RIGA TECHNICAL UNIVERSITY

AGRIS KAMENDERS

LOW ENERGY BUILDING ENERGY MODELLING

Summary of thesis

Riga 2011

RIGA TECHNICAL UNIVERSITY
Faculty of Power and Electrical engineering
Institute of Energy Systems and Environment

AGRIS KAMENDERS
Doctoral program in Environmental Science

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This study proposed for attaining Dr.Sc.Ing. degree and will be defended at 2pm on August the 29th, 2011 at the Faculty of Power and Electrical Engineering, 1 Kronvalda boulevard, room 21.

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CONFIRMATION STATEMENT

I, the undersigning, hereby confirm that I have developed this PhD. thesis, with is submitted for consideration at Riga Technical University, for attaining the degree of Dr.Sc.ing. and that this study has not been submitted to any other universities or institutes for the same purpose.

Agris Kamenders:………………………….

Date: ………………………

This dissertation is written in Latvian and contains: introduction, 4 chapters, conclusions, bibliography, 87 figures, 23 tables and 181 pages. The bibliography contains 168 references.

TABLE OF CONTENT

Background and current situation

Buildings are material and energy intensive engineering structures, and they are responsible for 40% of the collective energy consumption and 36% of the collective CO_2 emissions in Europe. Currently, long term priority goals for new building construction and extant building renovations are as follows:

- Raise building energy efficiency, approaching zero energy consumption levels;
- Increase the utilization of renewable energy resources for energy consumption by buildings;
- Reduce CO_2 emissions.

The reduction of energy consumption during building utilization is one of the most important factors for reducing building impact on environment.

Buildings in Latvia are characterized by significant potential for energy efficiency that can be gained by implementing building renovation. Figure 1 depicts the average energy consumption (kWh/m^2 per year) by buildings in Latvia currently, as well as the level of consumption required by Latvian building code. The average energy consumption for heating is approximately 180 kWh/m^2 per year, but in fulfilling the minimal requirement of energy efficiency per construction standard *LBN 002-01*, it is possible to achieve a level of energy efficiency that corresponds to energy consumption approximately of 85 kWh/m^2 per year. Current average energy consumption is four times higher than the energy consumption of a very low-energy consumption building (LEB), and 12 times higher than the consumption of a very low energy house (passive house). One of the tasks of this thesis is to analyze the opportunities for utilizing concepts of very low energy building in the climate characteristic of Latvia.

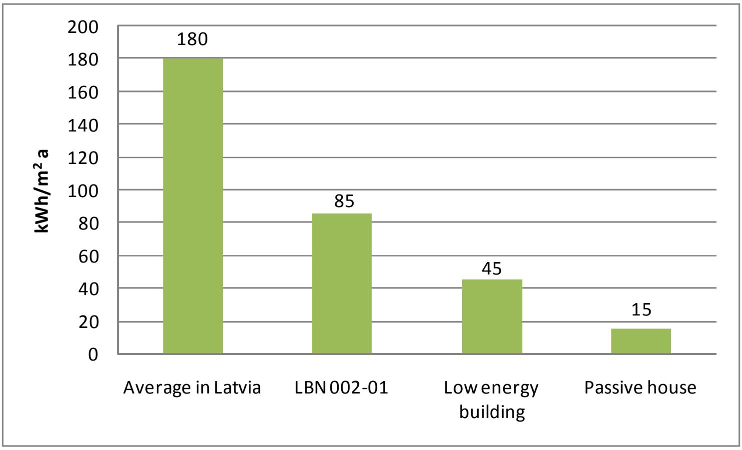

Figure 1: Comparison of energy consumption for heating

Utilizing the concept of passive house allows for the achievement of significant reduction of energy consumption in new building construction, as well as in extant building renovation. Still, work conducted for this thesis has found that while the specifications of particular elements and technologies developed by the Passive House Institute are suitable for Central Europe, they are not directly utilizable in Latvia in order to achieve LEB energy consumption levels. Several studies stress the necessity for economic analysis and methodology that would allow achievement of the best possible solutions for developing LEBs, and would require development of criteria that would help form energy and environmental policy.

Objectives

The goal of this dissertation's investigation is to develop a computer model that identifies and prioritizes energy efficiency measures for LEBs, in order to achieve optimal energy consumption. To achieve this goal, the following tasks are posed:

1) Develop an optimizing computer model for assessing the energy efficiency of Latvia's LEBs, from an economic and ecological perspective;

2) Evaluate the opportunities for utilizing the very low energy building (passive house) concept in a Latvian climate;

3) Form a model for calculating a building's energy use, applicable to instances of LEBs and utilizable for renovation work planning.

Research methodology

The work conducted for this thesis includes development of a model that calculates and optimizes building energy consumption applicable to the conditions in Latvia. The developed model has been validated and is applicable for modeling building energy consumption after renovation and LEB energy consumption. The model has been validated by comparing measurement data with calculated data, utilizing verification tests, and comparing acquired, calculated data with results from a dynamic modeling program. The computer model has been approbated in creating the design and plan of energy-efficiency measures for a multi-apartment building. The optimization task was solved using the multi variable optimization method.

Scientific significance

This thesis includes the development of a model for calculating and optimizing the building energy consumption applicable for conditions in Latvia.

This model is applicable for identifying measures for cost optimal level for energy performance and is utilizable for new-building projects and renovation work planning. The work conducted for this thesis analyzes the possibilities for utilizing the passive house concept in Latvia. This thesis provides criteria based on the construction standards currently enforced in Latvia and the characteristic climate conditions for enabling a building to approach passive house energy consumption.

Practical significance

The optimization work conducted for this thesis allowed for definition of sets of energy efficiency measures for optimal energy efficiency level for various types of buildings (series-based, multi-apartment building etc.) to be measured. The analysis demonstrates that in making long term investments (e.g., 35-year period) in measures for energy efficiency, it is necessary to implement complex renovations for buildings that enable achievement of energy consumption for heating that is lower than 40 kWh/m^2 per year. In the case of new building construction, small sized buildings (heating area smaller than 200 m^2) must have energy consumption lower than 35 kWh/m^2 per year for heating, and for larger buildings, lower than 25 kWh/m^2 per year.

This model could also be used to define criteria in developing government supported programs, which are intended to raise energy efficiency, and revised 2010/31/ES directives for establishing the requirement of energy efficiency in legislation in Latvia.

Work conducted for this thesis includes measurements of energy consumption data and of comfort criteria from Latvia's first LEB. These measurements demonstrate that it is possible to build a private house (heating area 191 m^2) whose energy consumption for heating does not exceed 35 kWh/m^2 per year. Acquired and analyzed results can serve as valuable reference material for further LEB projects.

Approbation

Work conducted in this thesis has been submitted to and discussed in international conferences and seminars.

