Energies **2013**, *6*, 4591-4606; doi:10.3390/en6094591

OPEN ACCESS

energies

ISSN 1996-1073

www.mdpi.com/journal/energies

Article

Method for Cost-Benefit Analysis of Improved Indoor Climate Conditions and Reduced Energy Consumption in Office Buildings

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Received: 23 May 2013; in revised form: 22 August 2013 / Accepted: 22 August 2013 / Published: 3 September 2013

Abstract: Indoor climate affects health and productivity of the occupants in office buildings, yet in many buildings of this type indoor climate conditions are not well-controlled due to insufficient heating or cooling capacity, high swings of external or internal heat loads, improper control or operation of heating, ventilation and air conditioning (HVAC) equipment, *etc*. However, maintenance of good indoor environmental conditions in buildings requires increased investments and possible higher energy consumption. This paper focuses on the relation between investment costs for retrofitting HVAC equipment as well as decreased energy use and improved performance of occupants in office buildings. The cost-benefit analysis implementation algorithm is presented in this paper, including energy survey of the building, estimation of occupants dissatisfied by key indoor climate indicators using questionnaire survey and measurements. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) analysis is used in the proposed method for data processing. A case study of an office building is presented in order to introduce an application example of the proposed method. Results of the study verify the applicability of the proposed algorithm and TOPSIS analysis as a practical tool for office building surveys in order to maximize productivity by means of cost efficient technical building retrofitting solutions.

Keywords: indoor climate; productivity; energy consumption; office buildings; cost-benefit analysis

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1. Introduction

Financial losses related to decreased office work performance in most cases are several times higher compared to the energy saved due to reduced indoor environmental conditions. Yet, with continuing stress on energy prices and overwhelming scientific consensus about the climate impact of fossil fuel depletion [1] energy efficiency should also be considered while discussing of human productivity-related investments as well as maintenance of HVAC systems. Space heating accounts for about 26% of all final energy consumption in the EU [2,3] and estimates show that in 2002 buildings accounted for 33% of the global greenhouse gas emissions [4].

Seppänen *et al.* [5] outlined a relation between human performance and air temperature based on various productivity studies. It showed that performance increases when the air temperature rises up to 21–22 °C and decreases by approximately 2% per 1 °C increase of air temperature in the range of 25–35 °C. The relationship was statistically significant within air temperature ranges below 20 °C or above 24 °C. The maximum performance is achieved at air temperature of *ca*. 22 °C.

Indoor air quality (IAQ) has impact on office work performance as well. Wyon [6] reported that poor IAQ could reduce office work performance by 6%–9%. Seppänen *et al.* [7] presented a study that incorporated the results of nine surveys and identified that increasing air change rate in the building from 6.5 to 65 liters per second per person results in an increase of productivity of the occupants. However, statistically significant results were obtained when the airflow was increased to 15 L/s per person (95%) and to 17 L/s per person (90%).

According to the study presented by Seppänen and Fisk, decreased occupant dissatisfaction with IAQ by 10% results in a 1.1% reduction of their productivity by while performing tasks such as text typing, calculating or editing. The results were statistically significant when the dissatisfaction with IAQ was in the range of 25%–70% [8].

Other indoor environmental factors such as humidity, frequency of occurrence of sick building syndrome symptoms have an impact on office work productivity as well. However, the thermal sensation of the occupants has a major influence on overall satisfaction with indoor environmental quality compared with the impact of other indoor environmental conditions [9]. Impact of thermal sensation can be expressed either using productivity as a function of predicted mean vote (PMV) or productivity as a function of air temperature. Using the latter, may require modifications of effects on productivity based on physical activity and clothing level of the occupants [10].

Air temperature in naturally ventilated buildings depends more on external conditions compared to mechanically ventilated buildings. The study performed by Bassam *et al.* [11] in naturally ventilated office buildings showed that thermal environment was mostly too warm during the warm season, and thermal environment as well as too low air movement dissatisfied more than the half of the occupants. However, more than 90% of the occupants were satisfied by thermal environment during the cold season.

Nikulin *et al.* [12] have presented Europe's climate forecast for the XXIst century. According to the study, annual air temperature would increase by 2–4 °C in northern Europe and 4–6 °C in southern and eastern Europe until the end of the century. Extreme alterations are expected on February. Regarding the forecast, day temperature range will splay out, inrush of brief strong winter frosts will be more frequent. The authors prognosticated a longer duration of the high sun range during an average season.

This would be extremely perceptible during May to September. Outdoor climate change in the future will most likely have even more significant effects on indoor environmental conditions.

