WOOD RESEARCH
57 (4): 2012
591-600

WOOD AS A CONSTRUCTION MATERIAL: COMPARISON OF DIFFERENT CONSTRUCTION TYPES FOR RESIDENTIAL BUILDING USING THE ANALYTIC HIERARCHY PROCESS

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(Received April 2011)

ABSTRACT

Considering the growing importance of energy-efficient building methods, timber construction will play an increasingly important role in the future. In order to determine advantages and disadvantages of using wood as a leading constructional material, different construction types were compared: solid wood, wood-frame, concrete, brick, and steel construction. To quantify the comparisons the Analytic Hierarchy Process (AHP) was used. AHP enables the inclusion of various parameters, including descriptive ones, in a mathematical model through which the importance of each construction criterion forming part of the system can be calculated in order to provide objective decisions for construction. Analysis revealed that the top ranked criteria in decision-making include quality of life, construction cost and depreciation costs. On comparing different construction types the wood-frame construction was considered as the most suitable option for residential building.

KEYWORDS: Wood construction, analytic hierarchy process, building criteria, residential building.

INTRODUCTION

Today, the construction of wooden prefabricated residential units is supported by strong arguments; innovations and improvements introduced in the early 1980s helped promote wooden prefabricated residential construction around the world. The following changes are the most important: transition from on-site construction to industrial prefabrication, transition from stickbuilding to modular construction, increased use of glued lumber in construction, development of environmentally friendly solutions for wood protection (Humar et al. 2004), and the shift from small to large panel system construction. The present times, characterized by specific circumstances in the sphere of climate change, witness an intensive focus of architect engineers, construction engineers, and wood-technology engineers on searching for ecological solutions and construction methods that would allow for greater energy efficiency and, consequently, for a reduced environmental burden. The choice of a construction material is the most important decision and it has long term consequences for the owner of the structure (Johnson 1990). The external environmental impact of building depends on the materials used and the energy sources utilized (Assefa et al. 2010). Timber as a construction material is positively associated with well-being, aesthetic and eco-friendliness, which are important factors in the choice of a certain building construction mode, however these attributes are not sufficient on their own to trigger the choice of timber as a construction material (Gold and Rubik 2008). The advantages of using more timber materials with lower embodied global warming potential, embodied carbon, and realistic end-of-life disposal options, position timber as the building material with the lowest carbon footprint (John et al. 2010).

The abovementioned and also some other criteria affect the selection of one assembly construction versus the other. The aim of this study is to identify the criteria that have a particularly strong influence on the choice of the material. The second objective is to evaluate different types of constructions for the residential building regarding the selected criteria. We compared solid wood, wood frame, concrete, brick, and steel frame construction. To evaluate the impact of various wide-ranging criteria several multiple criteria decision making (MCDM) models have been developed such as the Multi-Attribute Utility Theory (MAUT) (Brugha, 2004), the Simplified Multi-Attribute Rating Technique (SMART) (Lootsma, 1996). The analytic hierarchy process (AHP) (Saaty 1980) seems to be appropriate tool for our purpose.

The MCDM models have been already used in the field of wood technology and construction building. Oblak et al. (2008) used a computer program DEXi for development of qualitative multi-attribute decision model for stock management in a wood-industry company. A procedure for multi-criteria selection of building assemblies was used for a computer tool for selecting the best combination of building assemblies for each particular design situation (Nassar et al. 2003). Frenette et al. (2008) evaluated light-frame wood wall assemblies presenting a methodology for quantitative evaluation of a set of performance characteristics.

The AHP has been widely used in applications. Smith et al. (1995) analyzed factors affecting the adoption of timber as a bridge material, where more then 20 criteria were accounted. Lipuščec et al. (2003) used the AHP model for classifying wood products according to the environment burdening during the process of manufacturing. Chauhan et al. (2008) showed the application of AHP as a tool used in the housing sector to help in decision making. Yang et al. (2010) used the AHP model for the energy efficiency assessment in residential building. The application of the AHP in the multi-criteria analysis of the selection of intelligent building systems was performed by Wong and Li (2006). However the AHP or other MCDM models for ranking construction material for building has not been published so far.

