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Analysis and comparison of passive and climate-unadapted design in terms of resources, energy demands and thermal comfort by means of building simulation and life cycle assessment

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Abstract. The aim of passive design is to respond to the external climate using primarily structural means to achieve a comfortable indoor climate. The use of building technology is an additional measure. This paper compares the demand for resources, primary energy, and thermal and air-hygienic comfort of passive and climate-unadapted designs to determine the most energy-efficient and sustainable design. It also analyses whether user comfort suffers from reduced use of technical building equipment. For this purpose, a representative passive building model is compared with a climate-unadapted one. Comfort, primary and embodied energy are determined and compared by way of a simulation and life cycle assessment. The passive design presents a lower primary energy demand than the climate-unadapted one, even when embodied energy is taken into account. While the requirements of air-hygienic comfort are fulfilled equally in both types of buildings, the passive design displays better thermal comfort. This indicates that energy can be saved by employing a passive design.

1. Introduction

Progressing climate change demands an immediate reductions in energy consumption and CO_2 emissions. The construction sector is responsible for producing 38 % of all global CO_2 emissions [1]. Strategies for reducing CO_2 emissions not only improve the energy efficiency of buildings but also increase the use of renewable energies [2]. The consideration of energy efficiency increasingly incites discussions about the appropriate use of building technology. In this context, passive design is attracting an increasing amount of interest. [3] Passive methods aim at ensuring an acceptable standard of comfort, while minimising the required technical building equipment [4]. However, it is necessary to analyse whether the increased level of embodied energy input caused by the increased use of building materials leads to a higher required level of primary energy, despite the reduced use of technical building equipment. We, furthermore, need to consider whether the construction method has a negative effect on comfort. This paper considers and compares the consumption of both raw material and primary energy on the one hand and the thermal and air-hygienic comfort on the other of passive construction with those of climate-unadapted methods. The aim is to determine whether a passive design is more energy-efficient and sustainable than a climate-unadapted design over its entire life cycle, despite the high resource input needed to adapt it to the outdoor climate. It also analyses whether a maximum possible reduction in technical building equipment would be at the expense of user comfort. This paper presents and compares designs of a representative climate-adapted simulation model of an office building with an unadapted one for the warm-temperate climate zone in Munich, Germany.

2. Method

The location of the case studies was chosen on the basis of the maximum climatic requirements. The climate in Central Europe requires buildings to have adequate protection against radiation and rain in addition to appropriate insulation, ventilation and thermal storage [5]. The development of the climate-unadapted model was preceded by literature research on construction methods and typical representatives of the "international style", an uniform architectural style that mostly ignores climatic influences. This model was adapted into a passive design suitable for use in the warm-temperate climate zone, while retaining the form, floor area and building envelope. The development considerations incorporated recommendations for handling and typical representatives taken from the literature. A building simulation was performed using IDA ICE software to determine the energy requirements of the building services and the level of thermal comfort during the occupancy phase, according to the model devised by Fanger [6]. To obtain information about resource requirements, a life cycle assessment was conducted for both building models to ascertain the material and energy requirements outside the use phase with material data from the Ökobaudat database. The results were proved for plausibility by comparing with typical values from the literature. Finally, the results were analysed and compared.

3. State of the Art

Passive designs are a frequent subject for discussion among researchers. Some publications focus on the energy demand or the thermal comfort of traditional buildings. Passive design strategies have a positive impact on both thermal comfort and energy demand during operation. [7, 8] Some studies consider the possibilities of transferring passive strategies of traditional buildings into modern architecture [9, 10]. No analyses could be found of the embodied energy demand of passive designs based on a life cycle assessment. Neither could an example be found of an investigation of air-hygienic comfort in passive buildings. To fill this research gap, this paper compares a modern passive design with a climate-unadapted one. The study takes into account both thermal and air-hygienic comfort. It also considers embodied energy in addition to the energy demand during operation.

