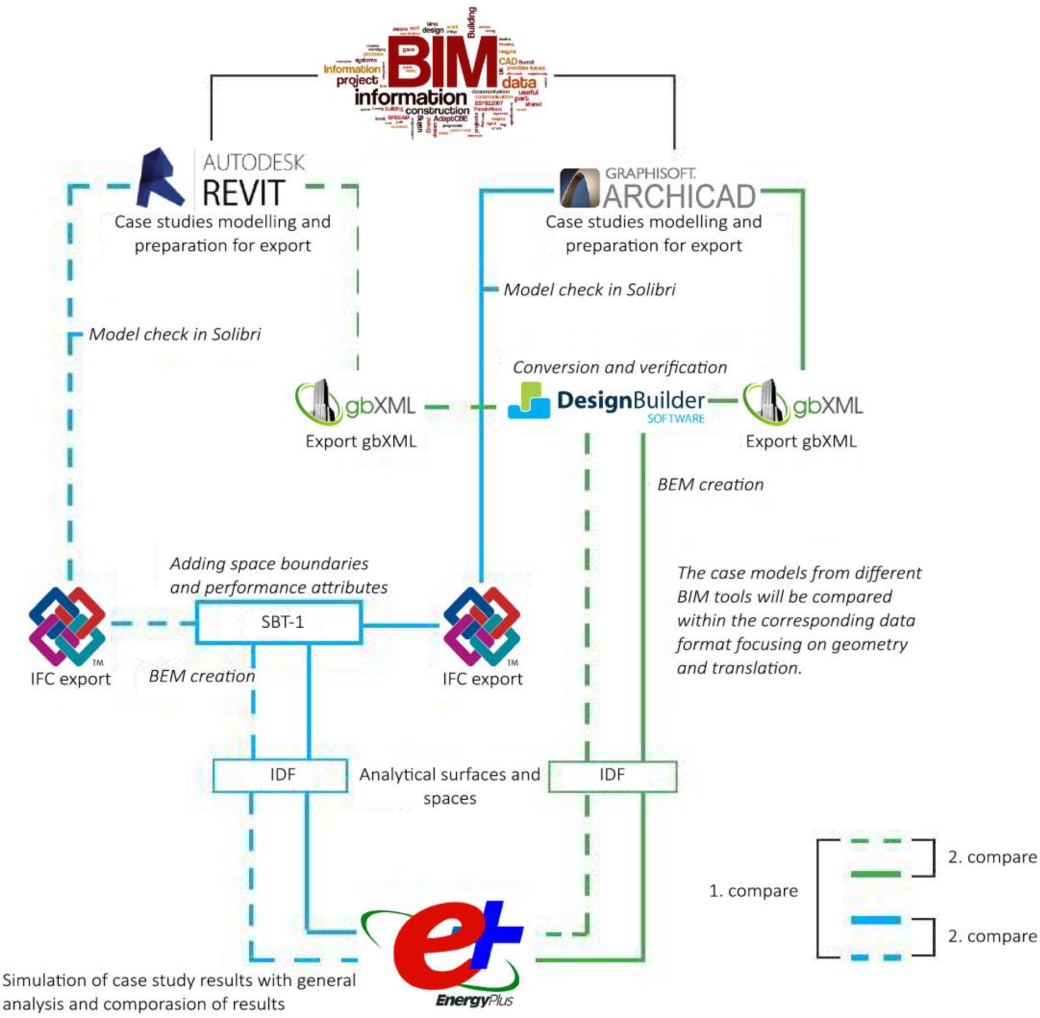

Figure 13: Two different workflows to transfer BIM data to BPS [22]

Results and conclusion of the study

The study found during the process of evaluation and comparison that both formats, IFC and gbXML, are capable of extracting and transferring spatial and geometrical information from BIM models for the purpose of BPA. Of course a *successful data export is strongly related to the quality of the building model, generated in a BIM-authoring tool.* [22]

To be able to sustain the quality of the exported resp. imported data, the analysis highly depends on the software that converts and prepares the information for the input into the tool EnergyPlus. The study focused specifically on 10 various cases of elements that reported the most errors by conversions. The results are shown in Tables 4 and 5.

Extracted building data	gbXML		IFC	
	ArchiCAD	Revit	ArchiCAD	Revit
Case 1 – Simple geometry	✓	✓	✓	✓
Case 2 – Virtual boundary	✓	✓	✓	✓
Case 3 – Column	✓	✓	✓	✓
Case 4 – Window	✓	✓	✓	✓
Case 5 – Window and door	✗	✓	✓	✓
Case 6 – Overhang	✓	✗	✓	✓
Case 7 – Terrace	✓	✓	✓	✓
Case 8 – Unheated space	✗	✓	✓	✓
Case 9 – Pitched roof	✓	✓	✗	✓
Case 10 – Sloped roof	✗	✓	✓	✓
Measured accuracy	70%	90%	90%	100%

Table 4: Comparison of extracted IFC and gbXML data (cross-marks represent the extraction failures) [22]

BIM generated building data	gbXML		IFC	
	ArchiCAD	Revit	ArchiCAD	Revit
Case 1 – Simple geometry	✓	✓	✓	✓
Case 2 – Virtual boundary	✗	✗	✓	✓
Case 3 – Column	✓	✓	✓	✗
Case 4 – Window	✓	✓	✗	✓
Case 5 – Window and door	✗	✓	✗	✓
Case 6 – Overhang	✓	✗	✗	✓
Case 7 – Terrace	✓	✓	✗	✓
Case 8 – Unheated space	✗	✓	✗	✓
Case 9 – Pitched roof	✗	✗	✗	✓
Case 10 – Sloped roof	✗	✗	✗	✓
Measured accuracy	70%	90%	90%	100%

Table 5: Comparison of processed IFC and gbXML data (cross marks represent the transfer failures) [22]

Looking at the default scheme, *gbXML stores building geometry in a pre-defined structure, which does not preserve the integrity of the geometric model*. *Its primary function is to facilitate work between BIM and building performance analysis.* This format gained preference in this field thanks to the positive experience. Users recommend to focus in future on creating *a more reliable and robust data format*. The format IFC was developed to fulfil the needs of the AEC industry to enable the exchange between the individual disciplines of BIM. IFC is an open data format that proved its ability to *capture the needed building geometry for conducting building performance analysis*. *More efforts could be invested by energy software vendors to use this format, given its promising way of storing and translating data.* [22]

Both tested formats, i.e. gbXML and IFC, showed in the particular performance studies that they need pre-processing tools for further analysis. As an example, DesignBuilder is used for the gbXML data conversion and IDF export and it is equipped with *an integrated platform for energy analysis with BIM and EnergyPlus*. However, to be able to perform analyses of this kind it needs a certain level of expertise. And in the second case unfortunately, the SBT-1 tool for IFC that enables simplification of geometry has not been further developed, despite its potential to convert complex geometry. *Currently the development is disrupted.*

In both cases, the processes were considered by the authors to be *tedious and rather time consuming*. They also intonate, that for *the whole process, applied tools and technical specifications* the users need to have a certain level of knowledge. In my opinion, this study displays in a nice and understandable way a good example of a comparison of the most common data exchange approaches for energy analysis with recommendations for development. The complete and detailed graphic representation of the comparison made by the team can be found in Figure 14. [22]

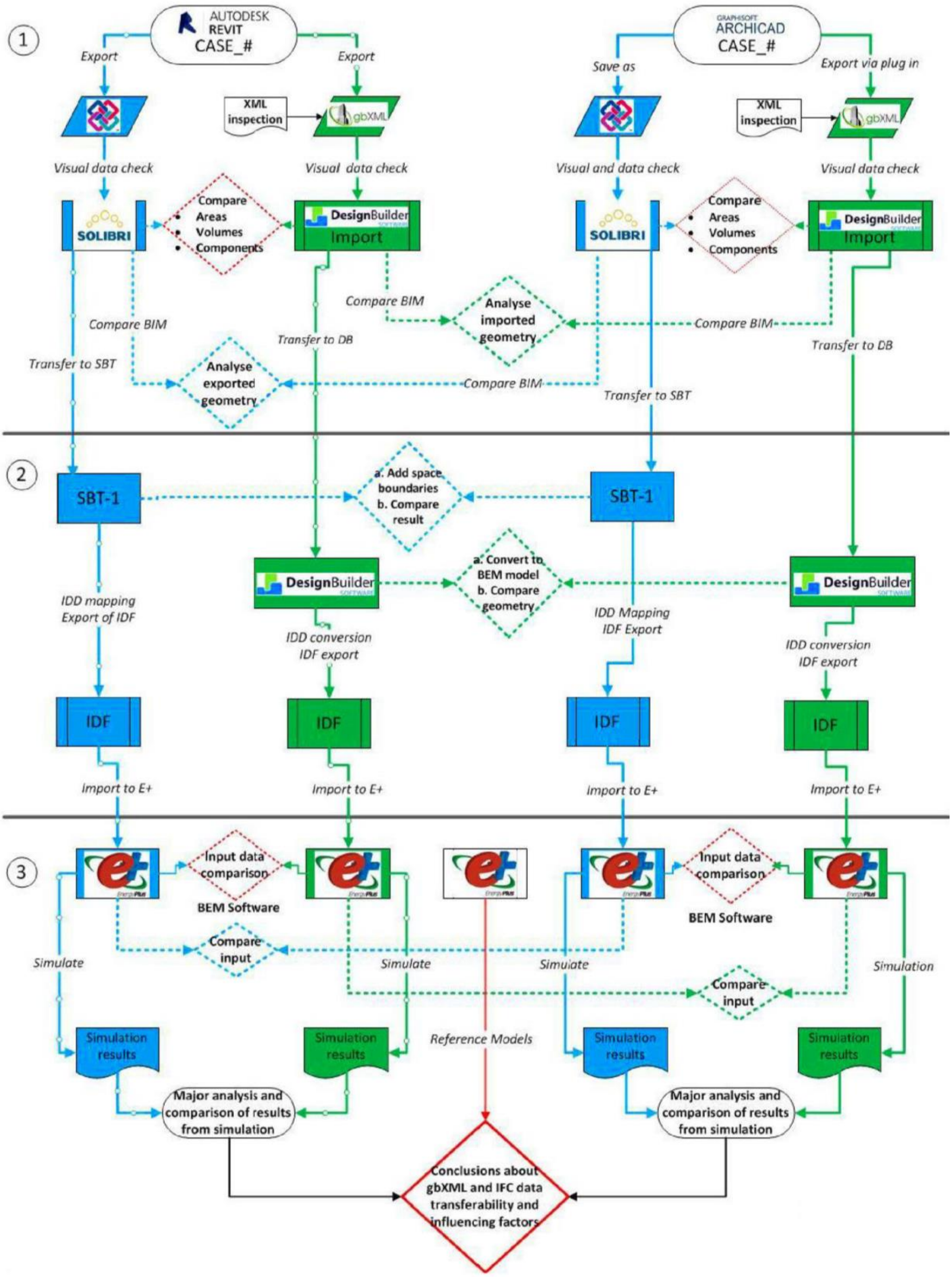

Figure 14: Detailed diagram of the tested approaches [22]

3.4 Levels of definition / detail / development

The Level of Development (LOD) represents an important aspect when it comes e.g. to the information delivery to stakeholders, where it is more appreciated to deliver accuracy of geometry recognizable by an official international standard. The LOD also has *The more reliable the digital information becomes, the more this information will be re-used not recreated, so saving time and money while increasing accuracy. Incomplete information in the process leads to miscommunications, assumptions and rework that adds costs and delays to projects.* [36]

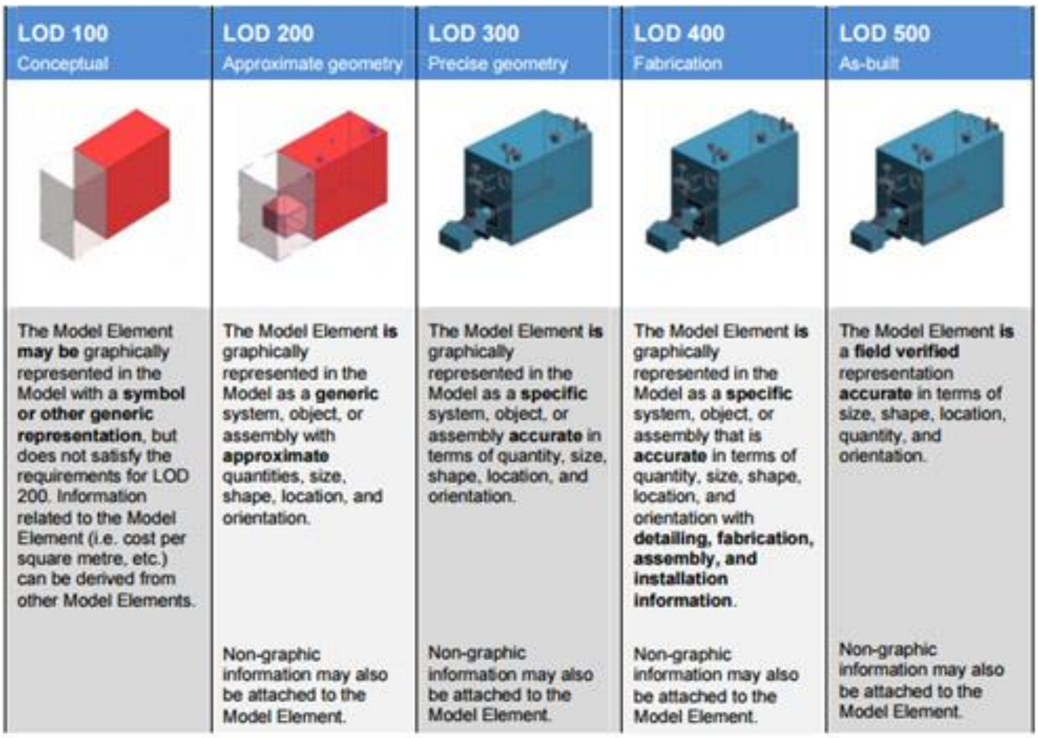

Figure 15: Levels of development in BIM [15]

Figure 15 shows an overview of the existing definitions of the LOD. These definitions may be also set as minimum requirements by projects depending on their stage, from conceptual to highly specified projects. The LODs are also cumulative, that means that each level includes fulfillment of all requirements of all lower levels. This brings a lot of clarity for the engineers and users in terms of precision of the modelled building.