Various authors have presented numerous studies dealing with energy efficiency and potential savings of renovation. However, more often than not, these ignore the effects of refurbishment actions on the productivity of the building occupants [13–15]. Nevertheless, there are studies showing that measures for improving indoor climate are cost-effective when health and productivity benefits resulting from improved conditions are calculated [16–22]. Wargocki *et al.* [23] have presented generalization of the studies in the field of indoor environment and productivity and outlined key aspects on how occupant productivity assessment could be integrated into cost-benefit calculations. Jensen *et al.* [24] have introduced a performance index (Π) which can be used to compare directly the different building designs and to assess the economic consequences of the indoor climate with a specific building design by using the Bayesian Network.

However, there is still lack of established procedures and descriptions which could be followed in order to perform thorough estimations. This includes performing questionnaire surveys as well as measurements of indoor environmental parameters. Later on, various tools could be used to collect data on energy performance of the building including energy simulation software. The systematic approach could be used for this kind of method including dealing with high level of uncertainties, as there are differences between reported effects of indoor environment on productivity.

In this paper, a method for cost-benefit analysis of existing office buildings in relation to energy use and office work performance is proposed. The results and conclusions of this study were based on the findings obtained by the theoretical model as well as experimental research. The core of the method is the algorithm of procedures which should be followed for cost-benefit calculations while retaining flexibility for adapting various probabilistic models as well as statistical analysis.