4. Analyse

4.1. Description of the building model

For the purpose of comparison, a climate-unadapted office building (Model A) was designed on the basis of data obtained from literature research on construction methods and typical representatives of the ‘international style’. The model was then adapted to the prevailing climate in Munich, according to recommendations from the literature (Model B). Both office building have 3 floors with a square based area of 900 m^2 with a concrete core for the staircase. There are several offices for up to two workers on all floors as well as a few offices for up to 6 Persons on the first and second floor. The rooms are 3 m high. Two scenarios are distinguished for analysis and comparison. In Scenario 1, the buildings have different structures, but the same technical equipment: A standard ventilation system with heat recovery but without cooling function and a gas boiler in combination with ideal heating and cooling elements. The supplied air can be heated to avoid too cold air flows, but the building is not heated via the ventilation system. Model B uses in both scenarios night cooling via windows to ensure the function of thermal storage mass used in passive design. In Scenario 2, the models differ in terms of both structure and technical equipment, as shown in Table 1. In addition to the structural differences between the two buildings, the positive effect of the use of environmental heat - in form of a geothermal heat pump in combination with floor heating (Model B) - compared to air conditioning with heating and cooling function and a standard gas boiler in combination with regular radiator (Model A) is also examined. Thus, not only the influence of climate adaptation is investigated but also the potential positive effect of renewable energies. The consumption parameters were related to the net internal floor area (NIA) in order to ensure clarity.

Table 1. Heating/cooling and air supply for Model A and B in Scenario 1 and 2.

Building design	Technology **Scenario 1**	Technology **Scenario 2**
Model A (unadapted)	Gas boiler; compression cooling and ventilation system (VS)	Gas boiler; compression cooling and Air conditioning
Model B (passive)	Gas boiler; compression cooling and ventilation system (VS)	Geothermal heat pump and ventilation system (VS)

4.1.1. Climate-unadapted building model – Model A. Model A has a skeleton structure consisting of concrete columns, which is enclosed by an all-glass facade with a steel frame covered by a trapezoidal sheet steel roof. The interior spaces are separated by lightweight metal stud and fire-rated glass interior walls, respectively. The modern insulation standards exceed the U-value requirements of the Building Energy Regulations (GEG) applicable to the location with 0.7 W/m^{2}K for the curtain wall and 0.17 W/m^{2}K for the roof [11]. External blinds prevent the entry of direct solar radiation from an indoor air temperature of 25°C. The technical building equipment for Model A for both Scenarios 1 and 2 are described in detail in Section 4.1 and can be seen in Table 1.

4.1.2. Passive building model – Model B. To enable climate adaptation, a high level of insulation of the building envelope is required [12]. Based on recommendations from the literature and an analysis of representative examples (Building 2226; Alnatura Campus), the glazing percentage of the south facade is set to around 40 % and to around 30 % for all other facades [13, 14]. Heat-storing building components can positively influence the indoor climate because of the sufficient differences between daytime and night-time temperature [15]. For this reason, a tamped clay wall and a reinforced concrete-clay composite are used for the ceilings, based on a design by Martin Rauch [16]. The interior walls are planked with clay panels. In summer, stored heat is dissipated by night ventilation through tilted windows. To avoid transmission heat loss, core insulation comprising 0.2 m of wood fibre is used for the solid wall, resulting in an U-value of 0.155 W/m^{2}K. The same glazing is used for the windows as in Model A, the frame is designed according to the passive house standard. The heat transfer coefficient of the roof differs little from that of Model A. Additional thermal storage mass is introduced by a 0.25 m thick concrete structure to counteract overheating. The technical building equipment for Scenarios 1 and 2 are described in Section 4.1 and shown in Table 1.

4.2. Simulation of comfort and energy demand with IDA ICE

In the following, the building models are simulated with IDA ICE 4.8 software to ascertain thermal and air-hygienic comfort as well as the energy demand during operation. A light output of 8 W/m^2 [17] is assumed and an activity level according to DIN EN ISO 7730 of 1.2 MET, with a covering of 0.85 ± 0.25 clo [18]. According to the recommendations in the EQUA handbook, a tolerance of 0.2 is used for equation solutions and 0.01 for settling in the simulation. Primary energy factors according to GEG 2020 were used to determine the primary energy demand.