Here I want to clarify that the correct term and meaning of LOD in relation to BIM is *Level of Development*. The abbreviation is sometimes also interpreted as *Level of Definition* or *Level of Detail.* There are differences though. According to the BIMForum in the U.S., *Level of Detail is essentially how much detail is included in the model element,* while the *Level of Development is a degree to which the element's geometry and attached information has been thought through.* This basically means, that the *Level of Detail* can be defined as input to elements, whereas the *Level of Development* is already an reliable output. [41]

3.5 EnergyPlus

EnergyPlus is a program for processing whole building energy simulations that *engineers, architects, and researchers use to model both* energy consumption (for heating, cooling, ventilation, lighting and plug and process loads) and *water use in buildings*. A few of the most relevant features and capabilities of EnergyPlus are listed here:

- Integrated, simultaneous solution *of thermal zones conditions and HVAC system response* without the assumption of the HVAC system meeting cooling and heating loads or simulating *un-conditioned and under-conditioned spaces*;
- Heat balance-based solution *of radiant and convective effects*, which produce *surface temperatures, thermal comfort and condensation calculations*;
- Sub-hourly, user-definable time steps *for interaction between thermal zones and the environment with automatically varied time steps for interactions between thermal zones and HVAC systems*. These elements enable EnergyPlus the modelling of systems with fast dynamics *while also trading off simulation speed for precision*;
- Combined heat and mass transfer model *that accounts for air movement between zones*;
- Advanced fenestration models including controllable window blinds, electrochromic glazings, and layer-by-layer heat balances that calculate solar energy absorbed by window panes;
- Illuminance and glare calculations *for reporting visual comfort and driving lighting controls*;
- Component-based HVAC *that supports both standard and novel system configurations*;
- A large number of built-in HVAC *and lighting control strategies and an extensible runtime scripting system for user-defined control*;
- Functional Mockup Interface import and export *for co-simulation with other engines*;
- Standard summary and detailed output reports but also *user definable reports with selectable time-resolution* (from annual to sub-hourly, all with energy source multipliers). [37]

EnergyPlus is a *console-based program that reads input and writes output to text files*. It uses various support tools such as IDF-Editor to generate input data *using a simple spreadsheet-like interface*, EP-Launch to manage input and output data and to perform serial simulations. It also works with EP-Compare to compare the results of two or more simulations graphically. There are also several extensive graphical interfaces for EnergyPlus available. DOE works with EnergyPlus the most, using the *OpenStudio software development kit and suite of applications*. [37]

3.6 Implementation of BIM in the Czech Republic

The BIM method started to be widely discussed in the Czech Republic in 2011. The impetus was the activities of innovative project developers who saw their development in the 3D area but at that time without any further over-use of data throughout the building's life cycle. There has not been much information about the transfer of BIM data and its meaning.

At present, there are already designs of buildings that are reported to have been processed using the BIM method. An interesting feature was the awarding of a special BIM prize for the Construction of the Year 2016 competition. In most cases, however, it was a partial use of BIM only for separate stages of the construction process. Moreover, given the fact that national standards are not defined, participants in each project have to agree on their own terms, which is in many cases above their professional and time possibilities. Data sets are created that have a different content and data structure and which are problematic in the later stages of the project. As of 2012, the ISO and CEN technical standards for the BIM method are gradually being adopted (see chapter 5.8), but they need to be developed for their application as well. to process their continuity with current practice.

In common practice, BIM modeling is most often found in architectural and building solutions for building documentation, partly in static calculations, with most of these being inputs from the building section. Similar results are for the part of TZB, where designers are better able to use outputs in the form of a BIM model (3D) for their designs as input and possibly provide back their 3D outputs for coordination. For these professions, however, this situation is very rare, especially because the habits and standards for 2D DOC documentation differ from the concept in the BIM method.

For the construction phase, some construction companies have come to the benefits that provide them with sufficient information from the previous stages. The main ones are:

- Preventing collisions on site, collision detection already at design stage;
- The possibility of planning the construction process and more accurate planning of the required material at a given time and amount;
- possibility to use prefabrication;
- the possibility of using automation;
- more precise control of work and quality.

There is a lack of better use of information in the downstream stages of the lifecycle for the extension of the BIM method in the Czech Republic. There is a lack of basic standards, i.e. rules and procedures, and a shift from the fragmentation of the overall process to cooperation. The solution is not only to define the basic requirements and rules, but to increase the awareness and education of all potential participants of BIM-based projects and especially those who can best utilize the resulting data. At present, the largest activity appears among the project companies; there is a lack of activity amongst the building documentation, building and construction managers. So where the BIM methodology is most beneficial.

An important issue that needs to be addressed remains the availability of BIM standards and tools for all those involved in the entire construction process. In general, standards in the form of Czech technical standards are available for a fee. Other standards created within the Concept will be publicly available free of charge. The SW tools for building the BIM model are available by a purchase. Some SW tools for viewing BIM are available free of charge as well though. [32]

4. Energy analysis of a referential building using BIM

It is time to turn knowledge into practice. This part of the thesis will introduce the referential building, prepare it for analysis and compare the differences/improvements between former and recent versions of Revit.

4.1 Initial building

The referential building is a family house in the location Hanspaulka in Prague, Czech Republic. The project was designed as subject by the candidature for the degree of Bachelor. The task required a detailed architectural study with the design with a conceptual solution of the HVAC correlating to the local engineering network and client requirements.

4.1.1 Project information

The house itself was designed as a residential villa for one family of max. 5 people with a total useful floor area of 387.99 m^2, excluding the exterior terraces. This parameter is key in the calculations, as we will see in the following chapters. The majority of the windows was designed to face the south side to achieve efficiency in solar gains. Nowadays, normally there is an obligation to design an HVAC system with recuperation in similar residential buildings (villas as this one). This case is no exception but no recuperation was added, nor a system for the humidity adjustment.

Figure 16: Front visualization of the referential building

Figure 17: View on the referential building from the street

As it is visible from Figure 17, the building uses two architectonical principles – an "double L" shape and two shifted boxes into each other. The design left the whole northern wall clean without any windows, a large window was placed above the staircase area into the roof (see section in Figure 19).

4.1.2 Floor plan description

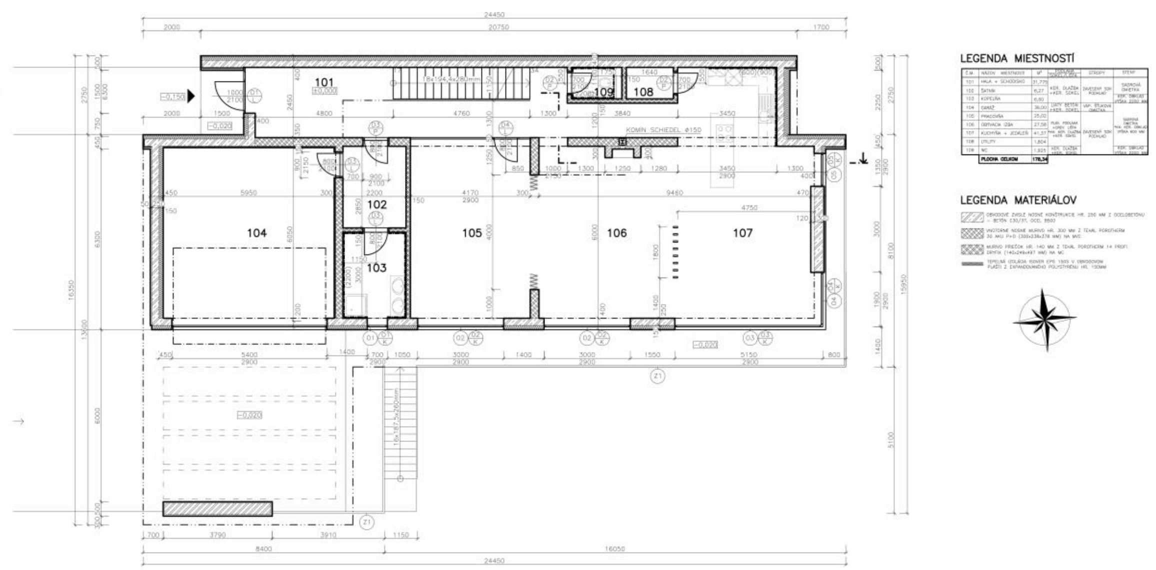

Figure 18: First floor plan

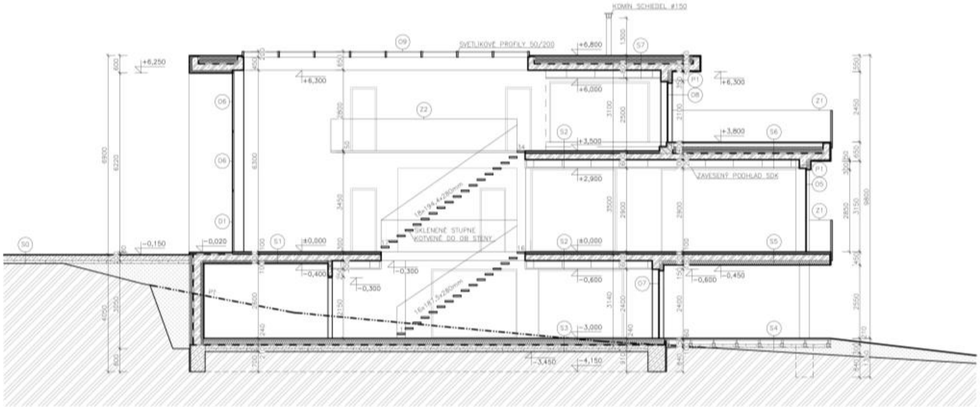

Figure 19: Section through the staircase area

A part of the thesis was the creation of a HVAC scheme to design a connection to the existing engineering network including water supply, gas, electricity and canalization. Figure 20 displays this scheme in the lowest floor of the building, where the main facilities, such as a gas boiler including a 100l water tank and central HVAC system delivering the heat throughout the whole building mostly via thermal convectors, are situated in the boiler room.