1. "RES-E Potential in Latvia," seminar "RES-E and Co-generation Policies in Central Europe," May 9 – 10, 2005, Poznan, Poland.
2. "Acquisition of Systemic Thinking. Eco-construction Project Analysis at Riga Technical University," conference "Environmental Science and Education in Latvia and Europe," February 8-9, 2007, Republic of Latvia's Ministry of Environmental Protection, Riga, Latvia.
3. "Energy Friendly Building Concept," conference "NorthSun 2007," May 31 – June 1, 2007, Riga Technical University, Riga, Latvia.
4. "Energy efficiency in Latvian hospitals", RTU international scientific conference session "Energy and Electrical Engineering," 2004, Riga, Latvia.
5. "Passive house in Latvia", RTU international scientific conference session "Energy and Electrical Engineering," 2006, Riga, Latvia.

6. “Energy-efficient single-family house design for Latvia”, RTU international scientific conference session “Energy and Electrical Engineering,” 2007, Riga, Latvia.

7. “Hybrid ventilation system in passive house”, RTU international scientific conference session “Environment and Climate Technologies,” 2007, Riga, Latvia.

8. “Building-Energy Consumption in Daugavpils”, RTU international scientific conference session “Environment and Climate Technologies,” 2008, Riga, Latvia.

9. “Multi-Objective Optimization Approach for Improving Performance of Building”, RTU international scientific conference session “Environment and Climate Technologies,” 20089 Riga, Latvia.

10. “Laboratory Work in Industrial Settings. Opportunities,” conference “ Environmental Science and Education in Latvia and Europe: Education for Long term Development,” March 14, 2008, Riga, Latvia.

11. “The 11th International Conference on Solar Energy in High Latitudes”, conference “Latvia: Energy Friendly Building Concept,” May 30 – June 1, 2007, Riga, Latvia.

12. “Financing Energy Efficiency Projects in Latvia”, report at conference “Tailored Financing Schemes for Social Housing Refurbishment,” November 20, 2008, Bratislava, Slovakia.

13. „Latvian multi-apartment blocks”, international conference “Energy Efficiency and Energy Services: What is the Secret of Successful Programmes?” November 28, 2008, Tallin, Estonia.

14. „Passive House Characteristics in Latvian Cold Climate”, conference “13th International Conference on Passive House 2009,” April 17 – 18, 2009, Passive House Institute, Frankfurt, Germany.

15. “First Passive House In Latvia: A Real Example”, conference “14th International Conference on Passive House 2010,” May 28 – 30, 2010, Dresden, Germany.

16. “Cost optimality and EnerPHit standard in Latvia”, conference “15th International Conference on Passive House 2011,” May 27 – 29, 2011, Innsbruck, Austria.

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4. Blumberga A., Kamenders A. Passive House in Latvia // Latvian Journal of Physics and Technical Sciences. Issue 6, 2006, p. 25–34.

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Structure of the thesis

This doctorate thesis was originally written in Latvian, and it contains an introduction, 4 sections, conclusions, a literature review and appendices, for a total of 181 pages, including 87 figures and a literature review of 168 sources.

1. Building energy model

Several studies stressed the necessity for economic analysis and methodology that would allow achievement of the best possible solutions for developing LEBs, as well as indicating the need to develop criteria that would help form energy and environmental policy.

Currently, standard criteria for LEBs have not been developed in Latvia. While the reviewed directive for energy efficiency defines qualified, LEB decision criteria, they are not expressed in terms of quantified, verifiable decision criteria.

Latvian construction standard poses only minimal requirements for energy efficiency, and in the case for new building construction, it is neither clear what standards must be met nor what technologies are utilizable in Latvia to achieve LEB levels.

In building renovation, there is a lack of clear methodology for assessing and achieving a cost-optimal energy efficiency level.

Calculation models are available that can help conduct an analysis of a building's energy balance, however, these models are not utilizable to determine the optimal energy consumption in the case of an LEB: Computer models developed in Latvia are neither applicable to calculations for LEBs, nor have they been validated for cases involving LEBs. Models developed in Latvia do not allow for the consideration of the impact utilities have on a building's energy consumption, and do not provide opportunities for integrating energy sources into the building's energy balance.

Developed model for a building's energy consumption consists of several calculation components:

1. Calculation of building transmission losses: This calculation includes the building's total envelope, roof or attic covering, windows, outer door, basement structure and necessary data.
2. Determination of heat loss due to ventilation system: This calculation employs parameters that impact heat loss via the ventilation system and air leakage.
3. Calculation of heat gains: This model includes calculations for heat gains and solar heat

4. Calculation of losses from the building's heating system: Considering the efficiency of the building's heating system, this calculates the system's heat losses.
5. Energy consumption and loss calculation for the building's hot water heater system: This calculation component includes data on heat losses of the water heater system, including the circulation loop, standing water in pipes and accumulation tank.
6. Economical and environmental calculations.
7. Optimization.

The goal of optimization is to find the set of energy efficiency measures for optimum energy efficiency that corresponds to specific criteria for optimality. The EPBD recast introduce the principles of cost-optimal energy performance. Likewise, the directive stipulates that in determining the cost-optimal energy efficiency level, participating countries must assess building life-cycle expenses. The cost-optimal energy efficiency level can be examined from the perspective of the individual or society at large. A private investor will base investments in energy efficiency measures for energy efficiency by evaluating the rationale of investments within existing economic conditions. On the other hand, evaluating investments in energy efficiency measures for energy efficiency within a broader context can consider other gains, which can include environmental benefits and security of energy supply. Thus, this thesis includes two different optimality criteria, where one illustrates the performance of investment and the other evaluates the effectiveness of CO_2 emission reduction.

The following optimality criteria were selected:

1) Cost-optimal energy efficiency level: The lowest global costs for one heated square meter in the selected period, LVL/m^2;

2) Optimal level of energy efficiency for CO_2 reduction: Largest reduction in CO_2 emissions versus global costs in the selected period, kg CO_2/LVL.

The general optimization curve, establishing the cost-optimal energy performance, is depicted in Figure 2.

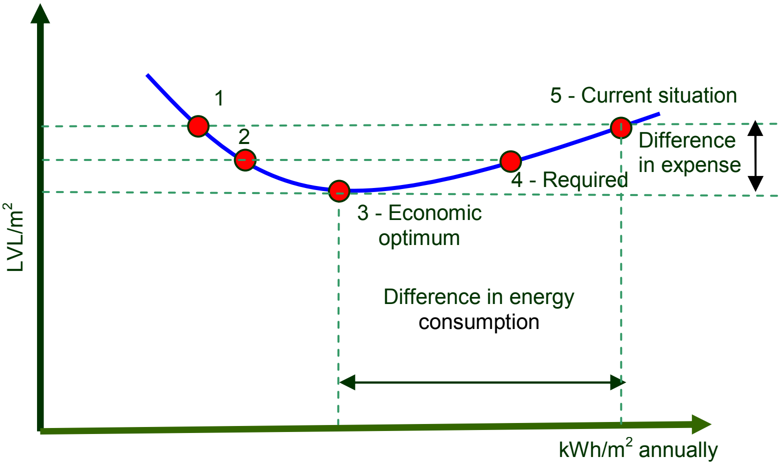

Figure 2: General optimization curve

Each point in the figure depicts different renovation alternatives. In considering real life situations, all possible combination of measures will not, of course, form one exact optimization curve, rather, sets will form a data cloud from witch an average curve can be derived. The cost-optimal energy efficiency level corresponds to the lowest, combined life-cycle expense in the selected calculation period. If the optimization curve is formed with optimal values that are very close in terms of expense, one would choose energy efficiency measures that provide the greatest reduction in energy consumption, in this way helping to achieve goals established nationally and by the EU.