MATERIAL AND METHODS

The analytic hierarchy process

The AHP method enables combining tangible and intangible and quantification of empirical data and subjective judgments. The method works at three levels: (1) Level one is the creation of a decision tree by defining key criteria that influence the goal of the problem. The criteria can branch into several subcriteria, down to the final level of alternatives. Alternatives are concrete possibilities, the objects of decision-making. (2) Level two are paired comparisons between two objectives at the same level with regard to the parent element at the next higher level. (3) The final level, level three, is the calculation of the priorities of the elements of the hierarchy and the synthesis of these results to determine an overall outcome. Then the analysis of the results is performed (Saaty 1994).

The level two is the heart of the AHP method. For paired comparisons a fundamental scale of the AHP (Saaty 1994), from 1 to 9 is used (Tab. 1).

Tab. 1: The fundamental scale of the AHP (Saaty 1994).

Value a_{ij}	**Description**
1	Criteria i and j are equally important.
3	Criterion i is slightly more important than criterion j.
5	Criterion i is much more important than criterion j.
7	Criterion i is proved to be more important than criterion j.
9	Criterion i is absolutely more important than criterion j.
2, 4, 6, 8	Middle values

A reciprocal value is assigned to the inverse comparison, i. e. $a_{ij} = 1/ a_{ji}$. Comparisons between individual objectives are gathered in a comparison matrix A.

For deriving priorities Saaty (1980) presented the eigenvector method, where according to the comparison matrix A the priority vector w = ($w_1,\ldots, w_n$) is obtained by solving the equation: $Aw = \lambda_{max}w$, where λ_{max} is the largest eigenvalue of matrix A.

For each comparison matrix A consistency ratio is computed in order to measure the consistency among the paired comparisons:

$$CR = \frac{CI}{RI},$$

where: $CI = \frac{\lambda_{max} - n}{n-1}$ is the consistency index and n is the order of matrix A and RI is average random consistency index computed by Forman (1990). The consistency ratio $CR < 0.1$ is considered acceptable. Otherwise, the matrix results are inconsistent and the decision maker should revise his judgments.

In the group case there are two basic aggregating methods: the aggregation of individual judgments and the aggregation of individual priorities (Forman and Peniwati 1998). Individual judgments a_{ij}^k, k=1,…,m for m decision makers should be aggregated into group judgment a_{ij}^{group} using the geometric mean method

$$a_{ij}^{group} = \sqrt[m]{\prod_{k=1}^{m} a_{ij}^{k}}\,. \tag{1}$$

Group judgments a_{ij}^{group} are gathered in the group comparison matrix A^{group}. The group priority vector is obtained from A^{group} by the eigenvector method. Geometric mean method is the only appropriate method for aggregation of individual judgments, as it preserves the reciprocal property (Aczel and Saaty 1983). It is suitable when the decision makers have similar objectives and their judgments are homogenous (Saaty and Vargas 2007). If there are different interests or different knowledge foundations in the group, the aggregation of individual priorities should be used. It is important to reach a consensus on final priorities. A consensus iterative model whose mathematical foundations are based on the philosophy of negotiations has been developed by Lehrer and Wagner (1981) and adopted for AHP by Regan et al. (2006).