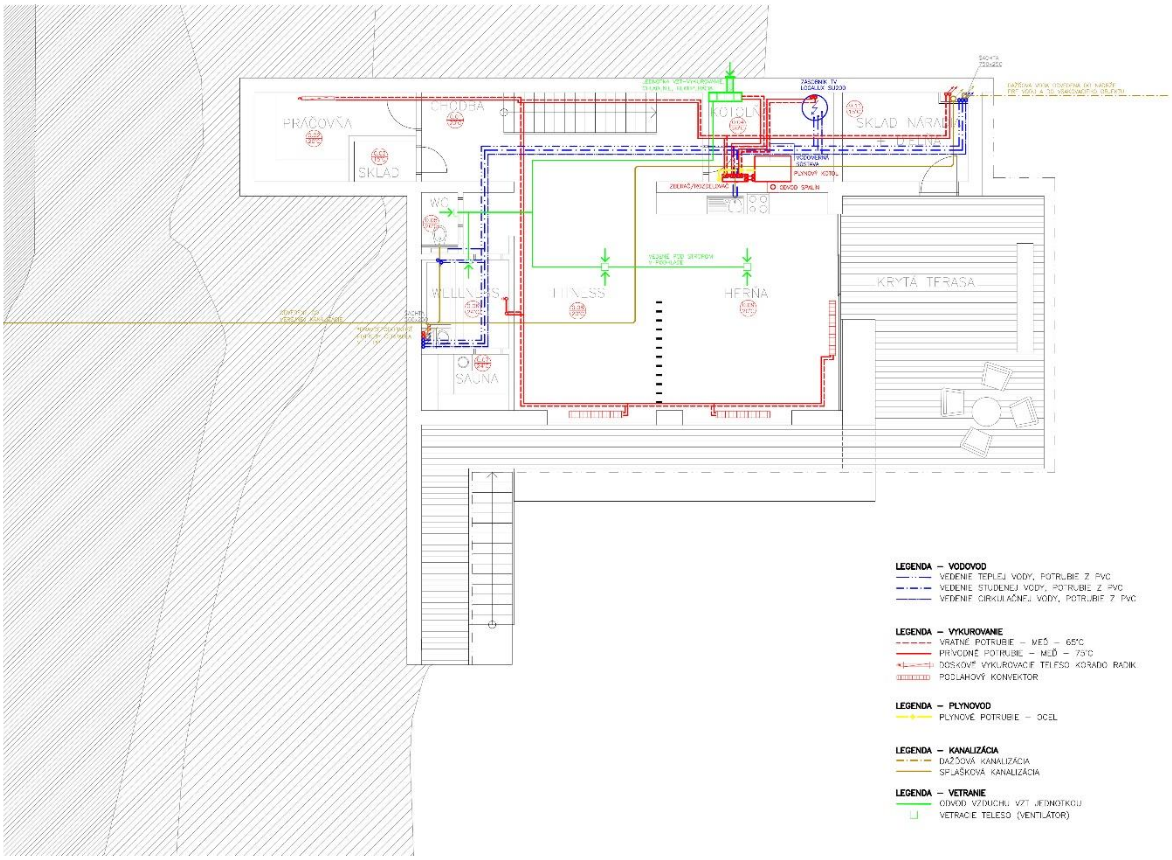

Figure 20: Scheme of the HVAC system in the lowest floor

4.2 Preparation of the BIM model

The original model was initially created in ArchiCAD 17. The first step to create an analysis in Revit was the export between the two programs. This was achieved by a simple "Save as..." procedure from ArchiCAD into the IFC format. Revit 2016 disposes with the IFC import function already – by the more recent versions, starting with 2017, it is necessary to install a plug-in. Except of a few features such as materials or library objects, the conversion redeemed the other geometry well. After doing so, it is important to set the correct heat transfer coefficients by all elements, as shown in the figures below.

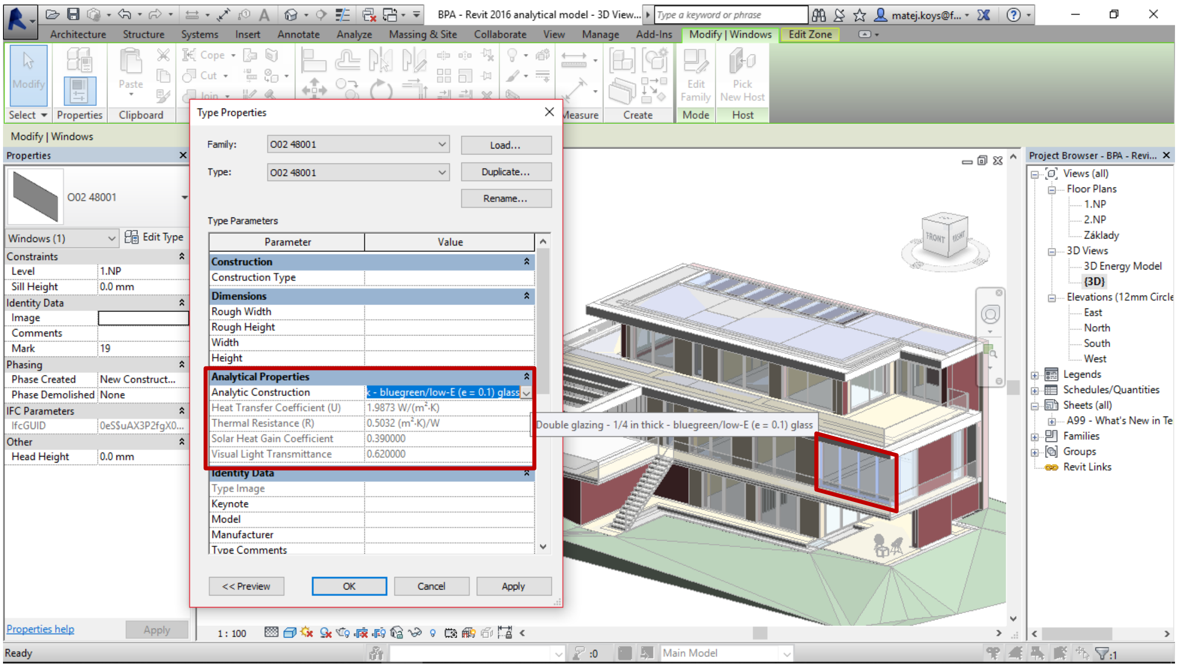

Figure 21: Adjustment of the window analytical properties (Revit 2016)

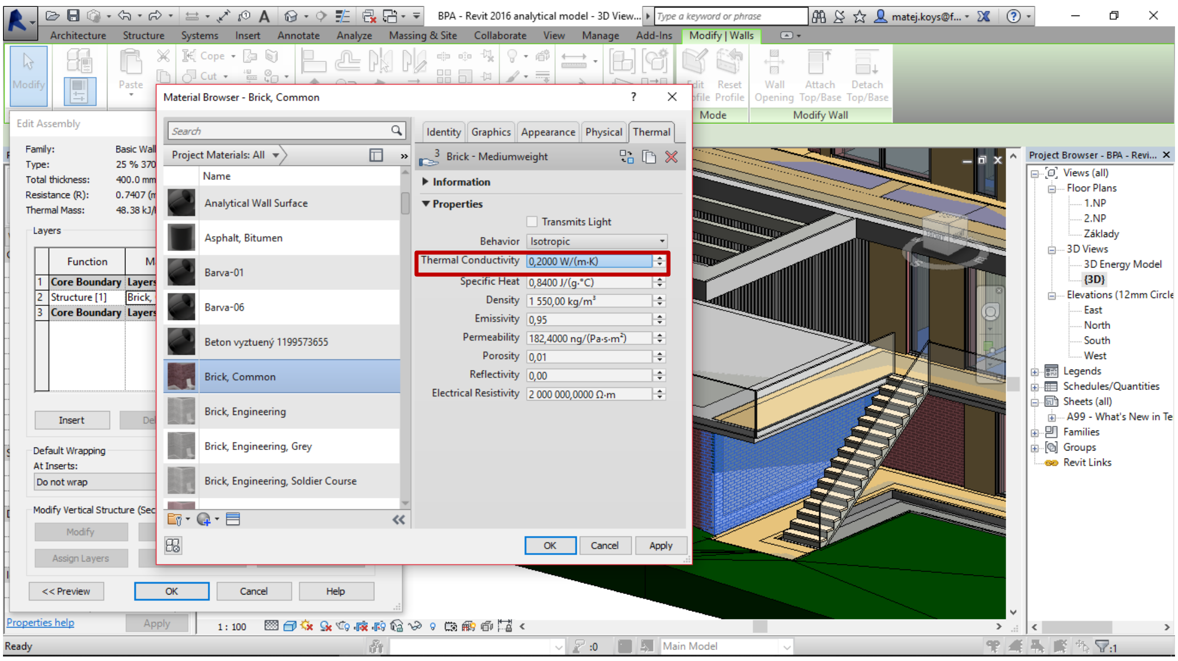

Figure 22: Adjustment of the heat transfer coefficients of the building envelope (Revit 2016)

To simplify the process of data import, the heat transfer coefficients from constructions like walls, roof or floors were pre-calculated in advance via a specialized software, where all individual layers e.g. insulation, bearing parts, surfaces etc. of these elements were included. The final coefficient was then inserted into the field of the thermal material characteristics.

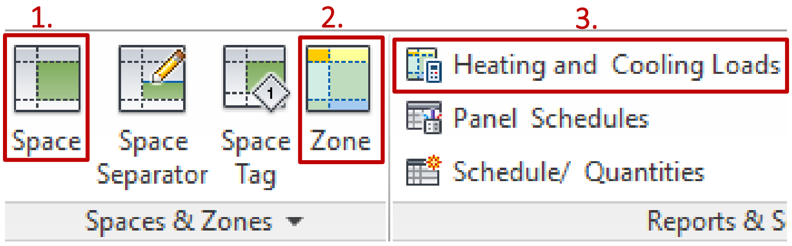

Figure 24: Tools for Space and Zones creation (+ Heating and Cooling Loads definition) (Revit 2016)

As Figure 24 already indicates, it is necessary to define the spaces of the rooms that we want to make an analysis for. For this, a very intuitive function was created for an automatic creation of these zone as shown in Figure 23. When this is done, it is possible then to create the HVAC zones (button nr. 2). The software will be then able to recognize the heated and cooled area, which is simplified by boxes. This procedure is well described in a study made by two Autodesk experts, Mr. Dzan Ta and Mr. Joe Gould. [40]

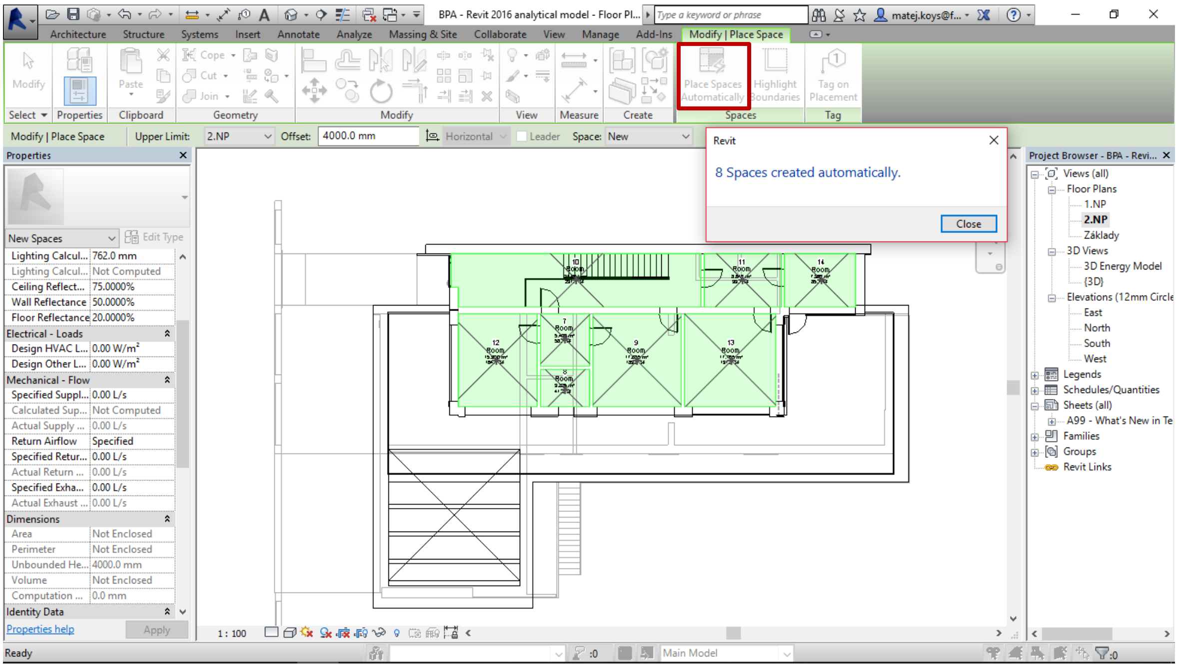

Figure 23: Auto-creation of spaces (Revit 2016)

Unfortunately I discovered the first difficulties or insufficiencies by the creation. As the legal obligation in the Czech republic states under Decree No. 78/2013 Coll., it is necessary to calculate the envelope heat transmission based on the floor area taken from the outer dimensions of the floors, which means including the whole circumferential constructions.

