Article no. 17

THE CIVIL ENGINEERING JOURNAL 3-2015

# SENSITIVITY ANALYSIS OF BUILDING STRUCTURES WITHIN THE SCOPE OF ENERGY, ENVIRONMENT AND INVESTMENT

*František Kulhánek[1], Kağan Poyraz[1*]*

1. *Czech Technical University, Faculty of Civil Engineering, Building Structures Department, Prague, Thákurova 7, 166 29 Praha 6, Czech Republic; kaganpoyraz@gmail.com (*Corresponding author)*

## ABSTRACT

The primary objective of this paper is to prove the feasibility of sensitivity analysis with dominant weight method for structure parts of envelope of buildings inclusive of energy; ecological and financial assessments, and determination of different designs for same structural part via multi-criteria assessment with theoretical example designs ancillary.

Multi-criteria assessment (MCA) of different structural designs or in other word alternatives aims to find the best available alternative. The application of sensitivity analysis technique in this paper bases on dominant weighting method. In this research, to choose the best thermal insulation design in the case of that more than one projection, simultaneously, criteria of total thickness (T); heat transfer coefficient (U) through the cross section; global warming potential (GWP); acid produce (AP); primary energy content (PEI) non renewable and cost per $m^2$ (C) are investigated for all designs via sensitivity analysis. Three different designs for external wall (over soil) which are convenient with regard to globally suggested energy features for passive house design are investigated through the mentioned six projections. By creating a given set of scenarios; depending upon the importance of each criterion, sensitivity analysis is distributed.

As conclusion, uncertainty in the output of model is attributed to different sources in the model input. In this manner, determination of the best available design is achieved. The original outlook and the outlook afterwards the sensitivity analysis are visualized, that enables easily to choose the optimum design within the scope of verified components.

## KEYWORDS

Sensitivity analysis, sustainable design, multi-criteria assessment, envelope structure

## INTRODUCTION

Considering the rise in the energy needs of the mankind, it is therefore necessary to balance the energy needs with environmental considerations through innovative and optimum technological ways. In this framework, energy efficiency comes to forefront as one of the key concepts that should be taken into consideration in these endeavors [1].

Good thermal insulation and compactness are key factors to achieve an energy efficient building. The designs cover construction components' energy assessment; ecological assessment and financial assessment.

There is a wide range of construction materials nowadays. The key point is using proper techniques by harmonizing correct practice and materials. Feasibility of the designs based on availability of materials. Therefore all materials used in the designs are accessible and already produced ones.

MCA is a decision-making way via evaluating multiple options that provides the best alternative between conflicting ones. MCA progress deals here within the sphere of environmental issues, energy outlook and investment cost. Dominant weight method-weighting method with implemented sensitivity analysis is used to find the optimum design for each envelope parts of a building. MCA of the different designs based on six criteria - T; U; GWP; AP; PEI and C (based on Turkish construction market prices) simultaneously.

The objective of this study is to find the most convenient design for the same structural place. The unclear qualification of between different designs is solved with sensitivity analysis.

## METHODS

In a situation where multiple criteria are involved confusion can arise if a logical, well-structured decision-making process is not followed. Another difficulty in decision making is that reaching a general consensus in a multidisciplinary team can be very difficult to achieve [2].

Under the light of specialized academicians' works, MCA is presented in the form of matrix which works as multiplying alternatives with criteria basically. That identifies the evaluation of each alternative connected to each criterion.

Dominant weight method-weighting method with implemented sensitivity analysis is used to find the optimum design for each envelope parts of a building. MCA of the different designs based on six criteria.

Six different criteria; thickness, heat transfer coefficient, cost, acid produce, primary energy content, global warming potential for three alternative construction types are elements of the sensitivity analysis in the paper. Each criterion has its own vector (d), weight (w) numbers.

Numerically, maximum weight or total weight number is "1" which is top number also for total weight element [Eq. 2]. All numeric values are converted to matrix system due to working system of the calculation. Numeric "vector" values and values of criteria are converted to matrix version called "dominance factor matrix" and "matrix values of the criteria" respectively. Multiplying weight and matrix of vector bring us "extended matrix dominant weights" which is used to calculate "dominance weight matrix" [Eq. 7, 8].

Depending on request or limits or experienced results optimum numbers for each criterion are taken into account and following that "calibrated values of the criteria matrix" is generated [Eq. 3, 5, 6].