The iterative process starts with the initial priority vectors $^0w^k = (^0w_1^k,...,^0w_n^k)^T$ of k=1,…,m decision makers. They are modified according to the level of respect assigned to the other decision makers. The weights of respect v^{ij}_s are calculated on the base of the differences between the priorities.

$$v_s^{ij} = \frac{1-\left|{}^0w_s^i - {}^0w_s^j\right|}{\sum_{j=1}^{n}\left(1-\left|{}^0w_s^i - {}^0w_s^j\right|\right)} \tag{2}$$

They are written in the matrices of weights of respect $V_s = (v_s^{ij})_{mxm}$. Let ^0P_s denote the vector of priorities of all decision makers of the criterion s: $^0P_s = (^0w^1_s,...,^0w^m_s)^T$. The revised priorities of the criterion s after the first round of aggregation result in $^1P_s = V_s{}^0P_s = (^1w^1_s,...,^1w^m_s)^T$. The aggregation in the next steps is repeated with the same weights of respect: $^rP_s = (V_s)^r\,{}^0P_s$. As r approaches infinity, the improved priorities of the criterion s converge towards the consensual priority w_S, which is equal for all decision makers. Convergence is guaranteed (Lehrer and Wagner 1981) and in practice, it is attained in a few steps.

The decision tree for the selection of building construction

The components of the decision tree for our problem are goal, criteria, and alternatives (Fig. 1). The goal of our problem is to evaluate different types of building construction.

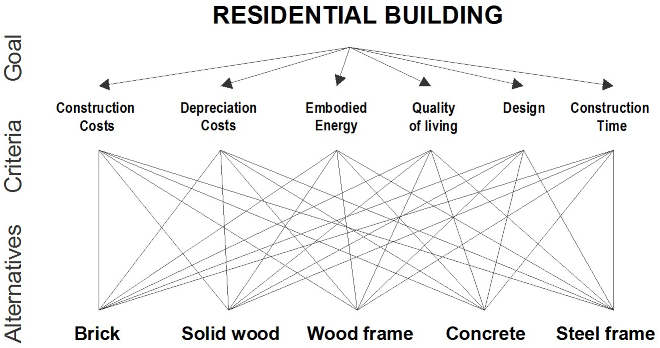


Fig. 1: The decision tree for choosing the most appropriate type of construction for a residential building.

There are the possible alternatives: Steel-frame construction, solid wood construction, wood frame construction, concrete construction, and brick construction. Which of these alternatives is the most suitable for the residential type of construction? The answer can be obtained by assessing the criteria that present the core of the decision tree. The selection of the criteria was conducted using the Delphi method (Gupta and Clarke 1996), which envisages several rounds of the process. In the first round, experts selected eighteen most important construction criteria: quality of living, design, energy efficiency, fire safety, construction time, material embodied energy, life time, reliability, construction costs, depreciation costs, mechanical resistant and stability, national building promotion, resistance to external factors, prefabrication, local disposability of material, global raw material price movement, advertising effects. In the second round, nine out of eighteen most important criteria were selected: Quality of living, design, energy efficiency, material embodied energy, fire safety, construction time, construction costs, depreciation costs, mechanical resistance and stability. Three out of nine criteria (mechanical resistance and stability, fire safety and energy efficiency) need to be fulfilled already by the construction standards and are therefore omitted from construction ranking. The remaining criteria applied in construction ranking are shown on Fig. 1.

Survey on paired comparisons of the criteria

Based on the decision tree, a questionnaire with paired comparisons of construction criteria with regard to the goal was composed. We desired to establish which criterion is more important for a residential type of construction and how much more. Eleven surveys were conducted. The research included only experts i.e. architect engineers, construction engineers, and wood-technology engineers from several countries. The transfer of expert knowledge into the model increased the credibility of the final model. The general public was purposely not included in the survey of paired comparisons because the model is based solely on expert criteria.

Tab. 2: An example of a result of paired comparisons.

Compared criteria			Result
1.	Quality of Living	: Construction Costs	3:1
2.	Quality of Living	: Construction Time	7:1
3.	Quality of Living	: Depreciation Costs	4:1
4.	Quality of Living	: Design	3:1
5.	Quality of Living	: Embodied Energy	3:1

An example of the result of paired comparisons is presented in Tab. 2. If the responses of the expert were not of acceptable consistency, the expert was assembled once more to assess his judgments.