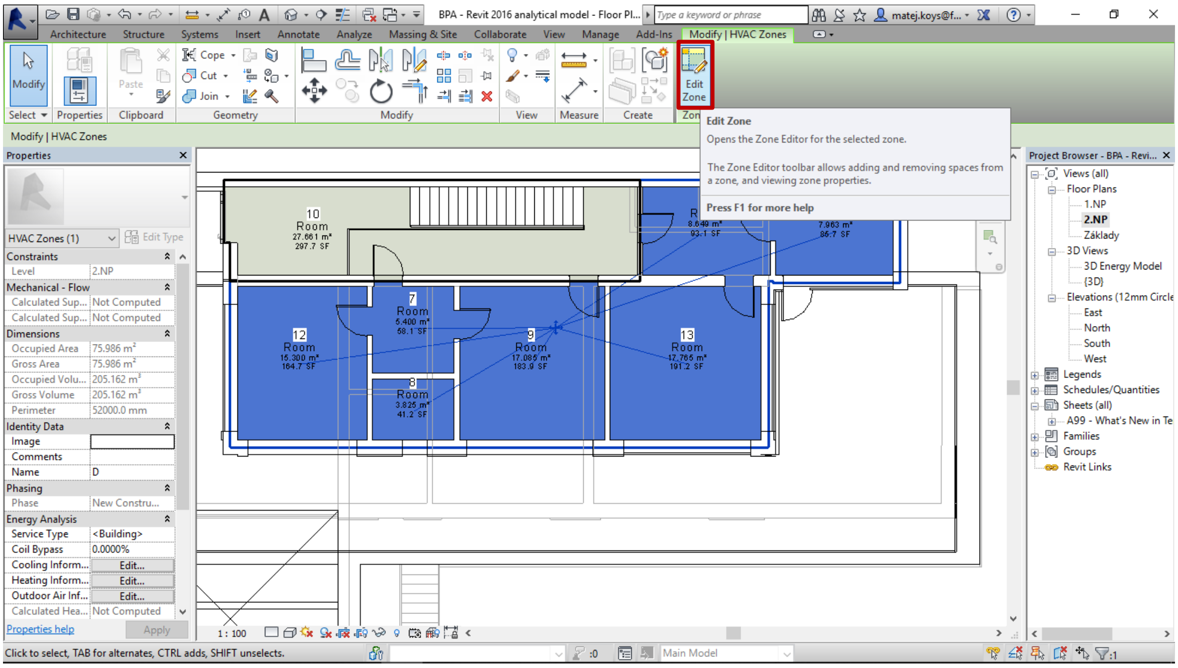

Figure 24: Adjustment of the zone (Revit 2016)

As illustrated in Figure 24, the zone (colored blue) is not accurate and has to be shifted to the outer edges of the constructions to get the correct floor area. As it was mentioned on the beginning of this chapter, the floor area excluding the constructions is 387.99 m^2. According to the project documentation, the floor area including the circumferential walls should be 482.70 m^2. But as Figure 25 shows, it is not possible to adjust these areas in this version of Revit. This alone causes already huge differences in the future calculations and makes it difficult to comply with the Czech standard. Unfortunately, the more recent version Revit 2018 did not fix this limitation by adding the respective function.

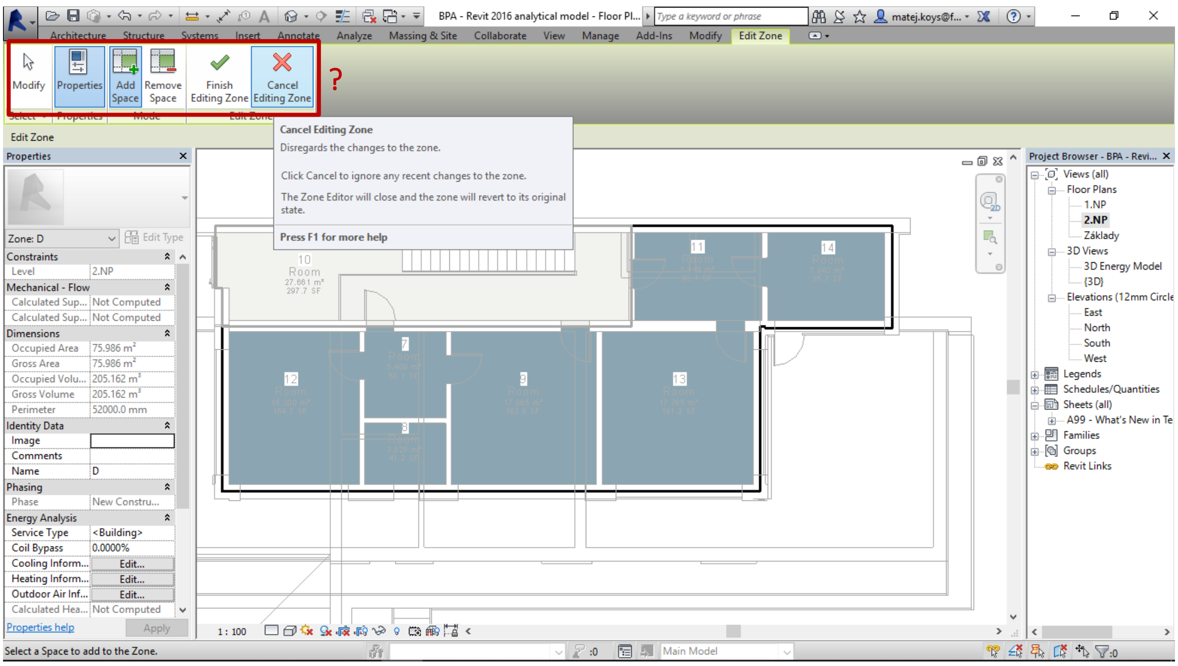

Figure 25: Adjustment of the zone – No availability for shifting the zone (Revit 2016)

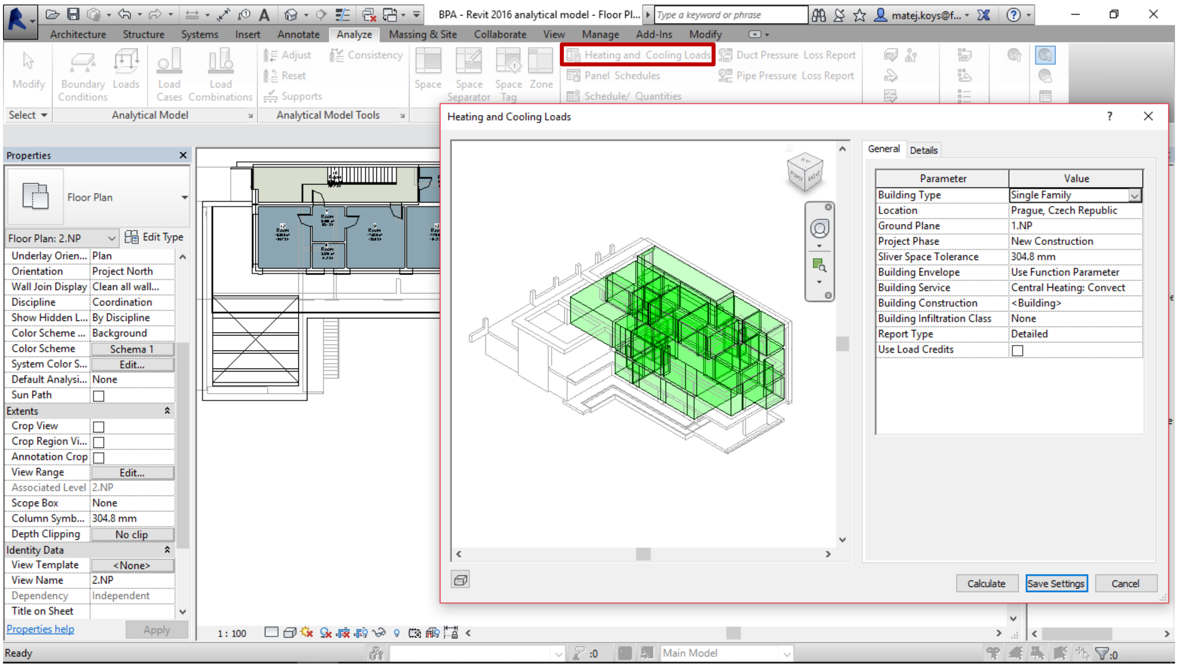

Figure 26: Definition of heating and cooling loads (Revit 2016)

In the setting of the Heating and Cooling Loads function in the task bar it is possible to adjust mainly settings as the building type (in our case "Single family"), the space tolerance (that could lead to more inaccuracies though), building infiltration class or the most important thing – Building Construction. As shown in Figure 27, it is necessary to uncheck all particular fields, where the parameters were set manually, otherwise the software works with an alternative solution. Here I saw another big example of discrepancy – predefined models only; e.g. by the windows it is not possible to pick a model with a U value lower than 1.4554 W/m²K. In the Czech republic 1.0000 W/m²K is a common thing.

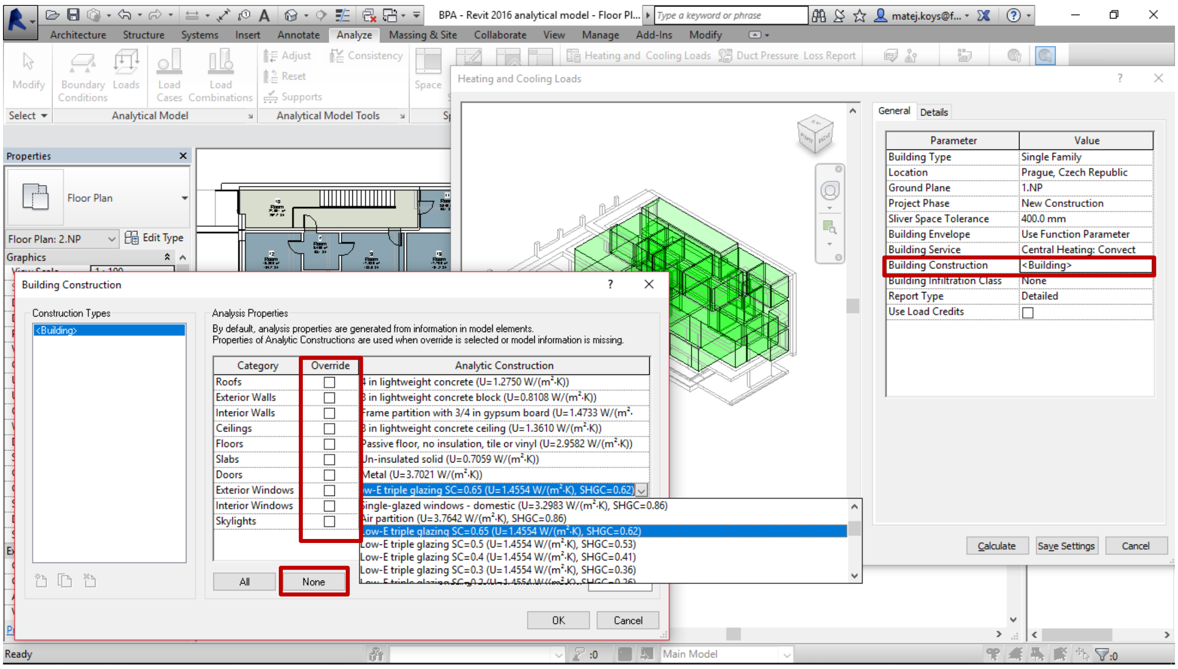

Figure 27: Building construction settings (Revit 2016)

5. Comparison of used calculation methods

This chapter analyses the results of two approaches – the selected built-in energy analysis tool in Revit designed by the Green Building Studio and the software Energie 2015, where an Energy Performance Certificate was created.

5.1 Method 1: Energy analysis in Revit

In the former versions of Revit that I checked (2016 and 2017), the analysis generates a report with illustrative graphics but most importantly – the consumption values of the corresponding heating and cooling loads. The more recent versions 2018 and 2019 both work with *Insight 360*, which does not generate reports anymore, that's the reason for choosing Revit 2016 as the main tool for the experiment.

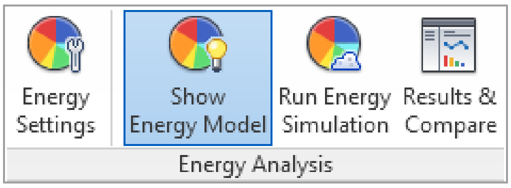

Figure 28: Energy analysis tools used in Revit 2016 or 2017

The experiment starts with accessing the basic Energy Analysis tools. The first thing to adjust here are the *Energy Settings* to prime the building with the right parameters for the simulation. By opening the option the window offers several adjustments but practically the same as shown in Figure 27 by entering the *Heating and Cooling Loads* button. Only the design of the window is different, unfortunately the most important setting options are missing here, as I will explain.