4.2.1. Air-hygienic and thermal comfort in the climate-unadapted building – Model A. Air-hygienic comfort is evaluated on the basis of the prevailing CO_2 concentration in a south-facing, second floor double office according to DIN 1946-2 [19]. The CO_2 limit value for good air quality (1000 ppm) is not exceeded over the entire period of use due to the operation of an air conditioning system. As thermal comfort is dependent on orientation, it is analysed in each cardinal direction in an office. The thermal comfort level is evaluated according to the criteria of Fanger [20]. The glass facade enables passive solar gains in winter, which influence the degree of thermal comfort. Incoming sunlight increases user comfort in the room. But as soon as there is no more direct solar radiation, comfort decreases due to the lack of sufficient storage masses. Without direct solar radiation, the PPD exceeds 10 %, which is still within an acceptable range. The maximum indoor temperature in the offices is always set to 26 °C in summer due to the presence of active cooling and external sun protection.

The PPD is mostly around 15 %. There are times in summer when the maximum temperature is slightly exceeded in all offices. On an annual average, with a PPD of 8.7 %, 91.3 % of the users are likely to be content with the thermal indoor climate. Figures 1 and 2 give an overview of the PPD and PMV in winter and summer for a south-facing office.

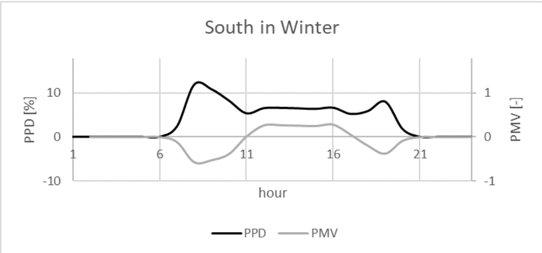

Figure 1. PPD and PMV for Model A in a south-facing office in winter.

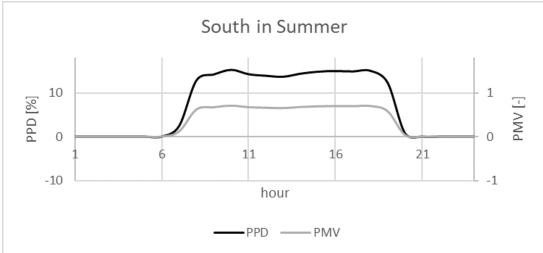

Figure 2. PPD and PMV for Model A in a south-facing office in summer.

4.2.2. Air-hygienic and thermal comfort in the passive building – Model B. Air-hygienic comfort in the Model B offices is also ensured at all times by mechanical ventilation. In summer, lower CO_2 concentrations are achieved by additional passive window cooling. Thermal comfort is also affected by the solar gains. The increase in comfort is not as great as in the climate-unadapted building, but it is more long-term, due to the thermal storage mass. The PMV of less than 0.5 in all orientations suggests that almost all users are satisfied with the thermal conditions in summer. This can be attributed to the cooling thermal mass and window area percentage. On particularly hot days, the indoor temperature of 26°C is, for a brief time, slightly exceeded; however the resulting cooling degree hours of 1 Kh are negligible. On an annual average, with a PPD of 5.3 %, 94.7 % of users are expected to be content with the indoor thermal climate.

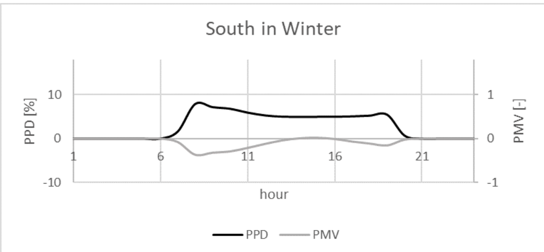

Figure 3. PPD and PMV Model B in a southern office in winter.

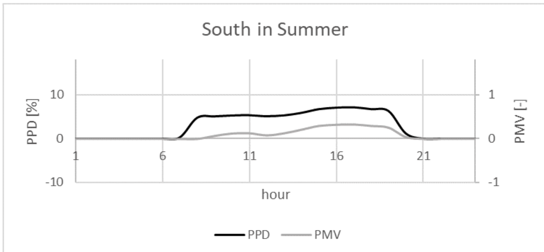

Figure 4. PPD and PMV Model B in a southern office in summer.