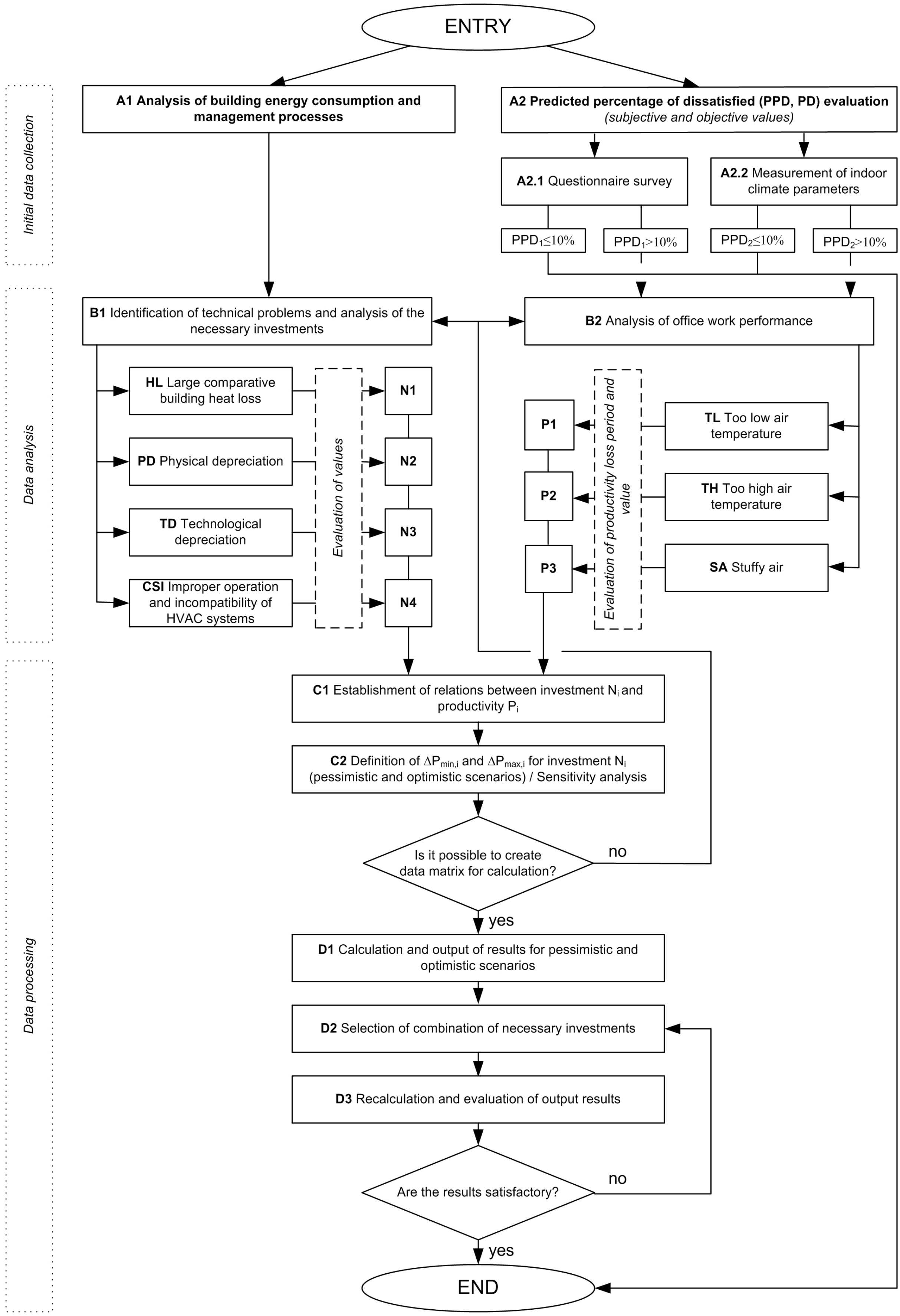
2. Methods

2.1. Description of the Energy Performance and Occupant Productivity Assessment Method

The Energy Performance and Occupant Productivity assessment method (EP-OP) for complex assessment of office building refurbishment in consideration of existing indoor environmental conditions, predicting increased office work performance, energy consumption and technical state of the building envelope as well as HVAC equipment was developed. The evaluation procedure in the form of an algorithm is presented in Figure 1. The main steps of the procedure are grouped into: (1) initial data collection; (2) data analysis and (3) data processing. The outcome of the solver calculations is a combination of measures for energy use reduction as well as productivity improvement. Each step of the procedure is described below.

The initial data collection step consists of analysis of energy consumption and control parameters of HVAC equipment as well as questionnaire survey of the occupants and measurements of indoor environmental parameters. Collected data should include percentage of occupants dissatisfied by indoor air quality and thermal comfort conditions (PD and PPD indices). PPD index could be obtained either by measurements using thermal environment measurement system containing operative temperature, relative humidity and air velocity sensors or by means of questionnaire.

Figure 1. Algorithm of EP-OP method procedures.



It is possible to evaluate office work performance according to thermal sensation vote as well. Measurements of air temperature are not sufficient for the EP-OP method as thermal sensation depends on the seasonal conditions, physical activity and clothing level of the occupants [10]. It could only be used for comparison with the results of questionnaire survey. Questionnaire survey or measurements of either CO_2 concentration in the occupied zone or ventilation rates may be used for determining PD value. There should be possibility for the occupants of the building to indicate the main problems related to indoor climate in the questionnaire and to attribute specific complaints to the season of the year (summer, winter as well as autumn and spring). Single time measurements may also provide investigator with additional data such as draught rate, poorly ventilated zones in rooms, *etc*. Results of long-term measurements such as air temperature or CO_2 concentration monitoring could be directly used for EP-OP analysis.

Collected data should include duration periods of dissatisfaction, e.g., office workers may be affected by too high an air temperature during the whole summer or only several weeks a year. Therefore, after obtaining seasonal dissatisfaction levels and duration periods it is possible to evaluate annual productivity losses. In the case where the PPD value obtained by both long-term measurements and questionnaire survey is below 10%, the assumption could be made that improvement of indoor climate will not result in a significant productivity increase. However, if the PPD value is above 10%, estimation of current productivity loss should be executed within the procedures of step 2. The margin of PPD value equal to 10% is used in the model as it corresponds to PMV range between −0.5 to +0.5 which are the limiting values in most standards [25]. However, the investigator may modify it for specific cases.

The energy performance analysis is implemented within the initial step in order to estimate average energy demand for space heating and cooling. In this step, thermal transmittance coefficients of the building should be either calculated or measured. Energy consumption calculations for determining annual heating and cooling demand should be performed according to the standards. Simulation software acquiring data of building energy performance or building energy certification tools could be used as well. This completes the initial data collection step.

The second step of the algorithm consists of data analysis. Therefore, the following procedures include identification of the technical problems related to energy consumption and calculation of the required investment for increasing energy efficiency of the building. Deterioration state of the HVAC equipment should be considered as well by performing visual inspection and determination of the status of HVAC systems. Data for determining deterioration state of the building may be obtained from either standards or manuals by using life spans of the equipment installed in the analyzed building.

Measures that could be implemented and refurbishment actions should be expressed in monetary value per one square meter of the building floor area using annuity methods. Expected energy consumption reductions may be estimated according to existing statistical data or documented results of the research and case studies.

The current productivity loss would be calculated using the data of either results of the questionnaire survey or long-term measurements. The data would be estimated according to predicted percentage of people dissatisfied by thermal comfort (PPD). Evaluation of thermal sensation vote would provide data required for the sensitivity analysis where both relations: productivity as a function of temperature and productivity as a function of thermal sensation should be used. Duration of the period when office employees are exposed to particular indoor climate conditions should be taken into account as well. Productivity loss would be calculated into annual monetary value per square meter of the building considering density of the occupants and average salary of the employees.

The third step of the algorithm involves data processing. The relations between possible building refurbishment actions, energy savings and productivity gains would be established and sensitivity analysis performed afterwards.