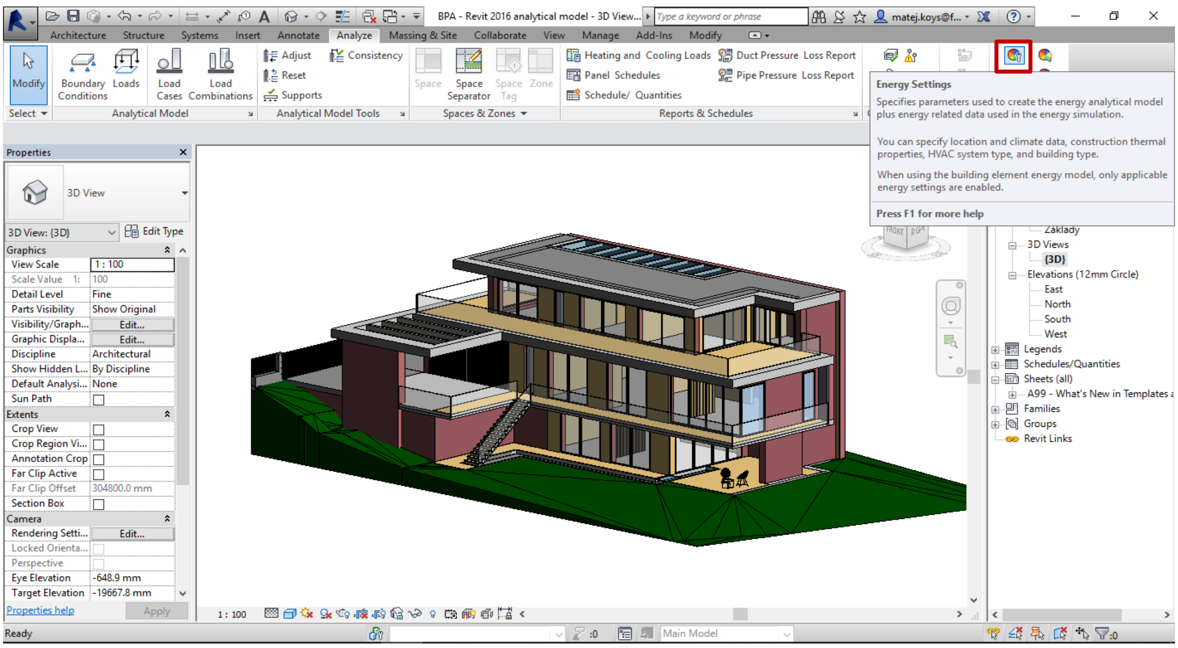

Figure 29: Energy settings (Revit 2016)

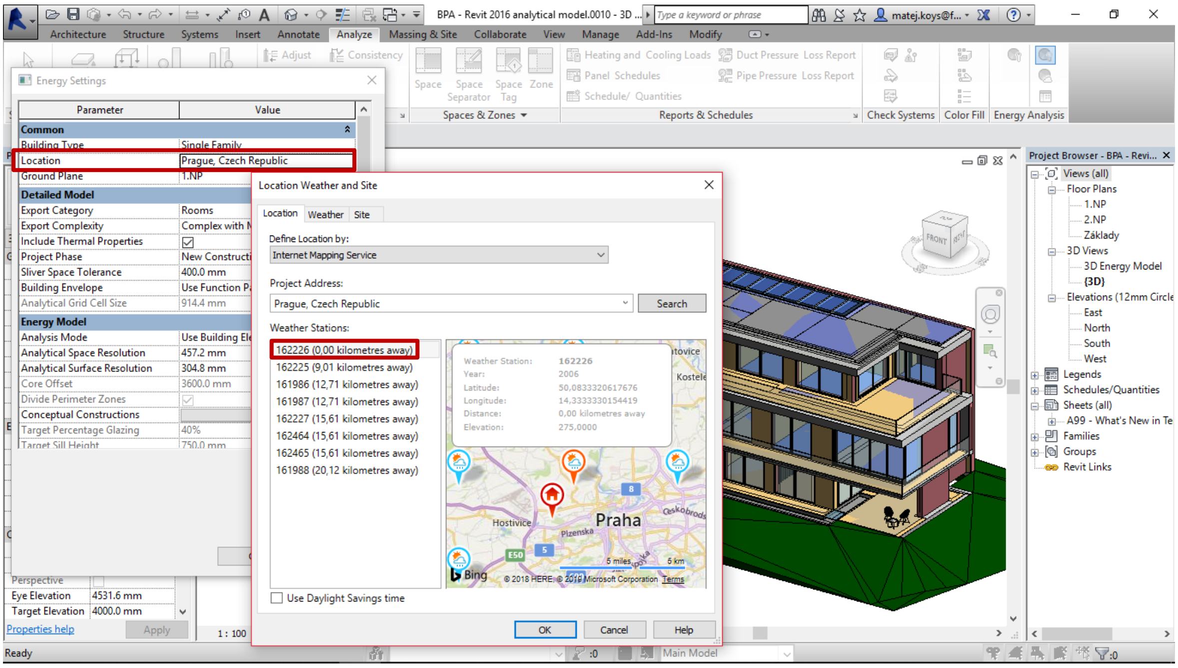

Figure 30: Location settings (Revit 2016)

The *Location* function seems to be working nice, offering data from several metheorological stations around Prague. The only disadvantage – the data is from 2006, which could have definetely been updated during 10 years. But now the most important thing – the *HVAC System* function. There is a lot to it, but not much positives. You can pick from several options and choose the system that fits the project the most. BUT: You can basically only do that and not change any data or create your own HVAC. From the description you cannot even see the the consumption in e.g. kWh/m^2, which is a key factor.

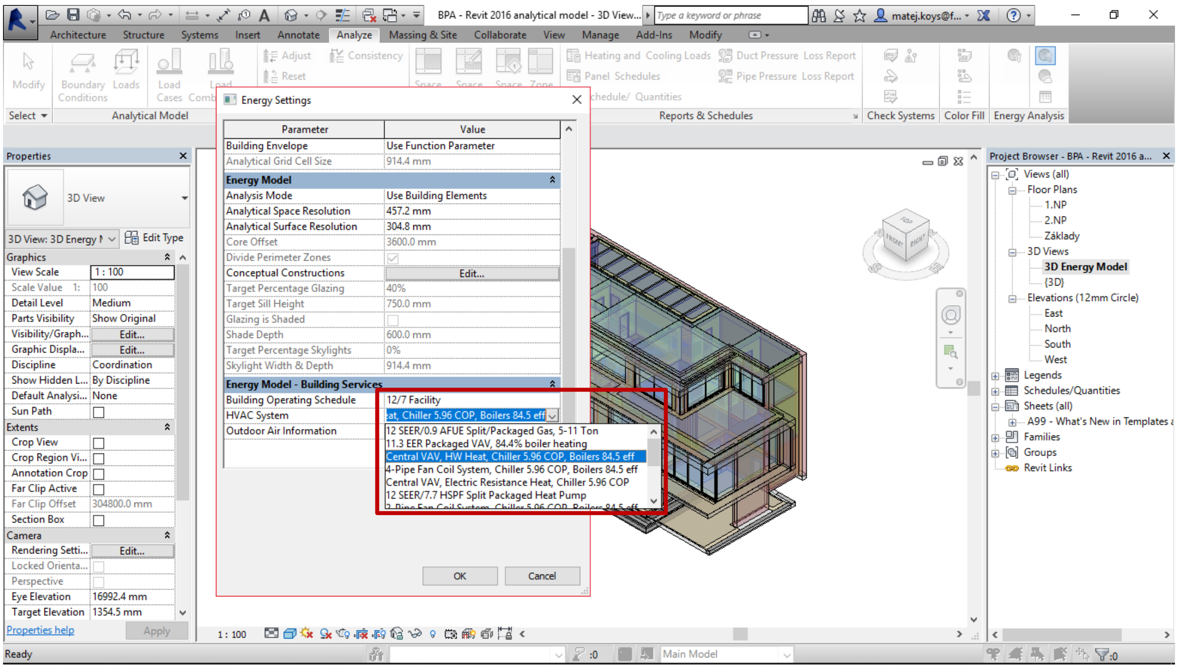

Figure 31: Selection of the HVAC system (Revit 2016)

You would have to run an analysis first and if the consumption is too high, you can choose another one and run the analysis again, but that's time consuming considering the analysis can take up to 15-20 minutes. Before I get to the analysis though, it's necessary to create an Energy Model first (see Figure 32 and 33) by a simple click on the function. This usually takes a few seconds and causes that the building zones are linked with the parameters set in the *Energy Settings* and real HVAC zones are created. This process is very intuitive as the figures below show.

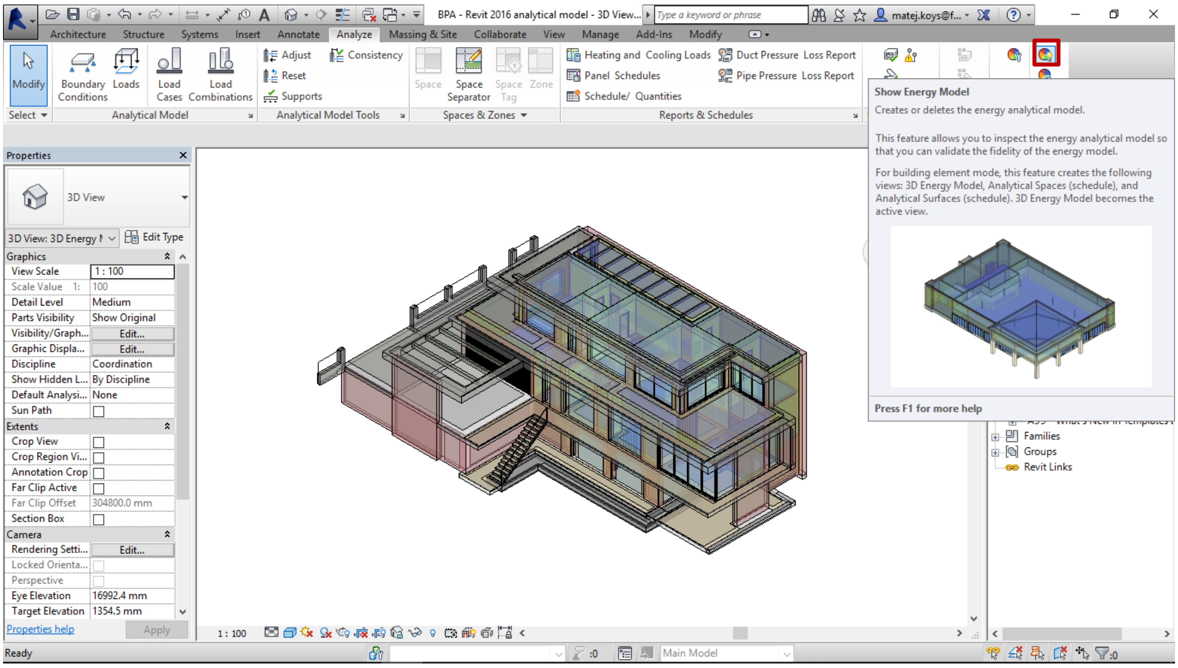

Figure 32: Creation of the Energy Model (Revit 2016)

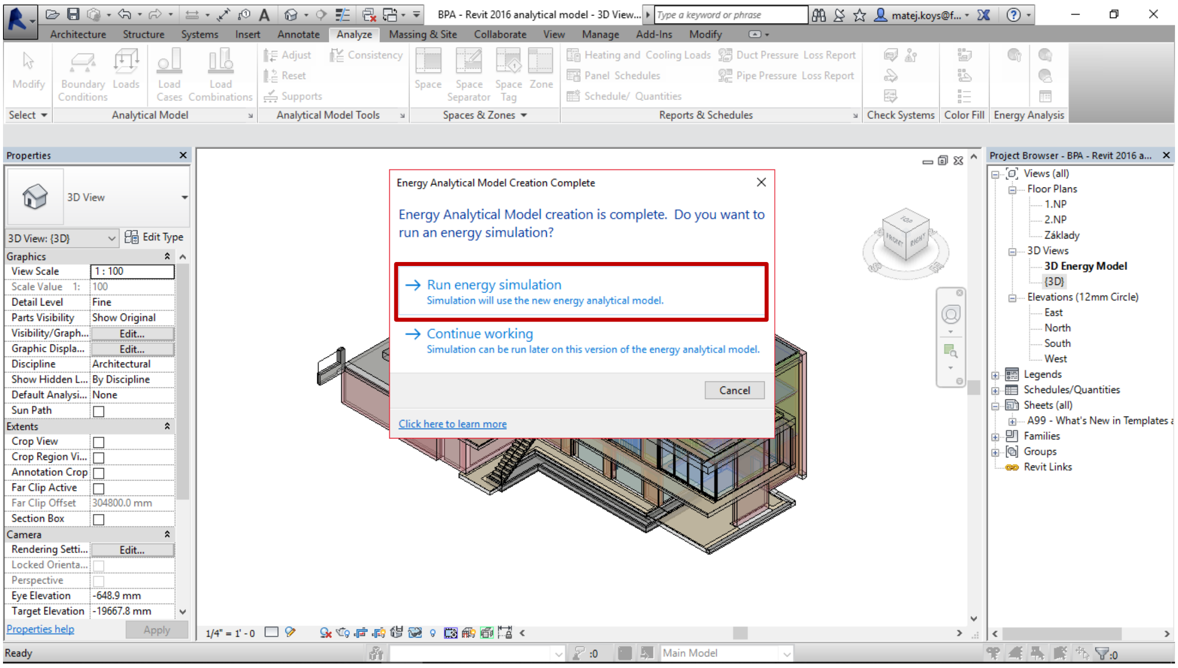

Figure 33: Running the energy simulation (Revit 2016)