As is shown in Figure 2, situations can occur where expenses are equal, but levels of energy efficiency are substantially different (as depicted in Figure 2 by the second and fourth scenarios). The fourth scenario represents minimal energy efficiency requirements, corresponding to the construction standard in Latvia; in the second scenario, measures for energy efficiency enable the building to be more in line with LEB decision criteria. In forming the optimization curve, it is possible to define differences between minimal energy efficiency requirements corresponding to the construction standard in Latvia, and to discern measures for optimal energy efficiency.

Global costs form a building's maintenance expenses, into which expenses are included for energy and investments in measures for energy efficiency. To calculate global costs as accurately as possible within a selected time frame, energy price increases and inflation are considered. Discounted global costs for a specific period is calculated by Equation 1:

$$I_{kop,d} = I_{pas} + \left(\frac{\left(\frac{Q_{apk}}{\eta_k} + \frac{Q_{kr}}{\eta_{kr}}\right) * T * \left(1 - \left(\frac{1+E_p}{1+R_R}\right)^P\right)}{1 - \frac{1+E_p}{1+R_R}} + \frac{I_{men} * \left(1 - \left(\frac{1}{1+R_R}\right)^B\right)}{1 - \frac{1}{1+R_R}} \right) * \frac{1}{1+R_R}, LVL \quad (1.)$$

where:
I_{pas} – own capital;
I_{men} – monthly payment to the bank, LVL;
R_R – real interest rate, %;
B – period of borrowing, years;
P – specified period of calculation, years;
Q_{apk} – energy consumption for heating, utilizing measures for energy efficiency (determined with the help of the energy consumption and ecological assessment module), MWh annually;
Q_{kr} – energy consumption for hot water needs utilizing measures for energy efficiency (determined with the help of the energy consumption and ecological assessment module), MWh annually;
η_k – heating distribution system and source (boiler) efficiency coefficient, %;
η_{kr} – hot water distribution system effectiveness, %;
T – energy tariff, LVL/MWh;
E_p – energy cost increase annually, %.

The decision criterion allows for comparisons between varied sets of energy efficiency measures for energy efficiency.

$$OPTe = \frac{I_{kop,d}}{A_{apr}} \to \min, LVL/m^2, \quad (2.)$$

where:
$I_{kop,d}$ – discounted global costs, LVL;
A_{apr} – assessed (heated) area, m^2.

As a decision criterion of effectiveness for CO_2 reduction, the generally recognized $kgCO_2/LVL$ is utilized, reflecting CO_2

emissions reduction per global costs within the selected calculation period. In this case, the decision criterion must be maximized. The general optimization curve is shown in Figure 3.

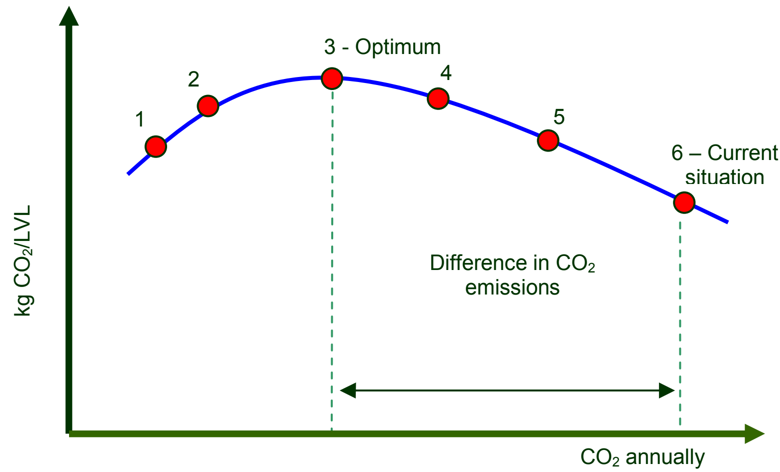

Figure 3: General optimization curve

Again, considering different alternatives will form a distribution, in which each point represents one particular alternative.

As a separate decision criterion for efficiency optimization, a specific criterion is offered, one which characterizes CO_2 reduction per discounted global costs within a selected period. This criterion is related to the building's consumption of energy, as well as the building's consumption of energy after implementing measures for energy efficiency and economic parameters of specific alternatives. CO_2 emission reduction is influenced by the heating system and energy source efficiency coefficient, building energy consumption and heating method that is used in the energy source.

$$OPTv = \frac{E_M * 1000}{I_{kop,d}} \rightarrow \max, kgCO_2 / LVL \quad (3.)$$

where:

$I_{kop.d}$ – discounted global costs, LVL;

E_M – reduced CO_2 emissions, t.

It is possible to establish a set of measures for optimum energy efficiency depending on the user's priorities, choosing one of the provided optimality criteria. The economic evaluation of energy efficiency measures does not incorporate supplemental benefits from measures of energy efficiency such as:

1) Increased energy independence;
2) Reduction of environmental influence (reduction of external expenses, possible gains from the CO_2 quota market);
3) Improved indoor climate, which can reduce the risk of illness and increase labor productivity;
4) Extend the building's technical life cycle and reduce maintenance expenses;
5) Increase the value of real estate.

The optimization process algorithm with the goal of lowest global costs in the calculated period is depicted in Figure 4.