The main concept of sensitivity analysis presented in this paper is definition of pessimistic and optimistic scenarios. Methods suggested by Wargocki *et al.* were used to combine evaluation of different indoor environmental parameters on productivity [23]. Refurbishment actions would have different impacts on productivity changes in different cases. For example, additional insulation of the building envelope may have no effect on productivity in a pessimistic scenario, however, it may lead to increased air temperature in rooms, and therefore predicted productivity gains may be included in the optimistic scenario. On the other hand, some actions may increase energy costs while having a positive effect on occupant productivity. As a part of sensitivity analysis of the model, it would be useful to check the range of productivity change from the perspective of air temperature as well as thermal sensation and use this range for calculations of pessimistic and optimistic scenarios.

Data collected within previous steps of EP-OP method would be processed using TOPSIS as a tool for determination of optimal solution. Matrix for application TOPSIS technique for pessimistic and optimistic scenario are produced. The result is obtained outlining technical measures, which should be taken in order to optimize energy use in the building and work performance of the employees.

2.2. The TOPSIS Technique

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was developed by Hwang and Yoon [26]. This method is based on the idea that the selected alternative should have the shortest distance from the ideal solution and the farthest distance from the negative solution [27]. The ideal solution may be defined as an imaginary action leading to the best possible results from all of the analyzed alternatives, e.g., lowest installation costs and both highest energy saving and productivity increase potential. A negative solution is the opposite of the ideal solution and emphasizes the worst set of results from the given alternatives. It evaluates the following decision-making matrix, which refers to *m* alternatives evaluated in terms of *n* criteria:

$$P = \left[x_{ij}\right] = \begin{matrix} a_1 \\ a_2 \\ \ldots \\ a_m \end{matrix} \begin{bmatrix} x_{11} & x_{12} & \ldots & x_{1n} \\ x_{21} & x_{22} & \ldots & x_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ x_{m1} & x_{m2} & \ldots & x_{mn} \end{bmatrix} \quad (1)$$

where x_{ij} denotes the performance measure of the *i*-th alternative in terms of the *j*-th criterion; a_i denotes alternatives.

Using the TOPSIS technique, various criteria dimensions are converted into non-dimensional criteria. An element x_{ij} of the normalized decision matrix *P* is calculated as follows:

$$\bar{x}_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}; \text{ for } i = \overline{1,n} \text{ to } j = \overline{1,m} \tag{2}$$

A set of weights x_{11}-x_{mn} defined by the decision maker is used with the decision matrix to generate the weighted normalized matrix $\bar{P}$ as follows:

$$\bar{P} = \left[\bar{x}_{ij}\right] = \begin{matrix} a_1 \\ a_2 \\ \dots \\ a_m \end{matrix} \begin{bmatrix} \bar{x}_{11} & \bar{x}_{12} & \dots & \bar{x}_{1n} \\ \bar{x}_{21} & \bar{x}_{22} & \dots & \bar{x}_{2n} \\ \dots & \dots & \dots & \dots \\ \bar{x}_{m1} & \bar{x}_{m2} & \dots & \bar{x}_{mn} \end{bmatrix} \tag{3}$$

The ideal, denoted as a+, and the negative, denoted as a-, alternatives are defined as follows:

$$a^{+} = \{[(\max_i \bar{x}_{ij} \mid j \in J), (\min_i \bar{x}_{ij} \mid j \in J')] / i = \overline{1,m}\} = \{a_1^{+}, a_2^{+}, \ \dots, a_n^{+}\} \tag{4}$$

$$a^{-} = \{[(\min_i \bar{x}_{ij} \mid j \in J), (\max_i \bar{x}_{ij} \mid j \in J')] / i = \overline{1,m}\} = \{a_1 , a_2 , \ \dots, a_n \} \tag{5}$$

where: J = {j = 1, 2, ..., n and j is associated with benefit criteria}; J' = {j = 1, 2, ..., n and j is associated with cost/loss criteria}.

It is reasonable to consider that the decision maker seeks to have a maximum value among the alternatives in the aim of benefit. The separation from the ideal solution is calculated by Equation (6). Similarly, the separation from the negative solution is calculated by Equation (7):

$$L_i^{+} = \sqrt{\sum_{j=1}^{n} \left(\bar{x}_{ij} - a_j^{+}\right)^2}; i = \overline{1,m} \tag{6}$$

$$L_i^{-} = \sqrt{\sum_{j=1}^{n} \left(\bar{x}_{ij} - a_j^{-}\right)^2}; i = \overline{1,m} \tag{7}$$

Relative closeness to the ideal solution is calculated as follows:

$$K_i = \frac{L_i^{-}}{L_i^{+} + L_i^{-}}, i = \overline{1,m} \tag{8}$$

The range of K_i varies between 0 and 1 and the closest to 1 is closest to the ideal solution. According to the presented EP-OP method, relative closeness to the ideal solution would be calculated twice for each alternative, using the values from pessimistic and optimistic scenario of occupant productivity change.