To compare different criteria, "weighting matrix criteria" is calculated via calibrated values of the criteria and weights. "Characteristic value of structural alternatives" is calculated by matrix multiplication of weights and matrix values of the criteria [Eq. 1, 4]. Multiplying the calibrated values with weights (matrix multiplication) brings us "weighting matrix criteria" which is the source for visualization of graph of multi-objective sensitivity analysis.

Optimization of component of building structures in terms of environmental issues, energy outlook and cost is the aim of this document following the presented designs. Key component formulas used for calculations are presented below [3]:

Characteristic value of structural alternative as follows:

$$V_{char,i} = \sum_{j=1}^{n} c_{cal\,i j} w_j \tag{1}$$

Calibration of criteria values as follows:

$$\sum_{j=1}^{n} w_j = 1 \tag{2}$$

DOI 10.14311/CEJ.2015.03.0017

Optimum (best) value as follows:

$$c_{cal,ij} = c_{ij} / B_{Vj} \quad (3)$$

Matrix of characteristic values of dominant alternatives as follows:

$$[V_{char,ik}] = [c_{cal,ij}][w_{d,jk}] \quad (4)$$

Calibrated matrix of criteria values as follows:

$$[c_{cal,ij}] = [\{c_{cal,i1}\},\{c_{cal,i2}\} \ldots \{c_{cal,in}\}] \quad (5)$$

Calibrated criteria values as follows:

$$\{c_{cal\,ij}\} = \frac{1}{B_{Vj}}\{c_{ij}\} \quad (6)$$

Transformed matrix of dominant weights as follows:

$$[w_{d,jk}] = [\{w_{d,j1}\},\{w_{d,j2}\} \ldots \{w_{d,jn}\}] \quad (7)$$

Dominant weights as follows:

$$w_{d,jk} = \frac{w_j d_{jk}}{1+(D_k-1)w_k}; \quad \sum_{j=1}^{n} w_{d,jk} = 1 \quad (8)$$

Underside of each design comes out of different layers as components of design and each component has different features of energy, environment, and cost matters. In this context, energy and environmental values are based on Austrian Institute for Healthy and Ecological Building (IBO) press [4]. However, numerical values for the cost calculation and energy matters are based on various sources and market research [5-15].

## APPLICATION OF DOMINANT WEIGHT METHOD

### External Wall Structures

The designed structures' thermal transmittance value vary between 0.105 and 0.113 W/m$^2$K which are lower than the recommended values for Passive Houses by ČSN 73 0540-2 [16]. However, these designs are oriented for theoretical approach. Depending upon feasibility conditions, thickness of the thermal insulation materials may be lowered.