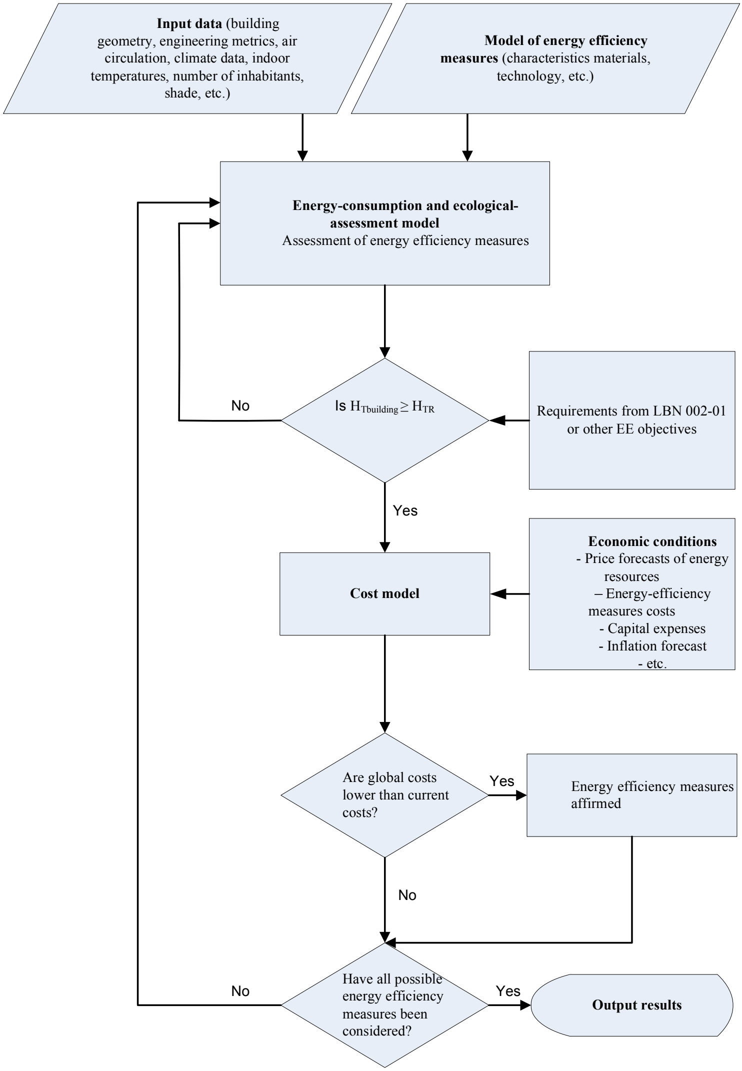

Figure 4: Optimization process algorithm

The optimization program developed in this thesis consists of several modules, of which the most important are the following:

1) *Raw data*: Consists of information regarding the analyzed building. Data include the building's geometry, heat and hot water systems, solar orientation of the building, shade, climate conditions maintained indoors (indoor temperature, air circulation), number of inhabitants, thermal performance of building shell;

2) *Model of measures for energy efficiency*: Consists of information regarding possible measures for energy efficiency;

3) *Energy consumption and ecological assessment model*: The building's energy balance is developed, with corresponding calculation of CO_2 emissions;

4) *Cost model*: Global costs are specified for the selected period of calculation, and an optimization plan decision criterion is calculated;

5) *Model representing economic conditions*: Factors include price forecasts of energy resources, inflation, borrower interest rates, percent of own capital.

2. Data analysis and analysis of low-energy building. Model validation

A building's energy consumption is determined depending on the mathematical model it is based on, thus it is important to assess how accurately the building's mathematical model represents the building's energy balance and enables consumption forecasting for both new building constructions, as well as building renovations. To assess the model developed for this thesis, a model validation was conducted. Currently, no internationally recognized methods or accepted testing criteria have been developed for energy consumption model programming.

There are three different ways for validating energy model programming:

1) *Building energy program validation, comparing a model's results with measurements of measured energy consumption.* This examination is an effective way to verify whether a developed model adequately describes a real building's energy consumption data. This kind of examination is often employed in practice. Still, this method can lead to a larger difference between measured and calculated data, because energy consumption measured data are influenced by many different factors that are unknown and difficult to define. If data do not match, it is very difficult to assess sources of error, because an

assessment can be conducted only as far as the information of measured data will allow.

2) *Diagnostic (verification) tests.* Validation occurs by calculating several examples that have been previously developed, and comparing acquired results with standard, given and correct results. Standard, given results are usually acquired through conducting detailed measurements in a laboratory and dynamic modeling. These validation tests give more opportunities to identify errors in the model, but they do not provide information on how the model represents real buildings. One example of this kind of test is the dynamic modeling program standard *EN 15265: Energy performance of buildings – Calculation of energy needs for space heating and cooling using dynamic methods – General criteria and validation procedures.*

3) *Comparison with verified dynamic simulation programs.* This type of validation is usually selected for modeling specific building types or components, which helps to assess various nuances of models.

2.1. Validation of the developed model with measured data

The data set used in this thesis includes public buildings, single-family houses and popular, series based multi apartment buildings that are renovated and non-renovated. Buildings include series 103, series 467, series 602, series 318, series 316 and series 104 multi apartment buildings.

The data analysis for this thesis uses data of energy consumption for heating buildings. The processed data set is comprised of analyzed buildings and their consumption over different years. In the processed data set:

1) Complex building renovations are not included (heat substations were set up, various windows were replaced):

$$m = 85$$

2) Complex building renovations are included:

$$m = 17$$

The decision criterion kWh/m^2 per year was selected for characterizing energy efficiency, and this indicator is widely used to characterize building energy consumption. It is used in legislated construction standards in Latvia and other countries. Values of measured energy consumption dependent on values calculated by using the model are shown in Figure 5.

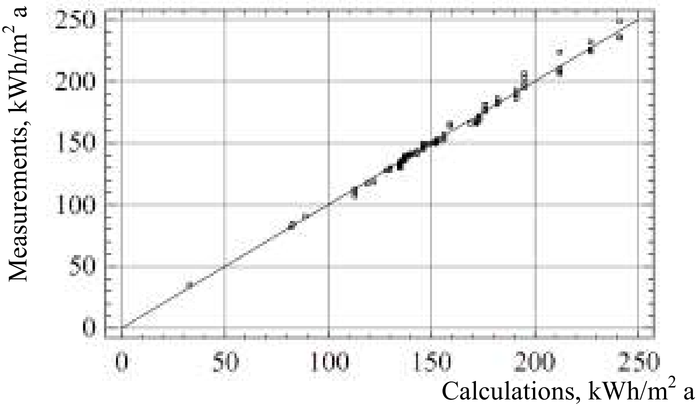

Figure 5: Comparison of building energy consumption between measured and calculated data

As is seen in Figure 5, there is a strong correlation between the two data sets, and the dispersion is low. The closer each individual data point is to the best fit line, the more accurately the developed model has been able to represent real energy consumption.

A regression and correlation analysis was conducted to quantitatively assess the data's relationship between variables and standard deviation. A linear model was selected for the regression analysis:

$$y = b_o + b_1.x_1 , \qquad (4.)$$

where:
y – values of energy consumption measurements, kWh/m^2 per year;
x_1 – values of energy consumption calculations, kWh/m^2 per year.

Graphical representation of the regression analysis' results are shown in Figure 6.

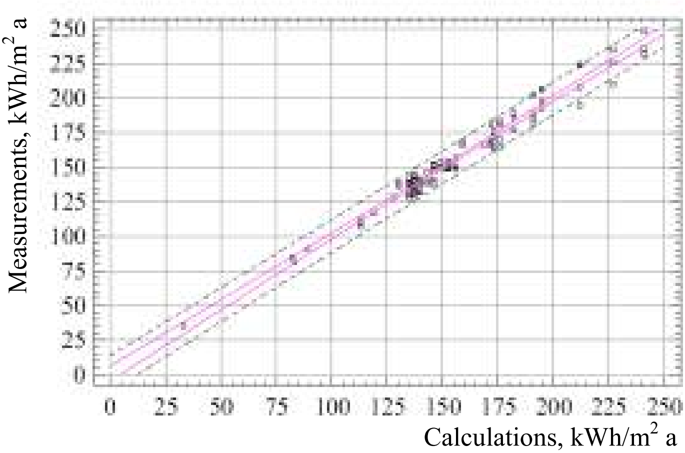

Figure 6: Data of energy consumption within 2σ intervals

The results demonstrate that the linear model accurately represents the relationship between measured and modeled results. The value of the coefficient of determination R^2 is 0.97, which measures that the model accounts for 97% of the variance of the measured results. The correlation coefficient R=0.985 demonstrates that there is a close dependence between the measured and modeled results. Regression and correlation analysis shows that standard deviation between modeled and measured results is σ = 5.89 kWh/m^2 per year. A confidence level of 0.95 corresponds to an interval of 2σ = 11.8 kWh/m^2 per year. The boundaries of the interval are shown in Figure 6.