The procedure follows by the final data processing step. During this step the output of the calculation would be analyzed and the combination of the measures for increasing energy performance as well as office work productivity is selected. It should be evaluated by the decision maker and the final solution may include several refurbishment actions, e.g., insulation of the building envelope and installation of cooling devices. However, the primary results of the calculations outline which measures are most beneficial for the investor.

3. Verification of the EP-OP Method

3.1. Description of the Case Study Building

An existing office building in Lithuania had been selected in order to present an application example of the EP-OP method (Figure 2). The building was built in Kaunas in 1950 and was refurbished in 2000. The floor area of the building is 960 m^2.

Figure 2. The view of the case study building used as an example case study for the EP-OP analysis.

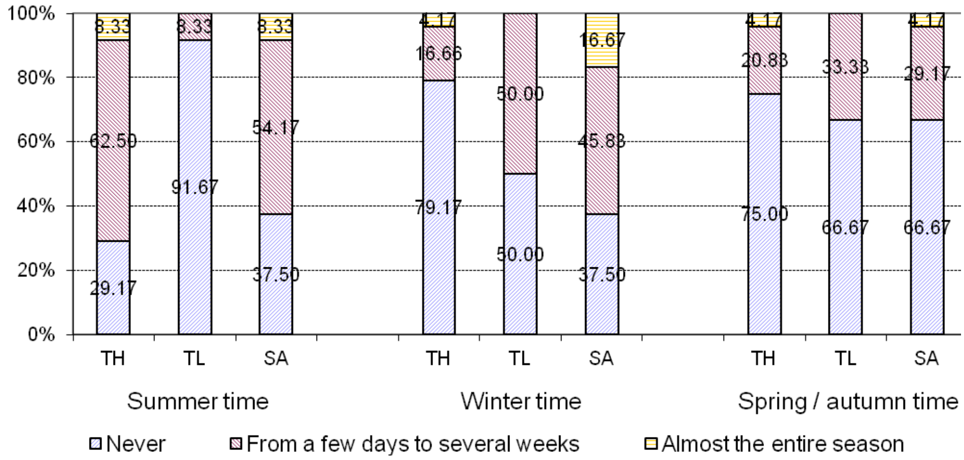
Energy class of the building is "E". Thermal transmittance coefficients for walls and windows are 1.12 W/m^2K and 1.60 W/m^2K respectively. Evaluated energy consumption for space heating is 241 kWh per square meter of net floor area per year. Offices are heated by two natural gas boilers of 40 kW heating power each. Estimated energy cost −0.08 €/kWh. Indoor air temperature is controlled according to the external air temperature by either compensating heating controller or adjustment of the thermostatic radiator valves. Employees working in the office are allowed to adjust thermostatic valves on the radiators to their thermal comfort needs. Energy demand for space heating and cooling was estimated according to requirements outlined in national standards and building codes.

Indoor air temperature during weekends and after working hours is being reduced by 4 degrees. During working days air temperature is being decreased from 5:30 pm to 7:00 am, and on Saturdays air temperature is set back to approximately 20 °C from 9 am till 2 pm because some offices in the building are also used on Saturdays. Natural ventilation has been installed in the building and consists of window fresh air inlets and passive stack air extraction from sanitary rooms. The occupation density in the building is less than 0.1 person per square meter, which is outlined in the standards [28] (34 employees per 461 m^2 of office area). Canteen and workshop is located in the rest part of the building. Based on the procedures of the initial data collection step of the EP-OP analysis algorithm (Figure 1) employees have filled out the questionnaires by indicating their thermal sensation, perception of air quality and humidity in the winter, summer, spring and autumn season. Operative temperature, air velocity and relative humidity had been measured during wintertime using the thermal comfort monitoring system (Innova 1221, Lumasense, Denmark). PMV and PPD indices were calculated by the software, using the PMV thermal sensation scale [25]. No measurements of ventilation rates or CO_2 concentrations were carried out. The assumption was made that such short term measurements would not present reliable data for long-term occupant performance calculations as it mostly depends on outdoor conditions.

3.2. Results

Results of the questionnaires for specific indoor environmental issues are presented in Figure 3. The values in the figure are shown in percent, where 0% means the statement is false and 100% means the statement is very true. 24 of 34 employees filled out the questionnaires. The type of work performed in the office involved calculations, accounting and engineering design. The questionnaire survey showed that 33.3% of the employees were generally not satisfied with the thermal environment in summer and 12.5% in winter. There was no dissatisfaction during the spring and autumn periods. Participants were mostly dissatisfied with intermittent air temperature, too high air temperature in summer, too low air temperature in winter as well as dry air in winter and stuffy air in both cold and warm seasons. Some more questions related to indoor environment such as dry air, draught, *etc.* were presented in the questionnaires. However, as they were not directly related to the selected actions for building refurbishment and did not indicate significant problems, so they were excluded from Figure 3.