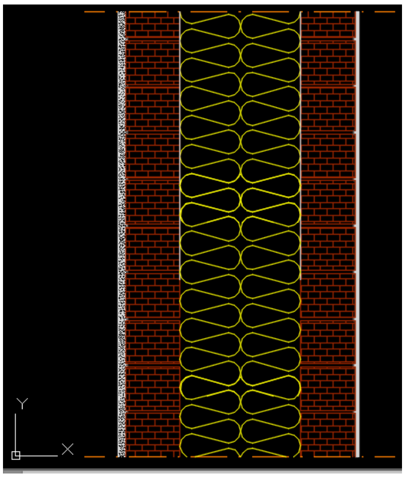

*Fig. 1: External wall design 1*

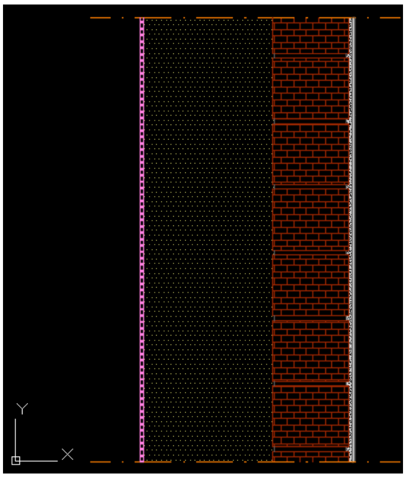

*Fig. 2: External wall design 2*

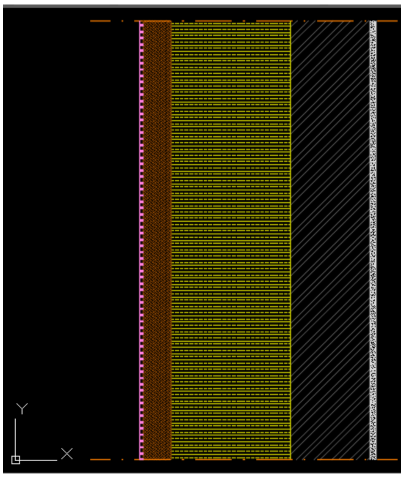

*Fig. 3: External wall design 3*

DOI 10.14311/CEJ.2015.03.0017

*Tab. 1: Components of each design*

| | Design 1 | Design 2 | Design 3 |
|---|---|---|---|
| **Material** | Lime Cement Plaster | Silicate plaster | Silicate plaster |
| | Honeycomb brick (190x190x135 mm) | EPS[1] | Wood wool lightweight panel (cement bound; 2x35 mm board) |
| | Glass wool | Honeycomb brick (290x235x190 mm) | Mineral wool (between wood C-post) |
| | Honeycomb brick (190x190x135 mm) | Lime Cement Plaster | Wood chip concrete hollow block masonry |
| | Gypsum plaster | Gypsum plaster | Lime Cement Plaster |

*Tab. 2: Vector, weight of each criterion and created dominance factor matrix*

| Nu | Criterion | Unit | Vector (d) | Weight (w) | Dominance Factor Matrix | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Thickness | Mm | 1 | 0.10 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | Heat transfer coefficient | $W/m^2K$ | 5 | 0.25 | 1 | 5 | 1 | 1 | 1 | 1 |
| 3 | Investment cost | Euro | 5 | 0.25 | 1 | 1 | 5 | 1 | 1 | 1 |
| 4 | Acid produce | kg $SO_2eq/m^2$ | 5 | 0.05 | 1 | 1 | 1 | 5 | 1 | 1 |
| 5 | Primary energy content | $MJ/m^2$ | 2 | 0.10 | 1 | 1 | 1 | 1 | 2 | 1 |
| 6 | Global warming potential | kg $CO_2eq/m^2$ | 1 | 0.25 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Total** | | | **18** | **1.00** | | | | | | |

*Tab. 3: Extension of dominant weights converted to matrix position*

| Weight | Extended Dominant Weights | | | | | |
|---|---|---|---|---|---|---|
| 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |
| 0.25 | 0.25 | 1.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| 0.25 | 0.25 | 0.25 | 1.25 | 0.25 | 0.25 | 0.25 |
| 0.05 | 0.05 | 0.05 | 0.05 | 0.25 | 0.05 | 0.05 |
| 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.20 | 0.10 |
| 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| **1.00** | **1.00** | **2.00** | **2.00** | **1.20** | **1.10** | **1.00** |

[1] EPS: Expanded polystyrene foam.

*Tab. 4: Converted dominant weights matrix*

| Dominant Weights | | | | | |
|---|---|---|---|---|---|
| 0.10 | 0.05 | 0.05 | 0.08 | 0.09 | 0.10 |
| 0.25 | 0.63 | 0.13 | 0.21 | 0.23 | 0.25 |
| 0.25 | 0.13 | 0.63 | 0.21 | 0.23 | 0.25 |
| 0.05 | 0.03 | 0.03 | 0.21 | 0.05 | 0.05 |
| 0.10 | 0.05 | 0.05 | 0.08 | 0.18 | 0.10 |
| 0.25 | 0.13 | 0.13 | 0.21 | 0.23 | 0.25 |
| **1.00** | **1.00** | **1.00** | **1.00** | **1.00** | **1.00** |

*Tab. 5: Criteria values of different designs*

| Nu. | Alternative Construction Types | Matrix Values of the Criteria | | | | | |
|---|---|---|---|---|---|---|---|
| 1 | External Wall 1 | 600.00 | 0.108 | 47.92 | 0.25041 | 955.96 | 402.248 |
| 2 | External Wall 2 | 535.00 | 0.105 | 34.35 | 0.27164 | 1,145.32 | 296.988 |
| 3 | External Wall 3 | 610.00 | 0.113 | 72.78 | 0.70147 | 1,939.43 | 127.386 |
| **Optimum Values** | | **500.00** | **0.100** | **50.00** | **0.30000** | **1,500.00** | **300.00** |