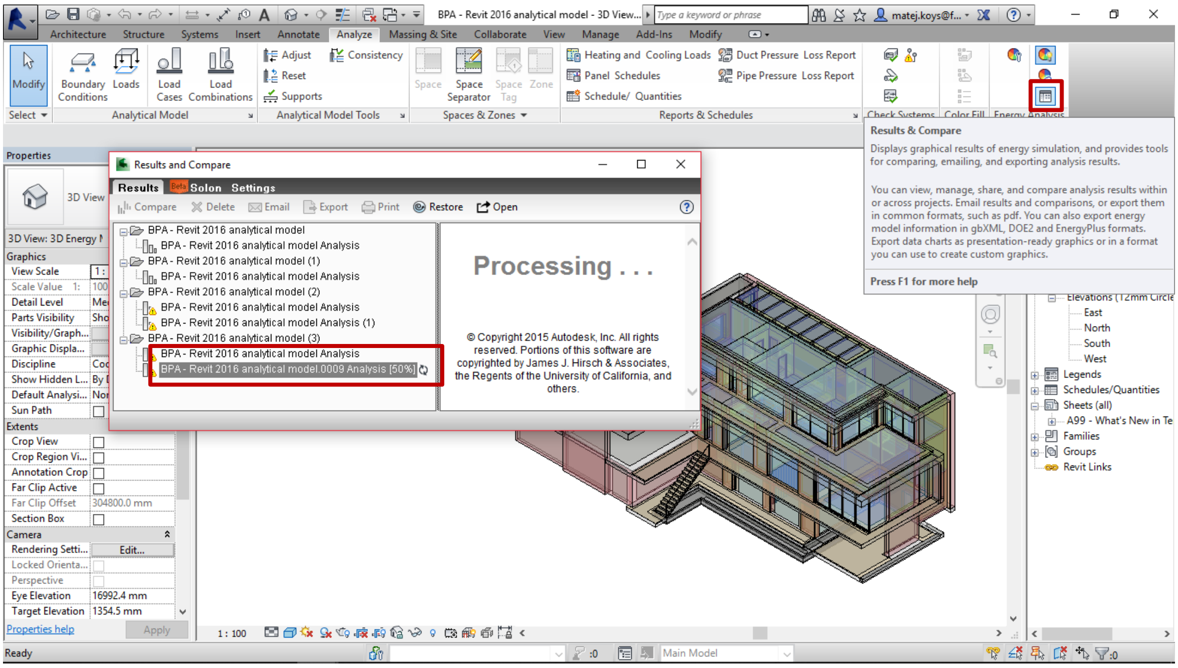

Figure 34: Generation of the results and report (Revit 2016)

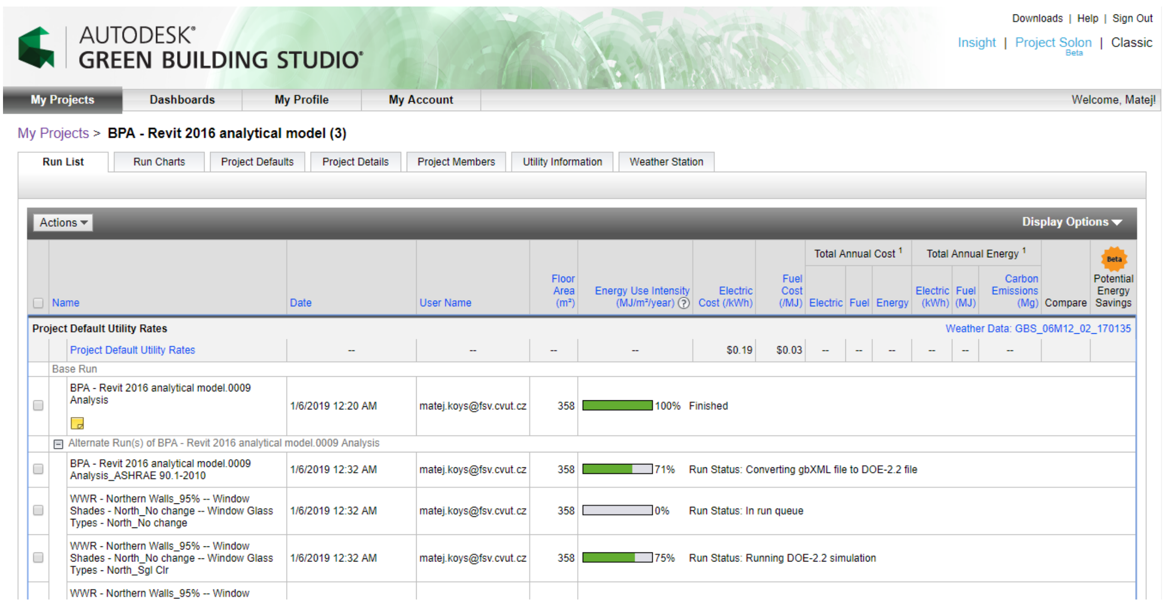

Figure 35: Linked analysis traceable by Green Building Studio

When the energy model is created, the actual analysis starts by generating the results, which takes the most time. The analysis worked smoothly only the first time when the *Building Construction* settings remained as preset. But when trying to run the analysis with own wall parameters, several error messages occurred (see in the *Results and Compare* window in Figure 34). Luckily, it was possible to run the function also via Green Building Studio, accessible through the gbXML conversion, where the walls and other manually adjusted elements were imported as well.

5.2 Method 2: Energy analysis in Energie 2015

As it will be shown on the next pages, the program Energie 2015 (developed by doc. Dr. Ing. Zbyněk Svoboda from the Czech Technical University in Prague, Department of Building Structures) represents a very detailed more sophisticated approach that offers a huge scale of settings and variables. Here I want to mention that this tool has an online accessible detailed manual [42] and due to the range of settings, only a few of the steps are mentioned in the upcoming figures. Since the creation of a new project is quite intuitive, the description starts with entering the "Entrance data" as shown in Figure 36.

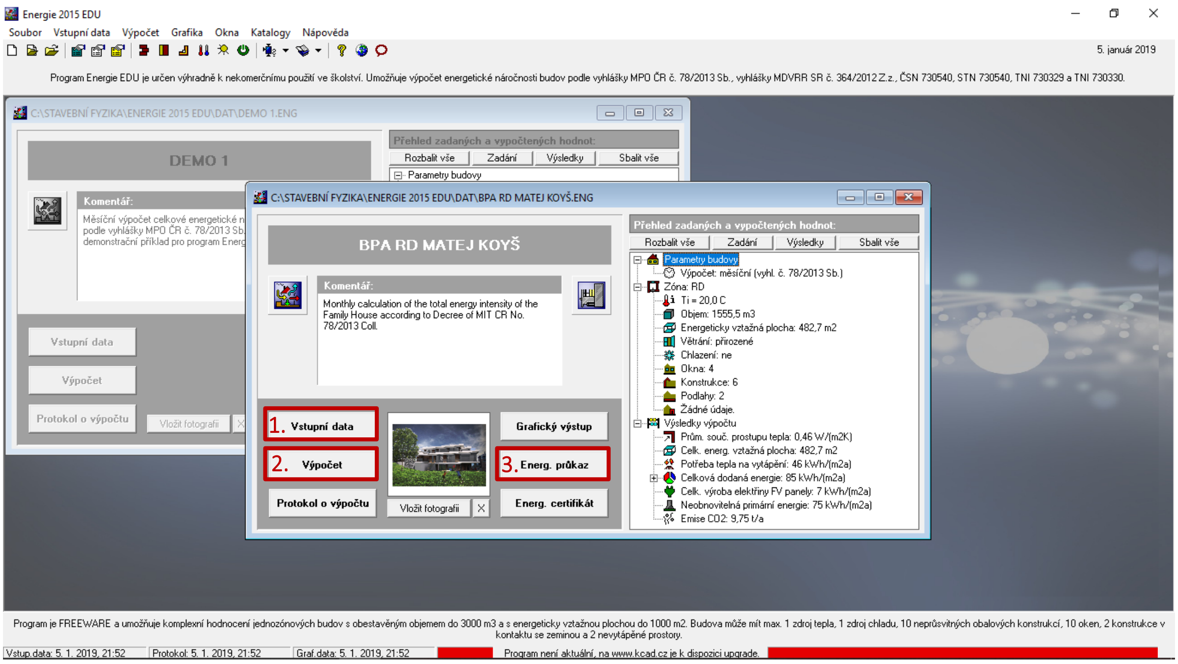

Figure 36: The Energie 2015 basic interface

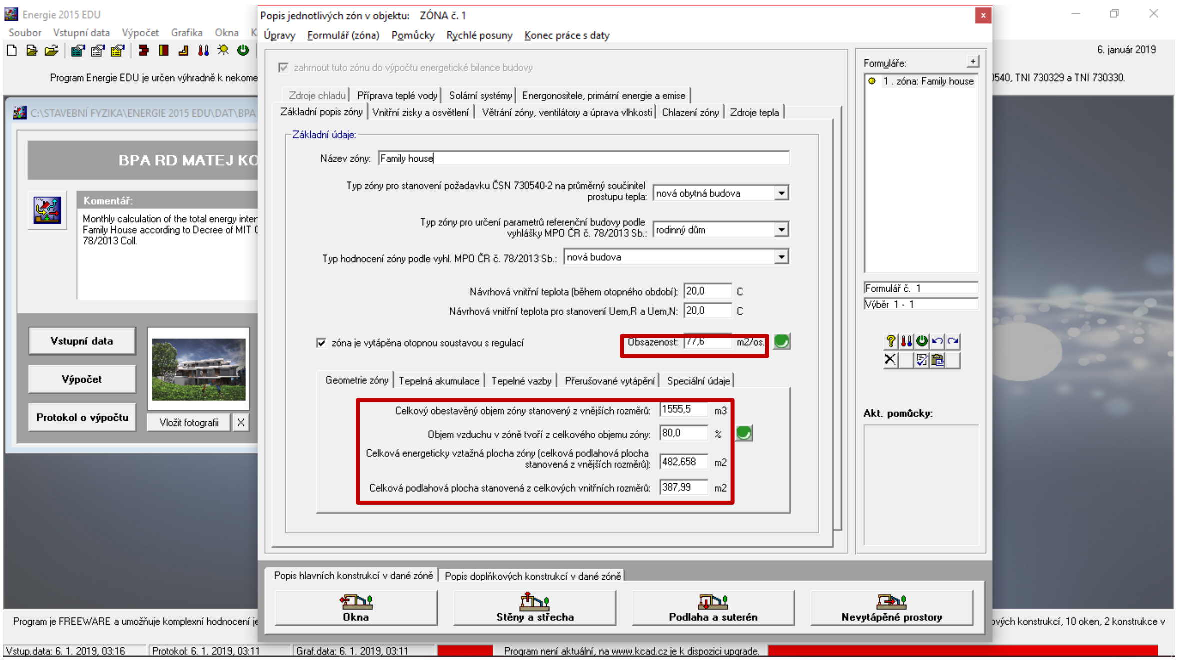

Figure 37: The "Entrance data" window (Energie 2015)

Based on the project documentation the U values for all particular constructions were calculated based on the Czech standard ČSN 730540, applying approved formulas. For quick use there are also online tools for heat transfer coefficients calculations. After obtaining these values, together with the corresponding areas they will be entered into the *"Basic construction parameters"* window. Further in Figure 39 the *"Energy carriers"* were set, in this case electricity and gas and their use within the building for particular functions, e.g. heating, hot water supply, lightning etc.

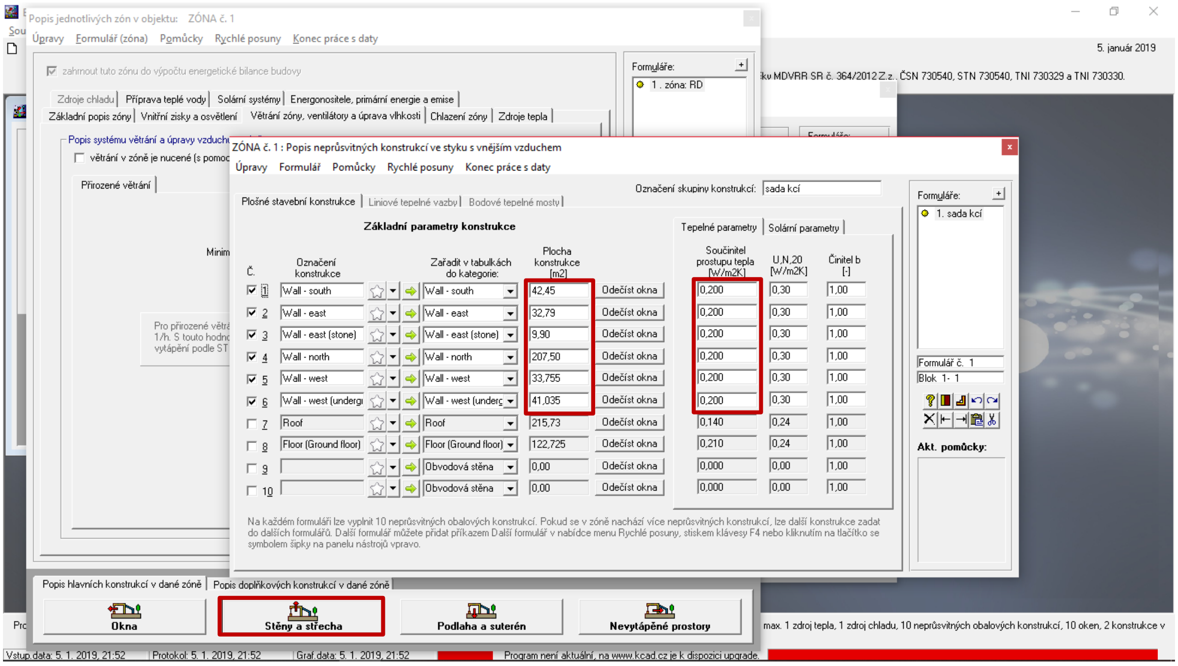

Figure 38: Basic construction parameters – Walls and roof (Energie 2015)