RESULTS AND DISCUSSION

Priorities of the selected criteria

After the experts' opinions had been collected, we joined them by the experts' areas: architecture, construction, and wood-technology. It is expected that the experts from the same field have homogenous judgments. This justifies the use of geometric mean method (1). The group judgments were gathered in the group comparison matrices. Following the eigenvector method, priority vectors for six selected criteria for three areas' comparison matrices were calculated. The final group priorities were obtained by applying the consensus model (2) to the three areas' priorities vectors. The group priorities for the criteria are in Tab. 3.

Tab. 3: Priorities and ranking of building criteria for residential building.

	Wood technology engineers	Architect engineers	Construction engineers	Consensus	Rank
Quality of Life	0.31	0.33	0.38	0.34	1
Construction Costs	0.25	0.14	0.15	0.18	2
Construction Time	0.10	0.06	0.04	0.07	6
Depreciation Costs	0.19	0.12	0.20	0.17	3
Design	0.11	0.25	0.09	0.15	4
Embodied Energy	0.05	0.09	0.14	0.09	5

The criteria quality of living is ranked highest and is stepping out (w = 0.34). The second place goes to the construction costs (w = 0.18), which is followed by the criterion of deprecation costs (w = 0.17) and design (w = 0.15). The criterion of embodied energy is ranked fifth (w = 0.09) and the construction time (w = 0.07) is ranked last.

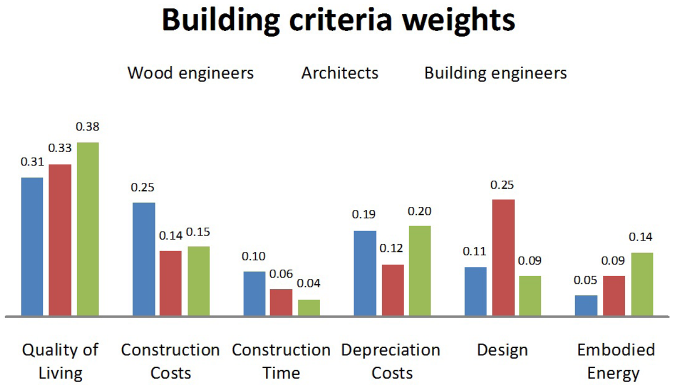


Fig. 2: Comparison of obtained priorities of the criteria in terms of team of experts who took part in the survey.

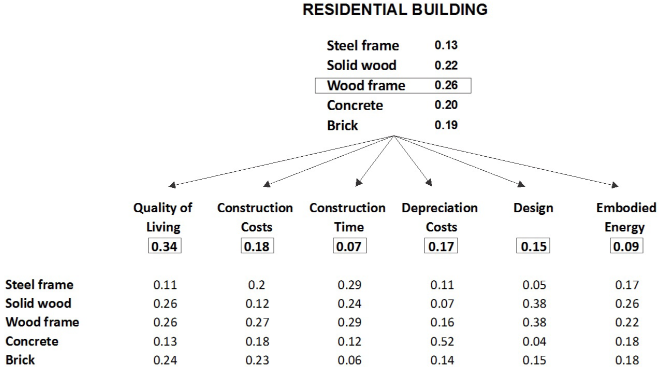
The comparison between the responses of the expert groups that participated in the survey (i.e., architect engineers, construction engineers, and wood-technology engineers) is carried out (Fig. 2). The group of architect engineers stood out among the experts, giving a higher assessment to the factor of Design in comparison to the others.

Assessment of Alternatives with Each Criterions

Five different types of construction were addressed in the research (alternatives in the decision tree): Solid wood, wood frame, concrete, brick, and steel frame construction. Each type of construction was assessed separately for each of the six key criteria of building construction. The weighting coefficients of the construction costs criterion were selected on the basis of average costs per square meter of the selected wall types. Depreciation costs were assessed based on the relation between the service life of the material and construction costs. Factors such as prefabrication level, drying, transport, knowledge, and experience in using elements affected the estimate of the construction time criterion. Quality of living was assessed based on the comfort, health and psychological factors. The weighting coefficients for the construction design criterion were estimated based on the indicators, such as functionality, span possibility, multistory construction, system solutions, and surface efficiency, and were selected on the basis of the survey. Embodied energy in building materials represents the non-renewable energy consumed in the acquisition of raw materials, their processing, manufacturing, transportation to site, and construction – it represents the relationship between building materials, construction processes, and their environmental impacts. It was defined as the commercial energy that was used in the process of making a product, bringing it to the market, and disposing of it (cradle to cradle) (John et al. 2010).