Figure 3. Levels of dissatisfaction by too high air temperature (TH), too low air temperature (TL) and stuffy air (SA) of the occupants obtained by means of the questionnaire survey performed in the analyzed building.



A significant number of employees complained of stuffy air during both summer and winter seasons. This was not the case during transient seasons which may be a result of window opening. The number of persons complaining of too high or too low air temperatures as well as stuffy air in spring and autumn was lower. It is been indicated by many authors that occupants perceive warmer air as being of worse quality. The assumption, that increasing air temperature during wintertime will not increase level of complaints by stuffy air, had been made in this analysis.

Short-term measurements of thermal environment had been performed in the analyzed building during wintertime. It showed that average measured value of PPD index was 9.14%, operative temperature and relative humidity was 21.8 °C and 32.3% respectively. According to the logic of presented EP-OP algorithm, using such measurement results only would lead to conclusion that no improvement action to improve thermal conditions during winter is required. However, as results received from the questionnaire survey indicated a PPD value of 12.5%, the evaluation of productivity losses due to too low air temperature in winter was carried out.

Specification of technical as well indoor environmental problems related to energy consumption and office work performance are presented in Tables 1 and 2, respectively. Average profit generated by one employee was estimated to be equal to 20% of average monthly salary of each employee which was approximately equal to 1000 € excluding taxes. It was considered that the profit was equal to 9 € per day per person, having in mind that the employees work 8 h a day, 22 days per month. Considering the density of the employees in the building the profit was equal to 0.66 € per day per one square meter of the office area.

Table 1. Specification of technical problems of the analyzed building related to energy consumption.

Index	Technical problem	Description of required investment	Required investment €/m^2 *	Annual savings €/m^2
N1	High comparative building heat losses	Energy class of the building—"E". Additional insulation for building envelope would lead to thermal energy saving of approximately 40%. Life time of the investment is 20 years.	5.24	7.70
N2	Physical depreciation	Conventional natural gas fired boilers installed 13 years ago are physically and technologically outdated and unreliable. Replacement of conventional natural gas fired boiler into a gas condensing boiler would save about 8% of the thermal energy [29]. Life time of the investment is 10 years.	0.87	1.54
N3	Technological depreciation	Natural ventilation does not provide the required ventilation rate (10 L/s per person) and does not save energy. Heat recovery ventilation with air cooling would save about 25% of thermal energy [30,31]. Life time of the investment is 10 years.	1.32	4.82
N4	Improper operation and incompatibility of HVAC systems	Indoor air temperature is being controlled according to the external air temperature by either compensating heating controller or adjustment of the thermostatic radiator valves. New controller functioning according to the weather forecast would save approximately 20% of thermal energy [32,33]. Life time of the investment is 10 years.	0.57	3.85

* Required investment was calculated according to the appraisement approved by Ministry of Environment of the Republic of Lithuania, 4th quarter of 2012 using the annuity method (interest rate for investments—5%).

Table 2. Specification of indoor environmental problems in the analyzed building related to office work performance.

Index	Indoor environmental problem	Summary of the questionnaire survey	Description	Approximate duration in days per year	Expected annual productivity gain	
					Pessimistic scenario (ΔP_{min})	Optimistic scenario (ΔP_{max})
P1	Too low air temperature	Indicated by 50% of employees during winter time (for period from several days to several weeks), by 33.3% employees in spring/autumn.	The maximum performance is achieved at ca. +22 °C. ΔP_{min} value was calculated according to thermal sensation vote while productivity as a function of air temperature was used for determining ΔP_{max} [23].	22	1% (0.14 €/m^2)	4% (0.58 €/m^2)
P2	Too high air temperature	Indicated by 70.83% of employees during summer time and by 33.3% employees in spring/autumn.		22	5% (0.73 €/m^2)	13% (1.90 €/m^2)
P3	Stuffy air	Percentage of dissatisfied in summer and winter is 62.5%, during spring and autumn is 33.3%.	Loss of productivity as a function of percentage of dissatisfied by air quality was used for this estimation [23].	88	5.5% (3.21 €/m^2)	5.5% (3.21 €/m^2)

The annual savings related to energy consumption presented in Table 1 were calculated without evaluation of possible price increases. Required investments were estimated for four refurbishment alternatives including cost of equipment, installation, rebalancing, *etc*.