*Tab. 6: Calibration of the criteria values*

| Nu. | Alternative Construction Types | Calibrated Values of the Criteria Matrix | | | | | |
|---|---|---|---|---|---|---|---|
| 1 | External Wall 1 | 1.20 | 1.08 | 0.96 | 0.83 | 0.64 | 1.34 |
| 2 | External Wall 2 | 1.07 | 1.05 | 0.69 | 0.91 | 0.76 | 0.99 |
| 3 | External Wall 3 | 1.22 | 1.13 | 1.46 | 2.34 | 1.29 | 0.42 |

*Tab. 7: Compare of different criteria*

| Nu. | Alternative Construction Types | Weighting Matrix Criteria | | | | | |
|---|---|---|---|---|---|---|---|
| 1 | External Wall 1 | 0.120 | 0.270 | 0.240 | 0.042 | 0.064 | 0.335 |
| 2 | External Wall 2 | 0.107 | 0.263 | 0.172 | 0.045 | 0.076 | 0.247 |
| 3 | External Wall 3 | 0.122 | 0.283 | 0.364 | 0.117 | 0.129 | 0.106 |

*Tab. 8: Characteristic value of structural alternative and dominant alternatives*

| Nu. | Alternative Construction Types | $V_{char}$ | Matrix of Characteristic Values of Dominant Alternatives | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1 | External Wall 1 | 268.18 | 1.07 | 1.08 | 1.01 | 1.03 | 1.03 | 1.07 |
| 2 | External Wall 2 | 250.91 | 0.91 | 0.98 | 0.80 | 0.91 | 0.90 | 0.91 |
| 3 | External Wall 3 | 305.05 | 1.12 | 1.13 | 1.29 | 1.32 | 1.14 | 1.12 |

DOI 10.14311/CEJ.2015.03.0017

## COMMENTARIES

Sensitivity analysis distributed as 40% of environmental performance; 25% economic performance; 25% energy performance and 10% physical feature. Besides that, environmental parameters are divided into three sub-parameters as 5% acid produce; 10% primary energy content and 25% global warming potential. The progress of assigning weights can be iterative.

Under the circumstance of changing the multiplying element-vector factors' values, it has been found that:

Vector factor is not such effective to change the optimal order of thickness criteria. In the case of increasing or decreasing the importance all designs goes closer or further from the centre of the diagram.

Cost of the design is highly sensitive for "external wall 3" design. From the point of cost of investment the design shows disadvantages when the vector value is increased. The other two designs shows opposite behavior which means in the case of high vector value, "external wall 3" goes away from the centre of the diagram and "external wall 1" and "external wall 2" designs come closer to the centre. However, order between "external wall 1" and "external wall 2" designs does not change; in high or low vector values "external wall 2" design seems the most available one.

Heat transfer coefficient and acid produce criteria show very similar behavior as the thickness criteria. However it is clear that the biggest change is visible for "external wall 3" design. In the case of increased vector value "external wall 3" design goes away from the centre of the diagram. Anyway, "external wall 2" design seems as the best one for these criteria for different vector values.

If we increase numeric value of vector factor of primary energy content criterion, there is an interesting progress that "external wall 3" design seems as the last option and beside that, mostly favorite one -"external wall 2" behaves more sensitive than "external wall 3" design. For example, if we set up vector factor as "50"; "external wall 1" design comes closer to the centre than "external wall 2" design. This case is valid only when vector factor is more than "10".

Global warming potential criterion is the most interesting one due to numerical number of the vector. "External wall 3" design is the last case for overall criteria. However, for example, if the numeric value of the vector is "5"; the optimum design is "external wall 3". In the case of this vector value is "1", the optimal order from the best to last be as "external wall 2", "external wall 1" and "external wall 3". We can sum up as that "external wall 3" design is the most sensitive one for this criterion.

In the case of using ineffectual vector factor like "1" for all criteria, the optimal order from the best to last one as "external wall 2", "external wall 1" and "external wall 3" respectively.