Measured and calculated energy consumption, arranged in ascending order, are shown in Figure 7.

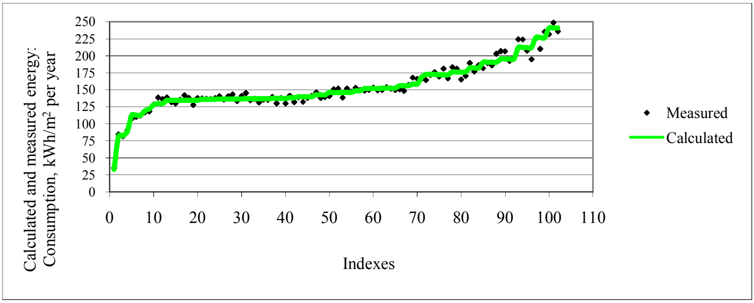

Figure 7: Changes of calculated and measured energy consumption

Figure 7 is a graph of data whose values have been ranked from smaller to largest, and then a comparison between calculated and measured energy consumption was conducted. The graph shows that the dispersion of the measured energy consumption is uniform relative to the calculated data curve and is not dependent on the building's energy consumption.

In comparing data, it can be seen that the model adequately represents various types of building energy consumption data. As it is anticipated that the developed model can help calculate energy consumption for installation of defined measures for energy efficiency, instances of building renovations are examined closely.

2.2. Low energy building in Latvia

The work conducted for this thesis includes energy monitoring and the indoor climate of the first LEB in Latvia. Monitoring consisting of the following long term measurements:

1) Indoor air temperature in all rooms of the building;
2) Outdoor air temperature;
3) Relative air moisture in the living room and bedroom;
4) Level of CO_2 in the bedroom;
5) Start up and shut down of ventilation equipment's antifreeze circulation pump;
6) Heat consumption for heating and hot water.

Measurements enabled preparation of precise raw data for the calculation model and to conduct a validation of the model for LEBs.

To validate the model for LEBs, measurements of energy consumption and necessary inputs were conducted, as well as development of a dynamic calculation model using the *TRNSYS 16* program environment.

The dynamic model for LEBs enabled tracking of peak load changes of temperature and heating in different zones. To precisely determine the building's peak heating load, an analysis based on hourly rates was conducted. The results are shown in Figure 8.

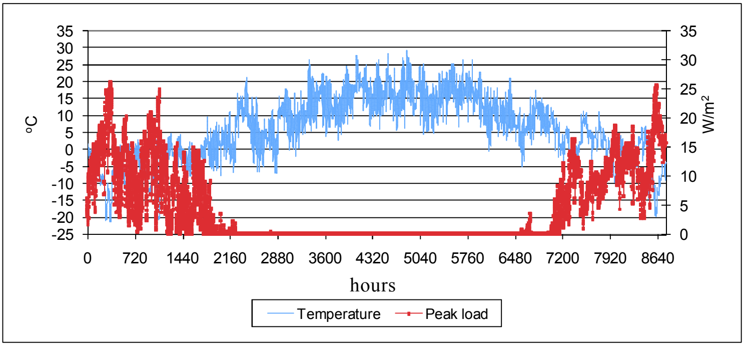

Figure 8: Building's peak load, depending on outdoor temperatures

As is shown in Figure 8, peak heating load often exceeds values of 10 W/m^2, the highest value up to which it is possible to exclusively utilize the ventilation system for covering heating load. The highest peak heating loads are seen in January and February. These two months are examined more closely in Figure 9, to precisely determine peak heating load.

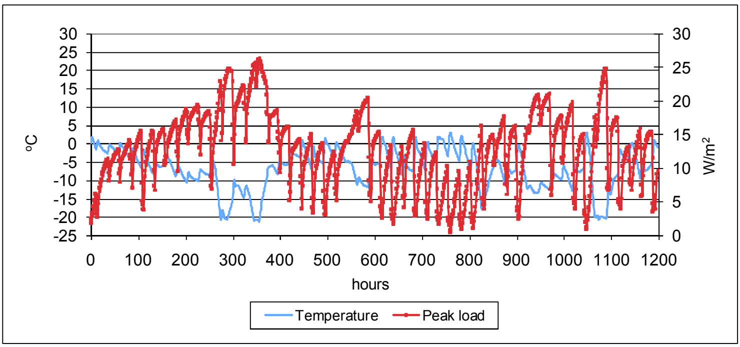

Figure 9: Peak heating load in January and February

As shown in Figure 9, the maximum peak heating load is 26 W/m^2. As it is not possible to cover this heating load using the building's ventilation system, heated floors were built in separate zones within the building.

For the measured energy consumption data to be comparable with calculated data, they were adjusted, assuming that climate conditions are uniform and the indoor temperature t = +20 °C. Adjusted energy consumption data are shown in Figure 10 on a monthly basis in 2010.

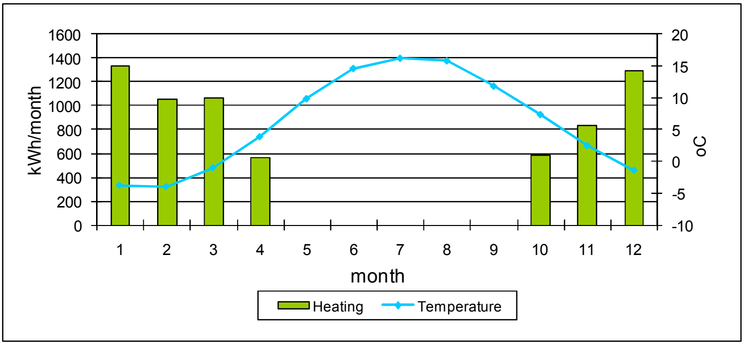

Figure 10: Energy consumption per month

The total energy consumption for the building in 2010 was 6719 kWh, or 35 kWh/m^2 a. In Figure 11, calculation results of the model are compared with measured data and data from the dynamic model.

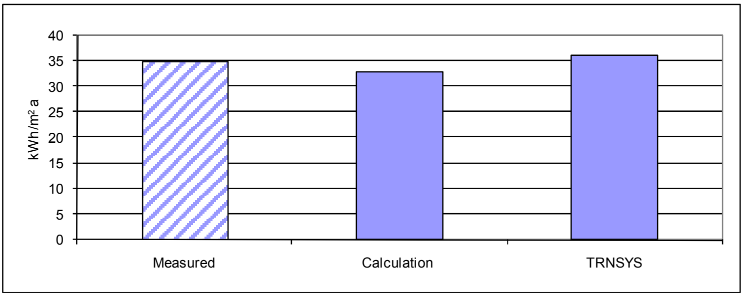

Figure 11: Comparison of energy consumption – measurements versus calculations

As is shown in the figure, the calculated energy consumption accurately represents energy consumption in the building.