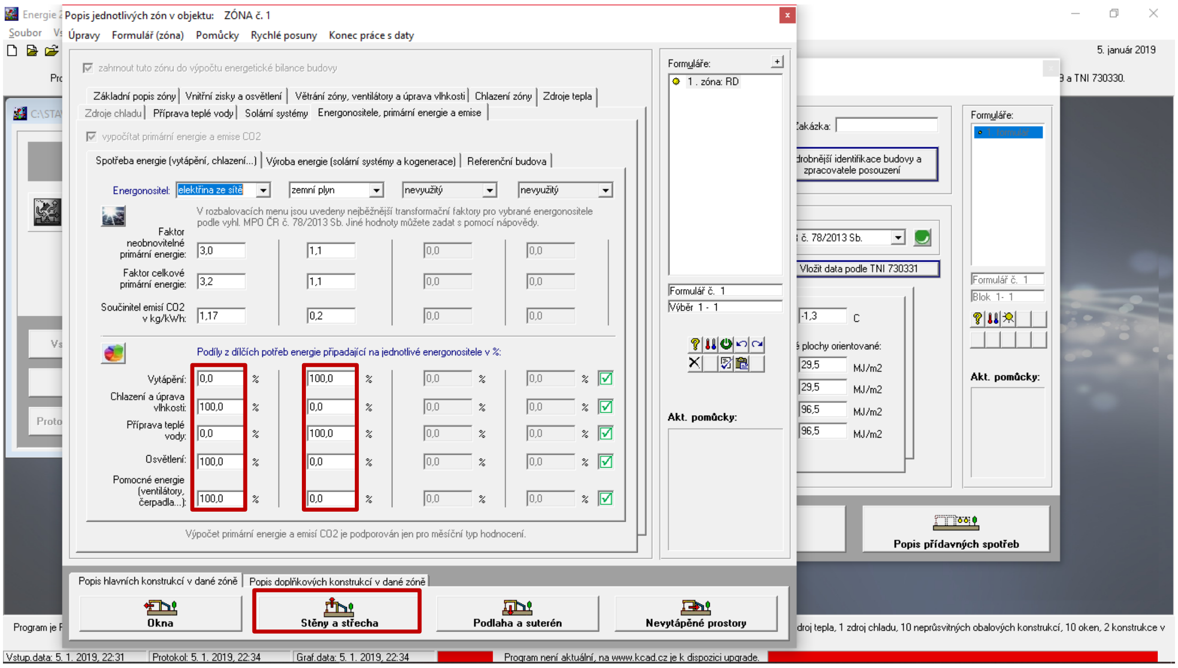

Figure 39: Energy carriers – Gas and electricity (Energie 2015)

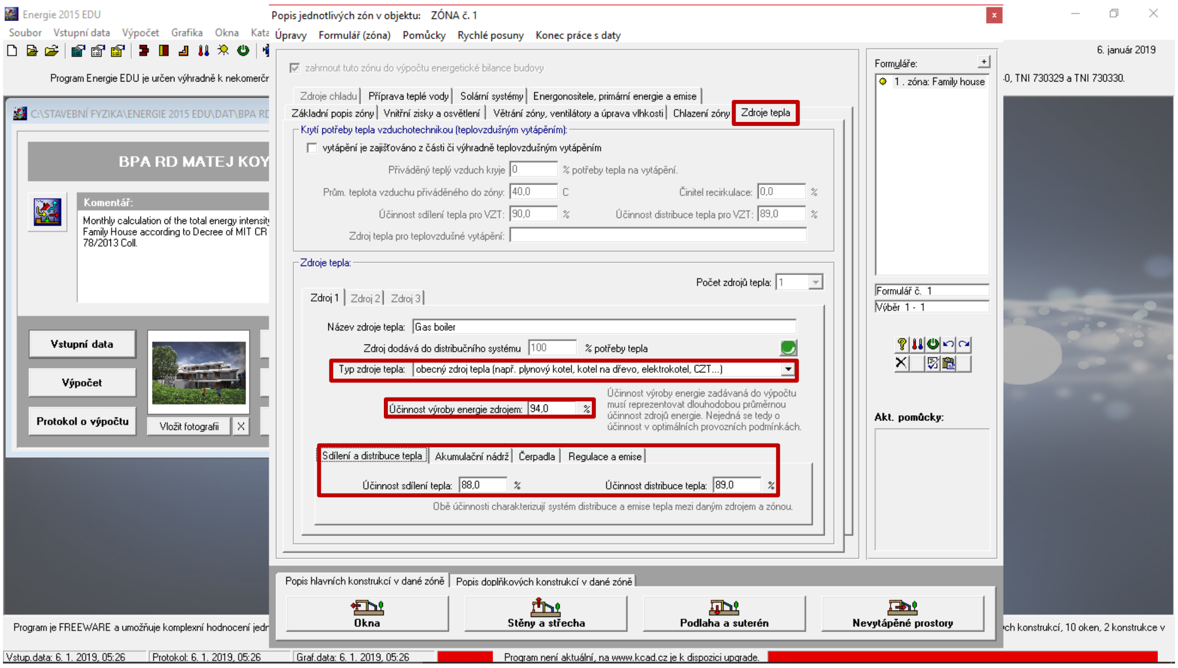

Figure 40: Setting of the heating system (Energie 2015)

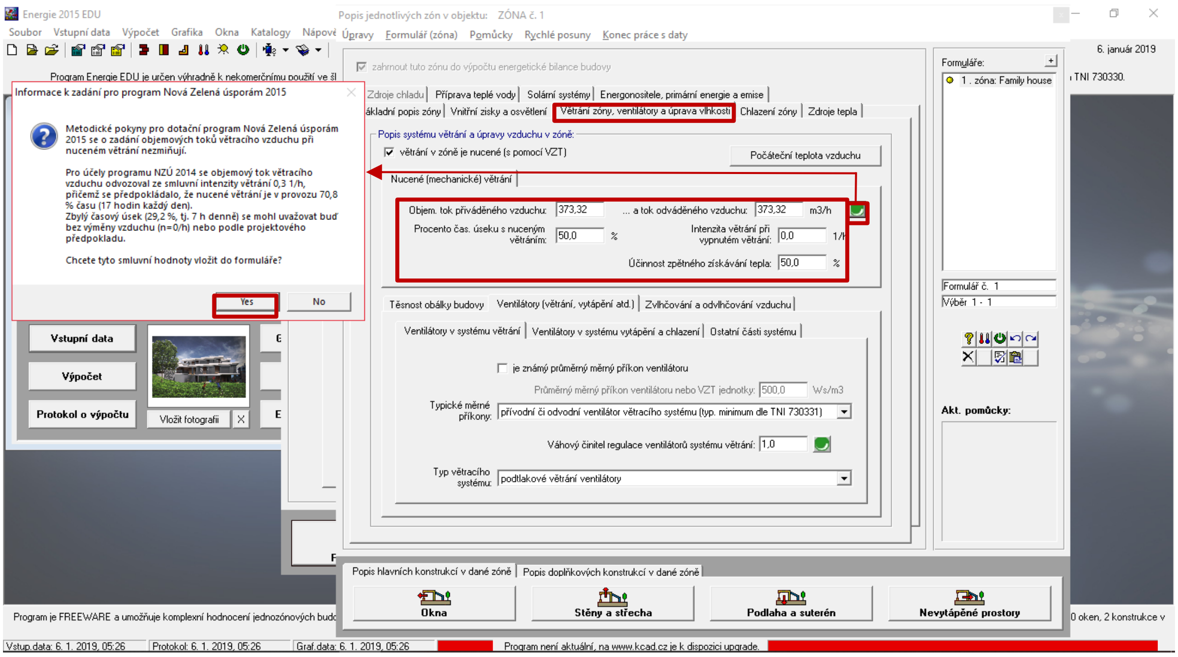

Figure 41: Selection of the ventilation system (Energie 2015)

Not to forget, the HVAC has to be set. A strong advantage here is that the particular disciplines can be set independently from each other; this allows various combinations of heating sources, air-conditioning and ventilation systems from diverse providers. By clicking on the green icons located on the right by certain categories it offers direct adjustment according to a new dotation program in the Czech republic “Nová Zelená úsporám“ (known as *New Green Savings Programme*) to achieve better standards simultaneously. A lot of other factors like windows and solar gains were set as well, the final steps nr. 2 and 3. are illustrated in Figure 36.

6. Results and optimization

At this point, both approaches performed an analysis of the referential building in two different ways and achieved various results. It is possible now to evaluate the shortcomings but also positive aspects of the tested approaches, while also comparing the outcomes.

6.1 Evaluation of the project

During the consulting of this thesis work with the architects and BIM specialists Ing. arch. Michal Egly and Ing. Petr Matyáš from the studio *di5* in Prague (cooperating also with czBIM and BIMFO), we discovered already the first potential issues and challenges in terms of accuracy and accountability of the new apparently well working built-in fast tools producing instant reports with minimum entrance data.

The idea of being able to produce results so fast interested me, but it also raised questions. When those tools are so efficient and accessible by everyone, why do architects prefer other software instead? Why did Autodesk design tools that have potential but are not used or maybe not developed enough? Since there was no similar study done so far on testing the efforts of Autodesk to make the life easier for architects and clients, I decided to tackle this challenge to create feedback.

With *di5* we also agreed to partially move the thesis also into a problematic sector of BIM, investigating the conversion of data for energy analysis using IFC and gbXML, and their impact on the model. The reason for this decision is the interoperability of BIM with diverse other BIM related programs, where conversion plays a key role in accuracy. The study of this topic became then part of the research of this workflow.

6.1.1 Method 1: Results - Autodesk Revit 2016 Energy Analysis tool

The first impression of the results was very promising, the software works with energy data such as heat transfer coefficients and location while producing detailed reports. But after looking deeper into this you will find a lot of question marks and insufficiencies from the producer, even though they had good intentions.

A few points to this are mentioned already in chapter 5.1. Key problem of this tool is the lack of possible editing and an insufficient scale of options due to the amount of PRF in RTS. When you have e.g. a certain window type you wish to use, you can basically only try to find a "match" as close as it will be possible, but this may cause huge calculation differences from the real values. The zone area cannot be shifted from the center of the wall towards the edge, which is also a big minus. But one thing had the biggest impact from all and I realized this after Mr. Egly stated to have received a value of approx. 160 kWh/m^2/year using the same tool on a different building. Interesting was that my first attempt also ended at this number. A number far away from the recent requirements.

After running several analyses, this number seems to be constant when choosing a certain HVAC system in the *Energy Settings* – after keeping the same HVAC and experimenting with other parameters, the value remained unchanged. Changing the HVAC for another one, I received even higher values of e.g. approx. 200 kWh/m^2/year. And this even after adjusting the walls manually from a heat transfer coefficient of 0.5 W/m^{2}K to only 0.2 W/m^{2}K. This is only an assumption though, since unknown errors might had occurred (software or user).

Nevertheless, the inability to adjust the HVAC efficiency percentage and performance is a huge limitation in case you want to achieve accurate, corresponding and reliable results. Examples of the results are displayed in Figures 42-44.