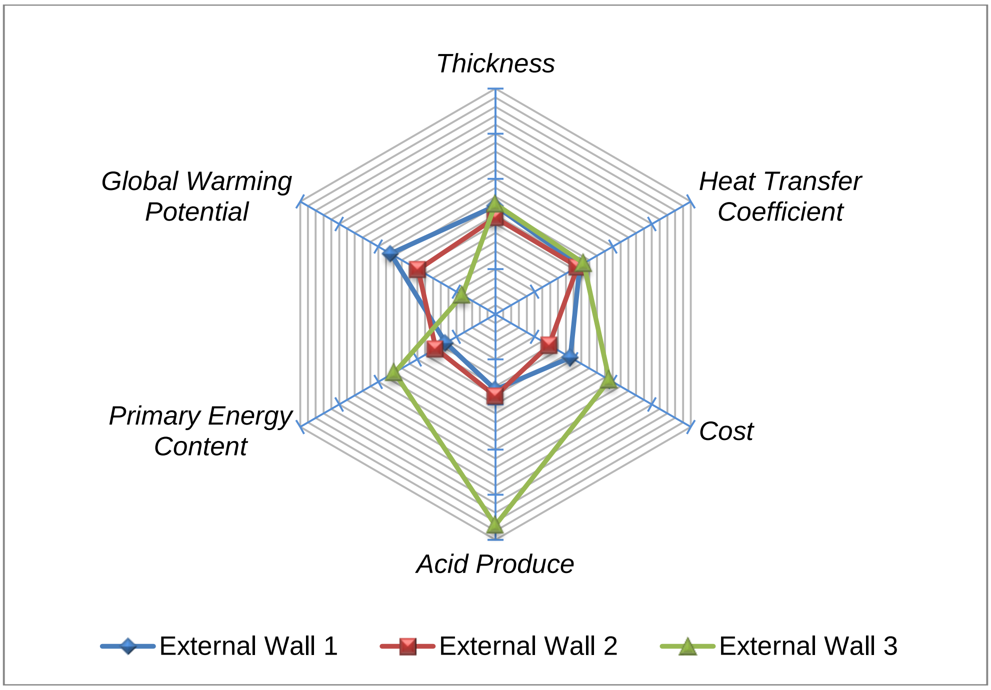


*Fig. 4: Comparison of different criteria*

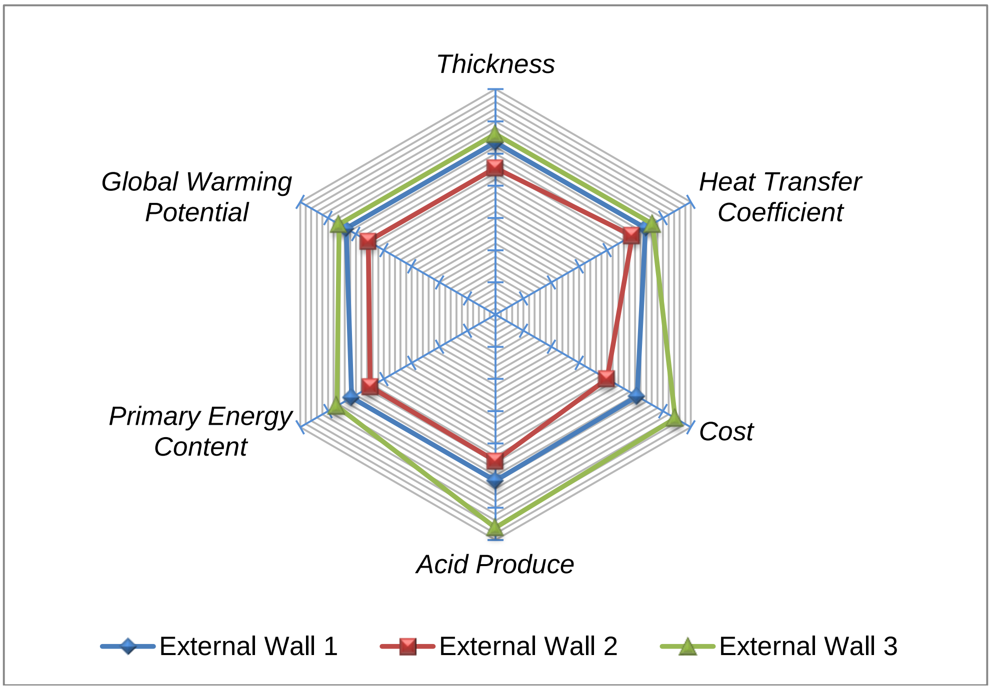


*Fig. 5: Multi-objective sensitivity analysis result*

## CONCLUSION

Sensitivity analysis can be called as “if and what” analysis for many fields. The mentioned analysis in the paper is applied for investigation of building components which consisted of different materials. The purpose of sensitivity analysis is to figure out matters which can influence the decision progress.

The try-out progress of multi-criteria analysis with the sensitivity analysis for different structural layers resulted with concrete result.