Results of the Decision Tree

The decision tree combines weights of importance for each criterion and alternative separately. The priorities of each construction type (alternative) were obtained through the matrix multiplication of values of alternatives and the criterion vector of priorities. Fig. 3 presents the decision tree for residential construction, showing that wood frame construction obtained the highest priority, whereas steel construction scored the least.



RESIDENTIAL BUILDING

Steel frame	0.13
Solid wood	0.22
Wood frame	0.26
Concrete	0.20
Brick	0.19

	Quality of Living 0.34	Construction Costs 0.18	Construction Time 0.07	Depreciation Costs 0.17	Design 0.15	Embodied Energy 0.09
Steel frame	0.11	0.2	0.29	0.11	0.05	0.17
Solid wood	0.26	0.12	0.24	0.07	0.38	0.26
Wood frame	0.26	0.27	0.29	0.16	0.38	0.22
Concrete	0.13	0.18	0.12	0.52	0.04	0.18
Brick	0.24	0.23	0.06	0.14	0.15	0.18

Fig. 3: The decision tree for residential building, the priorities of criteria, the priorities of alternatives with regard to the criteria and the final priorities of alternatives.

Fig. 4: The final priorities of different types of construction for residential construction.

The final priorities of different types of construction are shown on Fig. 4. Priority of the wood frame construction is the highest (w = 0.26) and is followed by the solid wood construction (w = 0.22), while the concrete and brick construction almost shared the third place (w = 0.20, w = 0.19). The steel frame construction (w = 0.13) was scored as last. The result was expected, because the positive trend towards low carbon wooden construction is an important starting point, not only for low-energy, but also for low-emission building with exceptional health and safety aspects. Using more timber in construction can reduce the carbon footprint of the building.

CONCLUSIONS

Construction building is a complex and multidisciplinary field. The decisions are influenced by various parameters like economic, type of construction, design, ecology etc. To rationalize decision process and to reveal the critical quality attributes application of mathematical models should be considered. Bridging over several fields of expertise, a multicriteria analysis process has the advantage of considering a number of these performance criteria simultaneously. It also brings the possibility of weighting the various criteria in respect of a specific design and building context.

Our case study showed the application of the AHP method for analyzing the decision criteria related to the residential buildings. Analysis revealed that the top ranked criteria in decision-making are besides load capacity, fire safety and energy efficiency obviously quality of life, construction cost and depreciation costs. Comparing different construction types the wood-frame construction was considered as the most suitable for residential building of various standards. Being a natural raw material, timber represents one of the best choices for energy efficient construction, since it also functions as a good thermal insulator, has good mechanical properties, and ensures a comfortable indoor living climate. It should be noted that very few buildings are made entirely out of a single material. Good, sensible building construction should combine the use of appropriate materials and technology.

In the future, such analysis should help professionals make a clearer choice regarding further optimizing and developing particular aspect of the building process, by giving them the possibility of comparing different alternatives on a common and comprehensive basis. Moreover, it can identify weak and strong aspects of wood building and thus it can give a new dimension to the promotion and marketing of wood buildings by allowing a better appreciation of the impact of individual parameters on other performance criteria. The findings of such models can be further integrated into strategies to increase the usage of timber as a construction material.

ACKNOWLEDGMENT

This study was a part of the Research Program "Wood and lignocellulosic materials" supported by the Ministry of Higher Education, Science and Technology of the Republic of Slovenia.

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