4.2.3. Energy demand of the climate-unadapted building – Model A. The results of the simulation show that the majority of the energy in both scenarios is required to heat the building, whereas cooling is only a minor component. There is little difference between Scenario 1 and Scenario 2, as shown in Table 2. When using an air conditioner instead of ideal cooling elements, the cooling energy decreases, but the electrical energy required for ventilation increases. The energy consumption parameters of the Institute for Housing and the Environment (IWU) regarding a study on non-residential buildings are used to check the model for plausibility and to classify the values obtained [21]. The actual usable floor area (UFA) is taken as the reference area, resulting in a final energy demand of 27.7 kWh/m^2_{UFA} for Model A. The average value of all buildings considered in the study, with different insulation standards and years of construction, is between 100 kWh/m^2_{UFA} and 150 kWh/m^2_{UFA}, and thus significantly higher. The most modern building, with a similar insulation standard to that used in Model A, results in a value of about 14 kWh/m^2_{UFA}. The final energy demand is somewhere in between these levels and thus represents a realistic figure. Consumption is very low compared to the average level, but almost twice that of the modern building. In the studies by the IWU, the cooling energy demand is only specifically given for different office spaces (single or double) and ranges from a very low rate of consumption of 3 kWh/m^{2}a to a medium-level consumption of 7 kWh/m$^2_{UFA}$. If we consider the cooling energy demand for the office space, we obtain a value of 5 kWh/m$^2_{UFA}$. Thus, the general level of consumption can be rated as low to medium [22].

Table 2. Final energy and primary energy demand for Scenarios 1 (Sc 1) and 2 (Sc 2) of Model A.

	Final energy demand [kWh/m$^2_{NIA}$*a]		Primary energy factors [-]		Primary energy demand [kWh/m$^2_{NIA}$*a]	
	Sc 1	Sc 2	Sc 1	Sc 2	Sc 1	Sc 2
Heating	20.8	20.2	1.1	1.1	22.9	22.2
Electrical Heating	0	0	-	-	0	0
Ventilation	1.6	2.1	1.8	1.8	2.9	3.8
Cooling	2.8	2.6	1.8	1.8	5.1	4.6
Artificial light	6.5	6.4	1.8	1.8	11.8	11.6
Sum	**31.7**	**31.3**	**-**	**-**	**42.7**	**42.2**

4.2.4. Energy demand of the passive building – Model B. For the passive building, a major part of the total energy is also required for heating in Scenario 1, as shown in Table 3. However, it is clear that the percentage is only slightly above 50 %. In addition, no cooling energy is required, due to the passive measures. The U-values of the passive building are almost the same as those of the modern building given in the IWU study. The final energy demand based on the usable floor area for the climate-adapted office building is also close to the 14 kWh/m$^2_{UFA}$ level of the modern building, which confirms the plausibility. [23] Scenario 2 shows the positive effect of using environmental heat. Although the electric heat pump has a higher primary energy factor than natural gas, the high coefficient of performance means that the overall energy requirement is much lower.

Table 3. Final energy and primary energy demands in Scenarios 1 (Sc 1) and 2 (Sc 2) of Model B.

	Final energy demand [kWh/m$^2_{NIA}$*a]		Primary energy factors [-]		Primary energy demand [kWh/m$^2_{NIA}$*a]	
	Sc 1	Sc 2	Sc 1	Sc 2	Sc 1	Sc 2
Heating	13.6	0.3	1.1	1.1	14.9	0.4
Electrical Heating	0	4.3	-	1.8	0	7.7
Ventilation	1.5	1.5	1.8	1.8	2.7	2.8
Cooling	0	0	-	-	0	0
Artificial light	7.3	7.2	1.8	1.8	13.1	13
Sum	**22.4**	**13.3**	**-**	**-**	**30.7**	**23.9**

4.3. Life cycle assessment

A life cycle assessment according to DIN EN ISO 14040 [24] is conducted to determine the embodied energy of the buildings over a period of 50 years. Embodied energy is defined as the energy that is required for manufacturing of materials, transportation and disposal [25]. The consideration of the embodied energy is highly relevant, as it has a significant impact on the environment [26]. The results of the energy life cycle assessment of the manufacturing (A1 A3), transport (A4) and disposal (C2-C4 & D) phases are shown below in Tables 4 and 5. The required end-of-life component replacement is summarized in Phase B2. Only the active erection and demolition phases are neglected due to insufficient data, although, according to some studies, these are negligible anyway. [27]