The basic principle of the visualized diagram bases on the distance to the centre as means the closer to the core, the better. The elementary condition was unclear for decision progress in the frame of multiple elements (see fig.4) due to different touch points of different criteria to the centre of the diagram. For example, the order starting from the best for global warming potential criteria is wall 3, wall 2 and wall 1 respectively. However, the same order changes as wall 2, wall 1 and wall 3 from the point of cost matter.

Eventually, it was succeed to locate each design with same order (see fig. 5) via the applied method. Therefore, uncertainty is removed for clear decision progress. Regarding to investigation of three different external wall structures; “External Wall 2” design seems as the best available one with the assigned weights. It should be also stressed that number of elements for multi-criteria assessment can be less or more.

## ACKNOWLEDGEMENTS

This study avails itself of doctoral thesis with title “Buildings with Low Energy Consumption for the Republic of Turkey” (2015) of Ing. Kağan Poyraz, Ph.D. with the supervision of Doc.Ing. František Kulhánek, CSc. at Czech Technical University in Prague.

## REFERENCES

[1] POYRAZ, Kağan. *Buildings with Low Energy Consumption for the Republic of Turkey*. Prague, 2015. Doctorate Dissertation. Czech Technical University in Prague. Vedoucí práce Doc.Ing. František Kulhánek, CSc.

[2] MultiCriteria Analysis. *Center for International Forestry Research: Local People, Devolution & Adaptive Collaborative Management Programme* [online]. 2009 [cit. 2015-07-30]. Dostupné z: http://www.cifor.org/acm/methods/mca.html

[3] HÁJEK, Petr. *Optimalizace a multikriteriální hodnocení funkční způsobilosti pozemních staveb: D24FZS2011*. Prague, 2014. Lecture. Czech Technical University in Prague

[4] AUSTRIAN INSTITUTE FOR HEALTHY AND ECOLOGICAL BUILDING (IBO). *Details for Passive Houses - A Catalogue of Ecologically Rated Constructions*. Vienna: SpringerWienNewYork, 2007. ISBN 978-3-211-29763-6.

[5] MINISTRY OF ENVIRONMENT AND URBAN PLANNING OF THE REPUBLIC OF TURKEY. *2013 Yılı İnşaat ve Tesisat Birim Fiyatları*. Ankara: İller Bankası, 2013. ISBN 978-1-111-16209-2.

[6] Wandelemente aus Holzspanbeton; Thermo-span IW 20/13 Innenwandsteine. *Baubook: Ökologische Bauprodukte* [online]. [cit. 2014-01-22]. Dostupné z: http://www.baubook.info/index.php

[7] *MaliyetAnaliz* [online]. 2014 [cit. 2014-01-04]. Dostupné z: http://www.maliyetanaliz.com

[8] *ODE Yalıtım Insulates the Future* [online]. 2013 [cit. 2013-01-09]. Dostupné z: http://www.ode.com.tr

[9] *Tunç Pazarlama* [online]. 2014 [cit. 2014-01-05]. Dostupné z: http://www.tuncpazarlama.com

[10] *Dinamik Isı A.Ş.* [online]. 2014 [cit. 2014-01-05]. Dostupné z: http://www.dinamik-izmir.com

[11] *İsolion Isı Yalıtım Sistemleri ve Kimyasalları* [online]. 2014 [cit. 2014-01-06]. Dostupné z: http://www.isolion.com.tr

[12] *İsolion Isı Yalıtım Sistemleri ve Kimyasalları* [online]. 2014 [cit. 2014-01-06]. Dostupné z: http://www.isolion.com.tr

[13] *Isover Saint – Gobain, Isover - the widest range of thermal, acoustic, and fire insulation* [online]. 2014 [cit. 2014-01-05]. Dostupné z: http://www.isover.cz/en

[14] *İzocam the Name of Insulation in Turkey* [online]. 2014 [cit. 2014-01-02]. Dostupné z: http://www.izocam.com.tr

[15] *Ankarapor* [online]. 2014 [cit. 2014-01-04]. Dostupné z: http://www.ankapor.com

[16] CZECH REPUBLIC. Tepelná Ochrana Budov - Část 2 Požadavky (Thermal Protection of Buildings - Part 2: Requirements). In: *Česká Technická Norma*. Czech Republic: Úřad Pro Technickou Normalizaci, Netrologii a Státní Zkušebnictví, 2011