2.3. Validation of the model with the EN 15265 standard

The developed model was also validated employing tests specified by the EN 15265:2007 standard. Test variations are provided to specify validation of the dynamic model for one room of the building, but they do not examine situations that involve transmission of heat from the first floor to unheated basements or into the ground as is found in real circumstances. Overall, the standard provides 12 different circumstances, of which six are applicable for seasonable calculation and were utilized for validating the developed model.

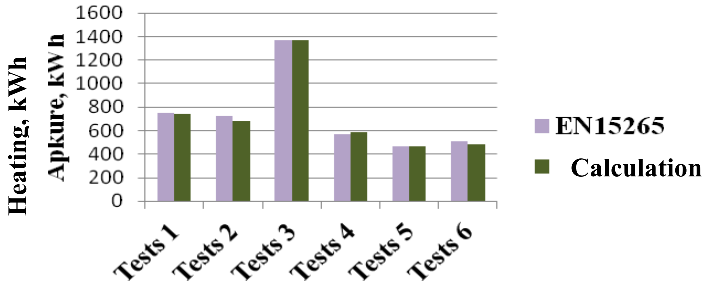

Figure 12: Comparison of results from tests and calculations from the model

Table 1 provides results in terms of numerical values, including the relative differences between the EN 15265 tests and calculated results of the model, expressed as percentages.

Table 1

Result comparison

Test	EN 15265	Calculated energy consumption	Relative difference
-	kWh	kWh	%

1.	748	745,62	-0,32
2.	722,7	677,32	-6,28
3.	1368,5	1367,48	-0,075
4.	567,4	591,32	4,22
5.	463,1	465,17	0,45
6.	509,8	482,93	-5,27

As can be seen, the largest difference is within 6%, which demonstrates the model's high degree of accuracy. According to the EN 15265 standard, models can be classified into three classes of accuracy: A, B and C. Class A corresponds to models with differences in results up to 5% compared with provided results; Class B corresponds to models with differences between 5-10%; Class C includes models with differences between 10-15%.

The developed model was validated, employing various validation methods:

1) Real energy consumption data for renovated and unrenovated buildings, and first LEB in Latvia;

2) Dynamic modeling program examination test EN 15265;

3) Dynamic calculation program *TRNSYS 16*.

The data analysis indicates that the developed model adequately represents building energy consumption, and it can be used to determine energy consumption. In order to increase the accuracy of the model for each case of a real building, the main factors must be determined in the process of conducting measurements.

3. Approbation of the model

As part of validating the model, the model's ability to forecast a building's energy consumption after renovations was analyzed in detail. Three different buildings were analyzed before and after renovations: Maskavas iela 1, in Rēzekne; Dzintaru iela 2, in Kuldīga; and Gaujas iela 13, in Valmiera. The fully developed energy consumption model was employed in the field for the multi-apartment building on Gaujas iela 13, including development of plans for the measures for energy efficiency, as well as determination of the building's energy consumption after renovation.

3.1. Dwelling renovation

The developed calculation model was approbated in practice by applying it in the development of the plan for the measures for energy efficiency, as well as in the forecasting of energy consumption after renovation, for the building located on Gaujas iela 13 in Valmiera. The analyzed building is a series 467, whose outside walls consist of expanded clay panels. The building has both a non-heatable basement and attic, which has a flat roof. The building's overall area is 2239 m^2 and heated apartment area is 1900 m^2. With the model's help it was determined that the building's post-renovation energy consumption would be 157 MWh per year or 83 kWh/m^2 per year for heating, and 57 MWh per year or 30 kWh/m^2 per year for hot water. The corresponding planned reduction in energy consumption from pre-renovation levels would be 51% for heating needs and 42% for hot water needs. It was determined that the overall post-renovation energy consumption would be 214 MWh per year or 113 kWh/m^2 per year.

During the renovation, an energy consumption monitoring system was built, which enabled analysis of the building's post-renovation energy consumption and indoor temperature. A comparison of measured and calculated energy consumption data is provided in Figure 13. Data of energy consumption are represented depending on outdoor temperatures, with each point depicting one month's energy consumption. The line shows the average monthly energy consumption before renovation; the other line shows the forecasted energy consumption post-renovation; and the triangles indicate measured results after renovation. As is shown, the forecasted, post-renovation energy consumption accurately represents the building's actual energy consumption.

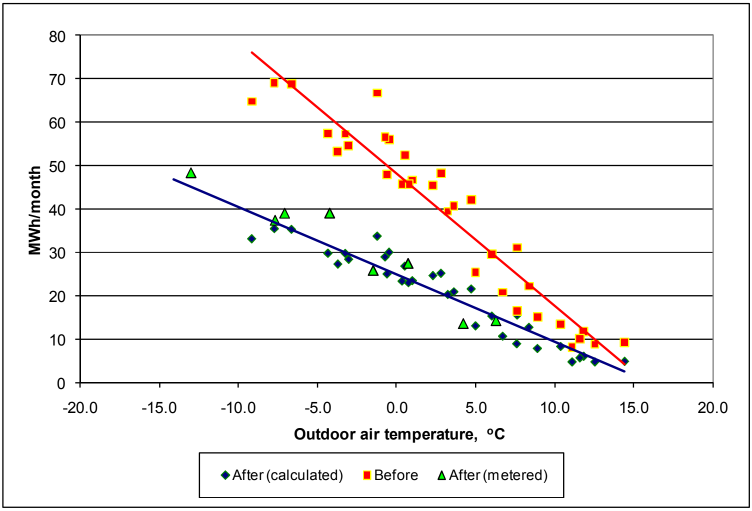

Figure 13: Energy consumption before renovation, forecasted energy consumption, and energy consumption after renovation

Measured and modeled data of the building's energy consumption per year, before and after renovation, are shown in Figure 14. It depicts measured data, adjusted for standard conditions, and calculated data from the model.

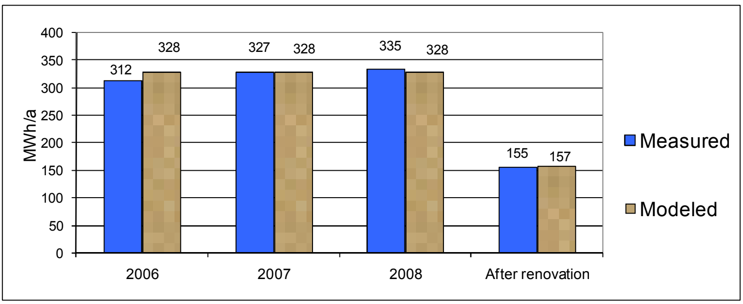

Figure 14: Measured and modeled energy consumption

As is shown in Figures 13 and 14, the developed energy consumption model accurately represents energy before and after renovation, and the difference between measured and calculated energy consumption is within 2%. For specified renovation work, the model forecasted heating energy consumption as 157 MWh, or a

49% decrease. In the case of the hot water system, the model forecasted a reduction of circulation loss from 61.9 MWh per year to 20 MWh per year, i.e., a 68% decrease.