Additional insulation of the building envelope was selected as the first building refurbishment alternative (N1). This alternative would not affect occupant productivity in the pessimistic scenario. However, reduction of heat losses of the analyzed building could reduce predicted percentage of employees dissatisfied by thermal comfort due to too low air temperature. Therefore, a possible productivity increase was included in the optimistic scenario. Replacement of conventional gas boilers by gas condensing boilers was analyzed as the second alternative having no effect on occupant productivity (N2). Installation of mechanical ventilation with heat recovery and cooling capabilities was selected as the third alternative (N3). The prices for installation were calculated considering that there is a false ceiling in the office with enough space for ducts. Mixing ventilation with locally produced AHU and air distribution equipment was selected, because in this case it would require minimum installation investment. It could reduce percentage of persons dissatisfied with stuffy air and too high air temperature in summer. Installation of a new heating system controller functioning according to the weather forecast data was selected as the fourth alternative (N4). This measure could be effective on energy consumption control as well as possible temporal productivity rise due to elimination of air temperature swings. The installation price of this alternative was calculated assuming that a new controller would be installed with the existing heating system.

Estimated effects of indoor environmental conditions on performance are presented in Table 2 alongside with the duration of particular exposure. Pessimistic and optimistic values are given in the table. Percentage of dissatisfied employees was calculated by adding percentage of persons who feel discomfort almost an entire season with the ones who feel discomfort in a period from several days to several weeks. Approximate duration of the exposure to particular conditions was calculated using data from the questionnaire survey where employees identified it in more detail. According to the results of the questionnaire, assumption was made that average time of exposure to uncomfortable conditions was 22 working days for P1 and P2 and 88 days for P3.

Estimated negative effect of dissatisfaction by stuffy air leaded to a 7% productivity loss in summer and winter and 4% in autumn and spring. However, employees felt dissatisfaction from a few days to a few weeks in the transient season as well. Assumption was made that for one month within a season employees are dissatisfied by air quality that gives approximate duration of 88 working days per year and an average productivity loss of 5.5. There was no difference between pessimistic and optimistic scenarios for this case.

Monetary value for loss of performance per one square meter of the building was calculated and integrated to building refurbishment alternatives N. Final data matrix for TOPSIS analysis is presented in Table 3, where links between building refurbishment alternative, required investment and its effect on energy performance and predicted productivity gains are shown. For example, installation of mechanical ventilation system with air cooling is assumed to provide benefit in reducing complaints related to both: too high air temperature in summer and stuffy air. In pessimistic scenario productivity gain is calculated according to highest single value achieved. Reducing complaints related to stuffy air would give a benefit of 3.21 €/m^2 per year. The optimistic value is achieved by adding the maximum expected savings related to the productivity increase due to reducing complaints of stuffy air and too high air temperature in summer and is equal to 5.11 €/m^2 per year

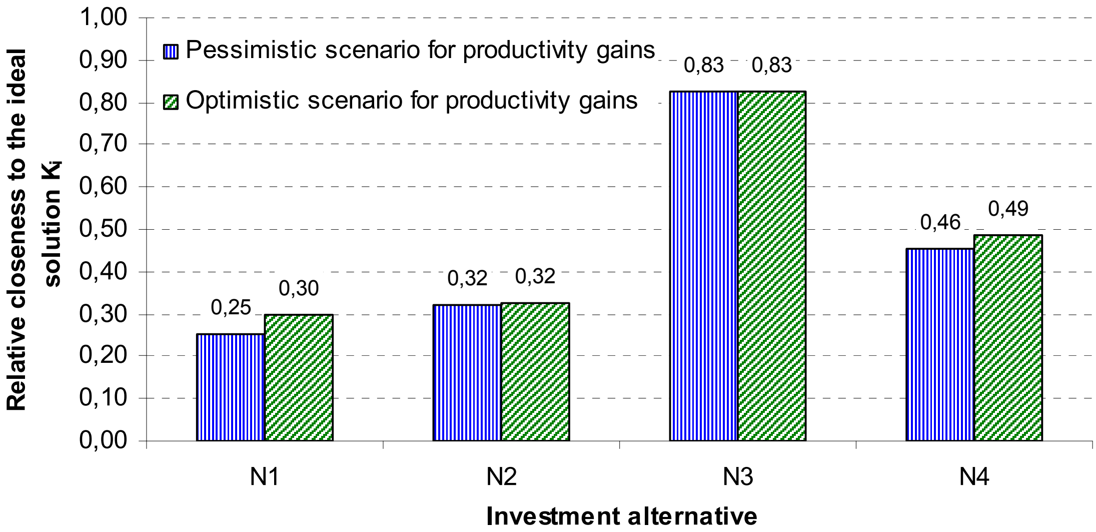
Table 3. Data matrix used for TOPSIS calculations.