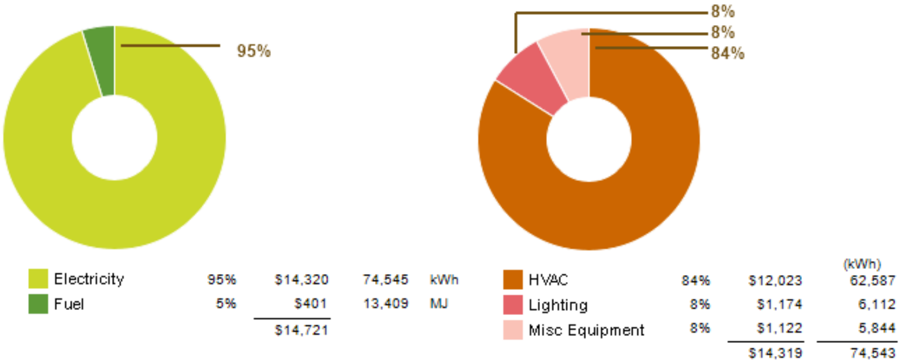

Figure 42: Annual energy use/cost (left) and electricity use (Revit 2016)

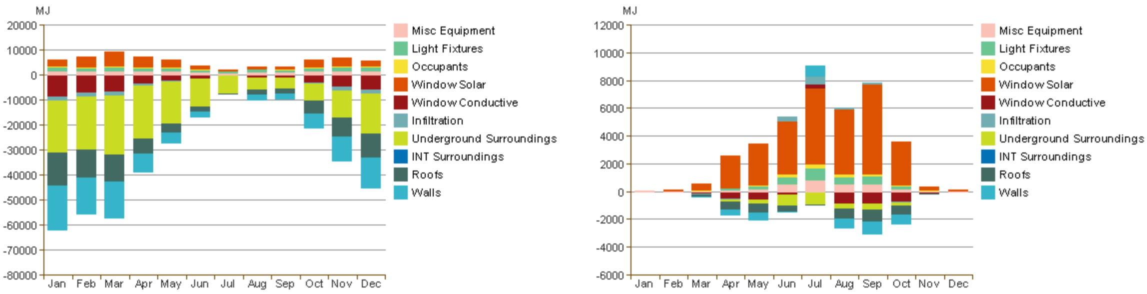

Figure 43: Monthly heating and cooling loads (Revit 2016)

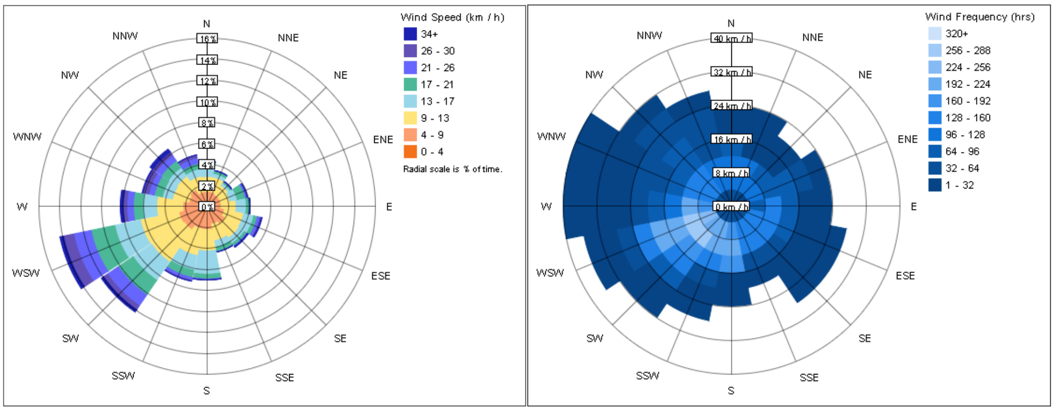

Figure 44: Annual wind rose – Speed and frequency distribution (Revit 2016)

6.1.2 Method 2: Results – Energie 2015

To this method there is not much to say. It is a very well known and tested approach used for the creation of Energy Performance Certificates. Although Energie 2015 works with high accuracy, it is still user-friendly and not very time consuming (but of course, it takes some time to study it, find the correct and suitable parameters).

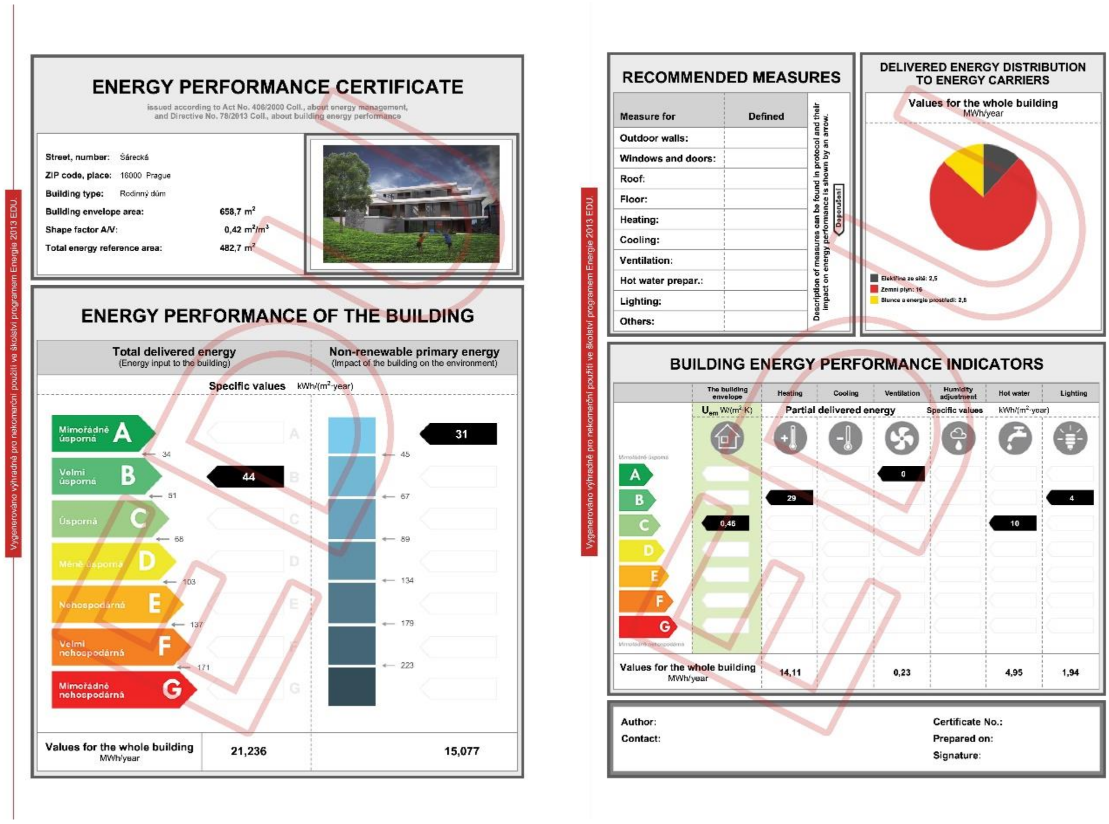

Figure 45: Energy Performance Certificate of the tested referential building (Energie 2015)

6.1.3 Summary and comparison of results

The key difference is in the calculation method. The radiant times series method uses periodic response factors (pre-calculated values) listed in a table. Due to the gaps in between of these values, there could be divergences and errors in further calculations in case there is no interpolation used or a similar method. The experiment clearly shows the variation in the elaborated methods – one approach where you can try to get close to your result and another one where you get your result.

Program	*Floor area (m^2)*	*EUI ($kWh/m^2/yr$)*	*EUI ($MJ/m^2/yr$)*
Autodesk Revit	378.00[2]	218.61	787.00
Energie 2015	482.70	44	158.40

Table 6: Comparison of the methods and results

[2] The area could not had been adjusted due to the missing free draw functionality in Revit for Zone editing and the area of 482.70 m^2 is correct for Czech requirements.

6.2 Optimization methods

Generally spoken, it seems that Autodesk created a functioning tool with an interesting and appealing concept but with numerous limitations. It reminds a bit of the development of the iPhone, where many user settings possibilities were cut down to essentials to ensure better stability. As it seems, something similar is happening to the energy analysis tools in Revit, where *Insight 360* by the most recent versions doesn't generate calculated values but proposes immediately solutions.

A good example of such a scenario is the *ECOTECT Weather Tool 2011*. For unknown reasons, Autodesk terminated the development of this tool and removed it from the product list entirely. The tool offered stereographic diagrams to check the position of the sun in certain days, detailed wind analysis, but also to generate the optimum orientation of a building (based on average daily radiation) and much more. Recently, still there are people searching for this tool because of the flexibility it offered.

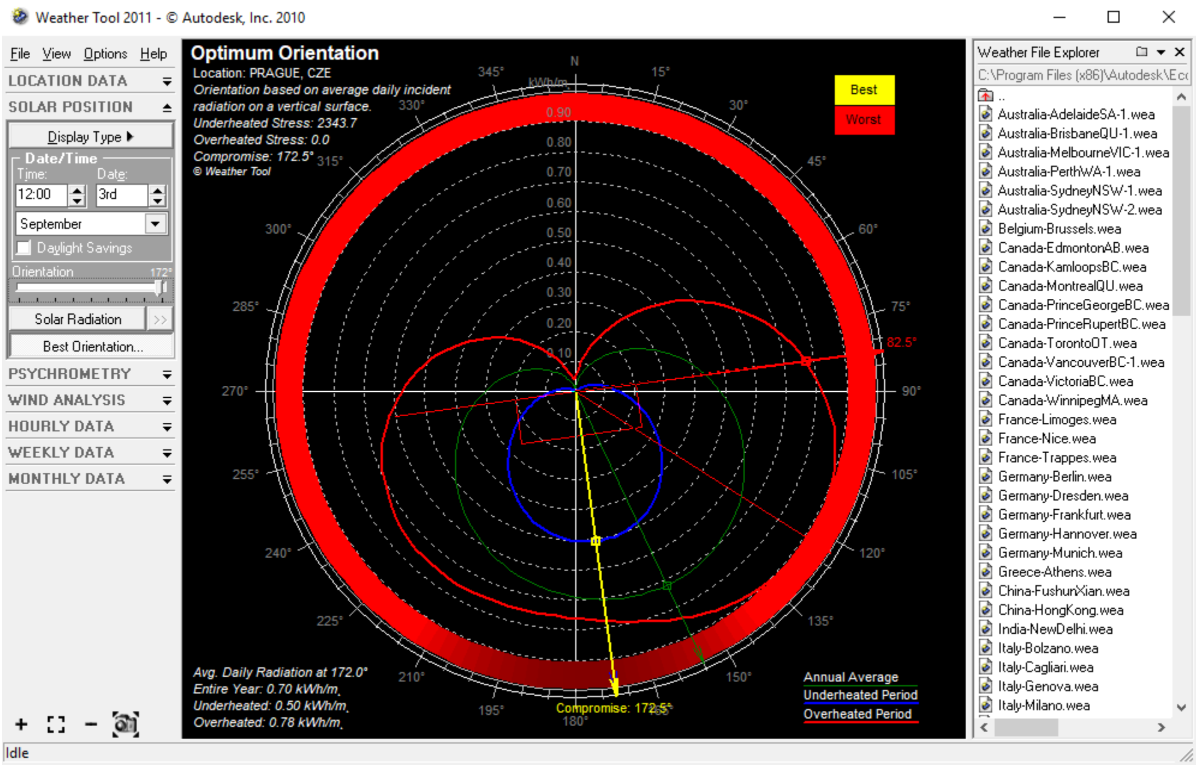

Figure 46: Optimum orientation function in ECOTECT Weather Tool 2011

But as it appears from chapter 3.2.1 of this thesis it seems, this tool was integrated into *Insight 360* and shows in charts saving options directly. You can adjust materials simply by dragging through the charts and obviously, it is the new direction of Autodesk Revit. But is it really the best one, when the materials offered in Revit 2016 had all significantly worse thermal properties than what the market actually has? Additionally, the feature seems unclear in terms of real changes to the project by just dragging charts. For this reason, to me the optimization would be in adding a feature allowing to insert own materials.

7. Conclusion

To those who it may concern – summary of the thesis, achievements and advise.

7.1 Conclusion

This workflow had two main goals. The first of them was to collect sufficient research in terms of the current trends regarding energy analysis tools in relation to BIM, since this represents a future pathway. Furthermore, the challenge consisted of analyzing the performance of the built-in energy tool in one of the most used BIM software in the world. Autodesk and Green Building Studio seem to have undertaken further steps in its development. The question is – is this really accountable and reliable software for design?

My straightforward answer would be – it depends what you need. As presented within the experimental stage, the limitations and inaccuracies of the tool make it very difficult to estimate the real potential savings, nor to comply with the law within the Czech Republic. It feels a bit like this software was created in an "American way", where things were made simple and user friendly, until you take it under a magnifier. Mainly the setting of the HVAC system makes it difficult, since the efficiency values of this setting are not displayed anywhere and the only thing you can do is to try out some of them and if it doesn't suit you, you can try another one. Additionally, this kind of approach did not change within the most recent versions of Revit so users cannot expect much flexibility in this in the future.

For this reasons the experts and engineers in the Czech Republic still prefer to have accurate results with particular entrance values known from the beginning since this way they still do achieve efficiency. They achieve it by using other BIM related energy software for analysis with corresponding conversion. The message of Revit's new trend *Insight 360* is a bit unclear with a lack of relevant explanation of *what is expected from the end-user*. Another point is that the HVAC options in *Insight 360* might be available in the USA only (indicated by the currency) and in Europe that information may not be relevant at all.

Nevertheless, I can confirm that these goals have been fulfilled since the accuracy of the tool has been tested, positive and negative aspects of the selected approaches have been evaluated, as well as sufficient research has been executed before.

7.2 Recommendations

Personally, I like the idea of a built-in energy tool that could simplify the process of data exchange and transcription. To achieve the most accurate results in such a case, Autodesk would have to change the direction a bit and enable direct energy data input with similar characteristics and range as the program Energie 2015. On the other hand, it is clear that the tool itself was created to help architect with the creation of an energy efficient design from the whole beginning of the process and this would represent too much input data from the start. A good start would be to enable the display resp. adjustment of the relevant HVAC system and object data as e.g. percentage of efficiency, indication of performance, temperatures of the medium, heat transfer coefficients etc. The possible consequence would be slowing down the process of getting instant results due to adding new parameters, which might the system take longer to process. This offers an opportunity as well though. Especially I also wish to recommend enabling HVAC zone area editing or space editing by shifting the distance to the outer edges of walls at least.

7.3 Future research possibilities for the Czech Republic

Based on the discussion with the studio *di5* the research should focus on the development of the IFC and gbXML data exchange standards, to enable conversion and stabilization of more complex objects and geometry between e.g. ArchiCAD and Revit or other.

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