3.2. Optimization example

The work conducted for this thesis included developing a computer program, with which it is possible to calculate energy consumption for heating and hot water, and to determine the optimum set of measures for energy efficiency, depending on the selected plan's decision criteria for efficiency.

Applying the developed model, three types of buildings were analyzed:

1) Multi-apartment building;
2) Public building;
3) Private house.

An example of optimization is provided for a multi-apartment building.

Optimization was conducted for two different time periods, 20 and 35 years. Depending on the number of selected measures for energy efficiency, individual sets of measures for energy efficiency are created as part of the optimization process. These sets are multiplied utilizing a Cartesian product, so that each set's element is multiplied with the respective element of other sets, in this way forming a defined number of resulting corteges. In the example provided, unique, examined sets of energy efficiency measures totalled 1 290 240, which were screened by the optimization process, calculating the assigned optimality criteria. As a result of optimization for the 35-year calculation period selecting the smallest global costs as the optimization decision criteria the optimal measures for energy efficiency were determined as follows:

1) Total wall insulation with 0.15 m thick insulation layer (insulation $\lambda \leq 0,04$ W/(m×K));

2) Attic insulation with 0.35 m thick insulation layer (insulation $\lambda \leq 0,04$ W/(m×K));

3) Front door replacement with glass pane door (insulation $U \leq 0,04\ 2$ W/(m^2×K));

4) Basement insulation with 0,07 m thick insulation layer (insulation $\lambda \leq 0,04$ W/(m×K));

5) Replacement of all windows with three paned windows, with select glass (4/12/4/15/4) and argon gas mix (($U_w \leq 0,9$ W/(m^2×K) and $g > 0,45$);

6) Mechanical ventilation and gas recovery (η > 75%) system, on average providing n = 0,5 h^{-1} indoor air exchange;

7) Insulating circulation pipe for hot water distribution and heating system distribution with 0.07 m thick insulation layer.

The resulting overall energy consumption of this set of measureswas Q_{kop} = 141.17 MWh per year or q_{kop} = 74.3 kWh/m^2 per year. Specific energy consumption for heating needs was q_{apk} = 41.13 kWh/m^2 per year, and the plan's corresponding efficiency criterion OPTe = 229.03 LVL/m^2. As the various sets of measures for energy efficiency are large in number, they are represented with a 10% step on each side of the optimal value, in order to determine the properties of the optimization curve. The results of the optimization are provided in Figure 15.

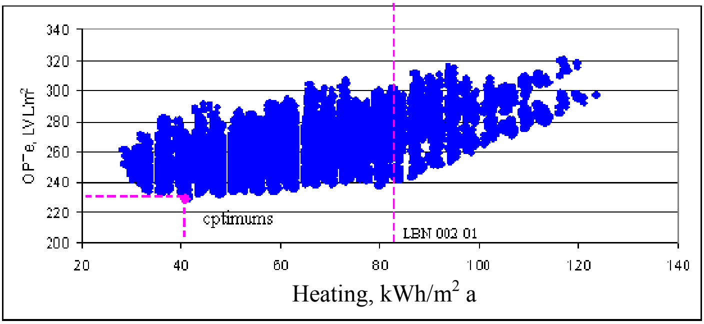

Figure 15: Results of optimization. Heating energy consumption versus OPTe (35 years)

Figure 15 shows the optimization results for a standard multi-apartment building for a 35-year calculation period. The optimum forms between 33 and 55 kWh/m^2 per year. If measures for energy efficiency were developed corresponding to Latvia's construction standard LBN 002-01, energy consumption for heating would be 157.7 MWh per year or 83 kWh/m^2 per year. Figure 16 shows the optimal overall energy consumption.

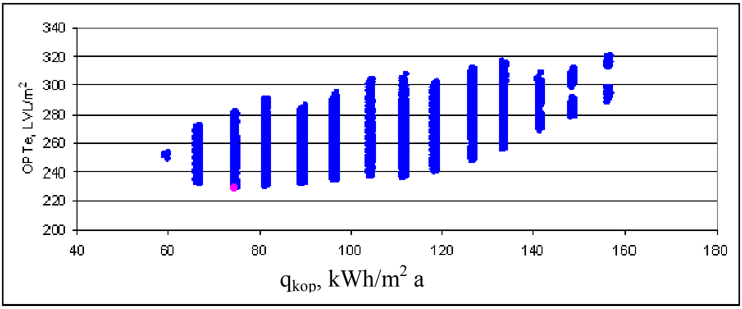

Figure 16: Optimization results. Overall energy consumption depending on cost plan's criterion of efficiency (35 years)

Defining the optimal set of measures for energy efficiency based on the perspective of efficiency of CO_2 emission reduction, it can be observed that the optimum forms if the specific consumption for heating is 33-36 kWh/m^2 per year. The calculated efficiency plan criterion OPT_v = 5.71 kg CO_2/LVL, specific consumption for heating is 35 kWh/m^2 per year and collective specific energy consumption is 62.06 kWh/m^2 per year. Figure 17 depicts the properties of optimization curve for the analyzed building.

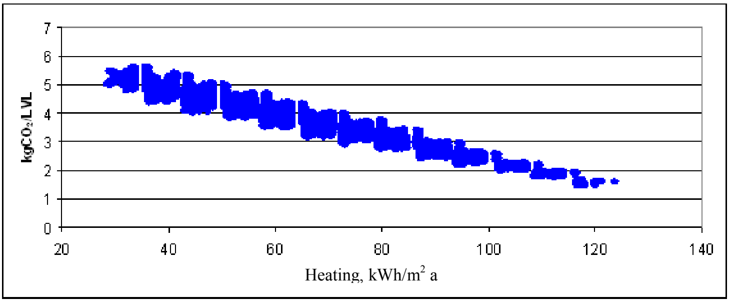

Figure 17: Optimization results. Heating energy consumption depending on the environmental decision criterion of efficiency (35 years)

Optimization was also conducted for a shorter time calculation period, 20 years. As a result of optimization for the 20-year calculation period selecting the smallest global costs as the optimization decision criteria the optimal measures for energy efficiency were determined as follows:

1) Total wall insulation with 0.10 m thick insulation layer (insulation $\lambda \leq 0,04$ W/(m×K));

2) Attic insulation with 0.20 m thick insulation layer (insulation $\lambda \leq 0,04$ W/(m×K));

3) Front door replacement with glass pane door (insulation $U \leq 0,04$ 2 W/(m^2×K));

4) Basement insulation with 0,07 m thick insulation layer (insulation $\lambda \leq 0,04$ W/(m×K));

5) Replacement of all windows with two paned windows (($U_w \leq 1,4$ W/(m^2×K) un $g > 0,5$);

6) Natural air exchange through window grates, cleaning out ventilation shafts and sealing leakages in ventilation. On average providing $n = 0,5$ h^{-1} indoor air exchange;

7) Insulating circulation pipe for hot water distribution and heating system distribution with 0,05 m thick insulation layer.