Investment alternative (see Table 1)	**Required investment €/m^2**	**Annual savings on energy €/m^2**	**Productivity gain, €/m^2 and relation to cause of the complaints**	
			Pessimistic scenario	**Optimistic scenario**
N1	5.24	7.70	n/a *	0.58 (P1)
N2	0.87	1.54	n/a	n/a
N3	1.32	4.82	3.21 (P2, P3)	5.11 (P2, P3)
N4	0.57	3.85	0.14 (P1)	0.58 (P1)

* n/a—abbreviation for "not affected", the value used in the matrix is equal to 0.

The TOPSIS technique was applied using the data from Table 3 where the ideal solution was defined by the lowest required investment of all alternatives as well as the highest benefits from reduced energy consumption and increased productivity. Results of the TOPSIS analysis are presented in Figure 4 considering minimum and maximum expected rise of office work performance due to refurbishment actions. Higher K_i value indicates higher relative closeness to the ideal solution for office building refurbishment.

Figure 4. Results of the EP-OP method application performed using the TOPSIS technique for the case study building (intervention actions: N1 is additional insulation of building envelope; N2 is replacement of heat generators; N3 is installation of mechanical ventilation system with heat recovery and air cooling; N4 is installation of new equipment for HVAC control).



It can be observed from Figure 4 that despite the use of pessimistic and optimistic values for productivity increases, the TOPSIS technique provides decision makers with quite stable results as it outlines relative combined value of closeness to the ideal solution based only on the selected alternatives. Installation of mechanical ventilation system with heat recovery and air cooling was found to be most beneficial of all alternatives in both the pessimistic and optimistic scenarios (K_i value is 0.83).

4. Discussion

Implementation of the procedures using the suggested EP-OP method algorithm is related to a high level of uncertainties when dealing with relations between indoor environment and productivity. Therefore, selection of pessimistic and optimistic scenario for sensitivity analysis is an important step within the data analysis and data processing procedures. Case study analysis revealed that using the TOPSIS technique both for pessimistic and optimistic scenario did not alter the final results considerably, as regards calculation of the relatively most cost effective solution amongst the selected alternatives. It is however important to note, that the alternatives should not be dependent on each other, e.g., heat recovery ventilation may be less effective without reducing air leakage of the building. Therefore, values for energy saving with or without renovation of building envelope might be different for such alternative as heat recovery ventilation.

Uncertainty of results when applying the EP-OP method may be provoked by inaccuracy of the initial input data such as selection of alternatives, identification of potential energy saving and productivity gain. It would be useful to apply a probabilistic approach for expected energy savings as well. This would lead to creating more matrices for the analysis where pessimistic and optimistic values of potential energy saving would be included.

The TOPSIS technique could also be improved by adding coefficients of significance for each analyzed criterion. In this case, decision makers should outline which criteria are most important for the case in the data input step. Higher values of significance for reducing energy consumption or increasing productivity might alter the final results of the analysis.

5. Conclusions

The EP-OP method for office building refurbishment analysis considering both energy efficiency and office work performance is presented in the paper. The method involves a set of procedures which include technical and energy consumption data collection, a questionnaire survey as well as measurements of the indoor environmental conditions. The TOPSIS technique is used in order to identify most efficient intervention scenario for decision makers.

A case study of the application of the EP-OP method for an office building in Lithuania is presented in the paper. It revealed that high energy consumption for space heating (240.8 kWh/m^2 per year), too low air temperature in offices during winter (50% of dissatisfied employees) and too high air temperature in summer (70.8% of dissatisfied) and poor indoor air quality (average percentage of dissatisfied employees is 47.9%) have been major problems in the building. The highest benefit regarding energy consumption and office work performance could be obtained by installation of fan-driven ventilation system with heat recovery and cooling (K value is 0.83). Improvement of HVAC systems control would be highly beneficial as well (K value is 0.46–0.49). It was identified that the pay-off from the above mentioned interventions would be relatively higher compared to such refurbishment actions as replacement of heat generators and installing additional building insulation.

Procedures of the suggested EP-OP method may be modified by the investigator using different PPD values as margins for the analysis in the initial step as well as applying various tools of building energy performance simulation, statistical analysis, *etc*. However, results of the case study showed that the EP-OP method can be used efficiently in order to combine energy performance and human productivity analysis in office buildings while handling uncertainties of initial data collection by use of TOPSIS technique. As this technique is based on determining the most cost effective solution, relative values are obtained between the selected alternatives and the difference between pessimistic and optimistic scenarios was not significant in the case study.

Conflicts of Interest

The authors declare no conflict of interest.

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