The resulting overall energy consumption of this set of measuresis $Q_{kop} = 215.53$ MWh per year or $q_{kop} = 113.44$ kWh/m^2 per year. Specific energy consumption for heating needs was $q_{apk} = 79$ kWh/m^2 per year, and the plan's corresponding efficiency criterion OPTe = 144.08 LVL/m^2. The results of the optimization are provided in Figure 18.

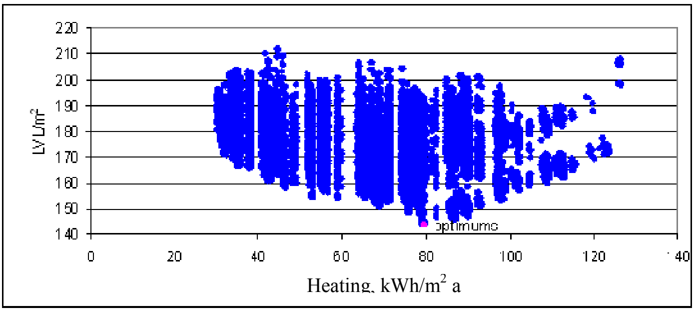

Figure 18: Optimization results. Heating energy consumption versus OPTe (20 years)

Figure 18 shows the optimization results for a standard multi-apartment building for a 20-year calculation period. The optimum forms between 75 and 85 kWh/m^2 per year. Figure 19 shows the optimization results for the plan's criterion of efficiency, selecting the indicator of CO_2 emissions reduction for a 20-year calculation period.

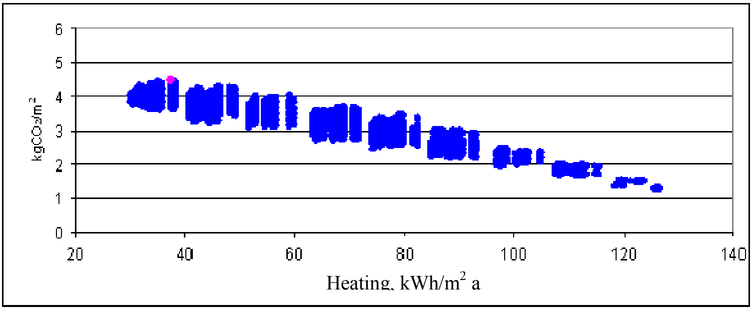

Figure 19: Optimization results. Heating energy consumption depending on environmental decision criterion of efficiency (20 years)

Determining the optimal set of measures for energy efficiency based on the perspective of efficiency of CO_2 emissions reduction, it can be seen that the optimum forms with the specific consumption for heating at 37 kWh/m^2. The calculated efficiency plan criterion $OPT_v = 4.45$ kg CO_2/LVL.

Conclusions

1. Work conducted for this thesis includes measurements of energy consumption data and of comfort decision criteria from Latvia's first LEB. These measurements prove that it is possible to build a private house (heating area 191 m^2) in Latvia whose energy consumption for heating does not exceed 35 kWh/m^2 per year.

2. A building's energy consumption calculation and optimization model has been developed, applicable for conditions in Latvia.

3. The developed model has been validated and is applicable to model energy consumption after renovation, and energy consumption by LEBs. Data analysis shows that there is no significant difference between the calculated and measurement data dependent on building energy consumption. The model is also applicable to analysis of LEB energy consumption.

4. The LEB concept is applicable and utilizable for conditions in Latvia. Utilization of the LEB concept enables achievement of significant reduction of energy consumption, for new building constructions as well as building renovations. Nevertheless, the work for this thesis has determined that while the specifications of particular elements and technologies developed by the Passive House Institute are suitable for Central Europe, they are not directly utilizable in Latvia in order to achieve LEB energy consumption levels. The indicating decision criteria developed for this thesis evaluate energy consumption for heating, in order to enable an approach to passive building requirements.

In order for buildings with conditions in Latvia to approach LEB indicators, they need to achieve the following indicators:

▪ For the climate in Latvia, the corresponding U value for the case of a private house:

- walls, roof, coverings < 0.08 $W/(m^2 \times K)$;
- windows < 0.65 $W/(m^2 \times K)$;
- recovery > 85%;
- building density $n_{50} < 0.4\ h^{-1}$;
- maximum utilization of solar energy in a passive manner;
- maximum compactness.

▪ For the climate in Latvia, the corresponding U value for the case of a multi-apartment building:

- walls, roof, coverings < 0.12 W/(m^2×K);
- windows < 0.65 W/(m^2×K);
- recovery > 80%;
- building density n_{50} < 0.4 h^{-1};
- maximum utilization of solar energy in a passive manner;
- maximum compactness.

▪ It is possible to achieve LEB indicators (< 15 kWh/m^2 per year) in Latvia.

▪ As the conducted calculations demonstrate, it is very difficult to achieve a smaller peak heating load than 10 W/ m^2.

5. The work for this thesis has developed an LEB dynamic-model program using *TRNSYS 16* with which the energy consumption and peak heating load were analyzed. The results of the calculations demonstrate that in the case of a private house (heating area smaller than 200 m^2) it is technically very difficult to build a house that has a peak heating load smaller than 10 W/m^2. Thus, in the case of a private house, it would be necessary to provide a supplemental heating system.

6. Monitoring of energy consumption and decision criteria representing comfort, as well as other measurements, of Latvia's first LEB enabled identification and description of several errors incurred during construction. This serves as a valuable source of information for future LEB projects.

7. Buildings in Europe have an enormous potential for energy efficiency in terms of technical attainability and economic viability that is not currently being properly utilized. Renovation of existing buildings in Latvia is occurring slowly. Often only a portion of a renovation is realized and mid-sized renovation projects achieve a low reduction in energy consumption (up to 25%). Measurements and data analysis conducted for this thesis demonstrate how complex renovations that conform to minimal requirements of the construction standard LBN 002-01 can achieve a 50% reduction in energy consumption for heating and hot water needs, and still providing high comfort. Calculations and analyses of renovation examples show that existing buildings can achieve a larger reduction of energy consumption (up to 80%).

8. Optimization conducted for this thesis enabled determination of optimal sets of measures for energy efficiency for different types (series-based, multi-apartment building; private house etc.) of buildings. The analysis demonstrates that in considering long-term (35-year calculation period) investments in measures for energy efficiency, it is necessary to implement complex renovations that enable achievement of energy consumption for heating that is lower than 40 kWh/m^2 per year. In the case of new building construction, small-sized buildings (heating area smaller than 200 m^2) must have energy consumption lower than 35 kWh/m^2 per year for heating, and for larger buildings, lower than 25 kWh/m^2 per year.

9. The developed model is applicable for identifying optimal measures for energy efficiency, and it is utilizable for new construction projects and renovation work planning. This model is utilizable for determining criteria in creating government supported programs intended to increase energy efficiency.