4.3.1. Embodied energy of the climate-unadapted building - Model A. The majority of the primary energy demand is attributed to the manufacturing phase (A1 A3), whereas the amount of energy required for transport and disposal is almost negligible, as shown in Table 4. Since the majority of building materials used can be recycled, Phase D has a negative value. The total primary energy required is 810 kWh/m^2_{NIA}. A total of 488 kWh/m^2_{NIA} is attributable to the glass facade, which is responsible for the majority of the total energy costs (almost 62 %). In Scenario 2, an additional expenditure of 43.9 kWh/m^2_{NIA} is required for systems engineering.

Table 4. Results of the energy life cycle assessment for Model A.

	A1-A3	A4	B2	C2	C3	C4	D
Non-renewable [kWh/m^2_{NIA}*a]	636.1	3.1	175.3	16.7	14.7	8.9	-137.2
Renewable [kWh/m^2_{NIA}*a]	84.2	0.3	13.1	1.1	3.6	0.8	-10.6

4.3.2. Embodied Energy of the passive building - Model B. In Model B, the majority of energy costs are again incurred during the construction phase, although the proportion attributable to transport is significantly higher due to higher mass. For Scenario 2, the energy expenditure required for building technology is 83.9 kWh/m^2_{NIA}.

Table 5. Results of the energy life cycle assessment for Model B.

	A1-A3	A4	B2	C2	C3	C4	D
Non-renewable [kWh/m^2_{NIA}*a]	399.8	55.9	78.6	30.9	22.5	1.9	-144.4
Renewable [kWh/m^2_{NIA}*a]	201.1	3.3	124.2	1.9	-66.1	0.3	60.3

5. Comparison

The comparison shows that the requirements of air-hygienic comfort are fulfilled equally in both buildings. Thermal comfort is slightly better fulfilled in Model B with an average level of 94.7 % compared to Model A, with on average 91.3 %. Visual comfort is a further factor that should be investigated and compared. However, visual comfort can only be determined to a limited extent by simulation using IDA ICE. In addition to daylight, view, and other aspects, it is also important to consider how often the blinds need to be lowered to minimise the risk of overheating. This could constitute a major restriction in climate-unadapted buildings with glass facades. [28]. Considering a primary energy demand in Scenario 1 over a period of 50 years, this results in a saving of 648 $kWh/m^2_{NIA}a$ or 22 % for Model B in comparison to Model A, as shown in Figures 5 and 6. The embodied energy demand is also higher due to the glass facade, which has a significantly higher energy input for production than the tamped clay facade of the passive model.

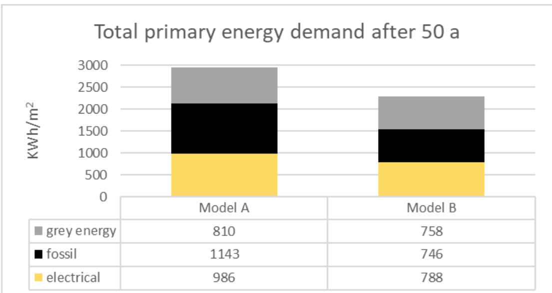

Figure 5. Primary energy demand in Scenario 1 for Models A and B after 50 years.

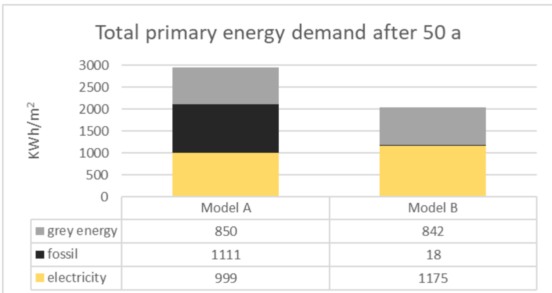

Figure 6. Primary energy demand in Scenario 2 for Models A and B after 50 years.

The passive design reduces the energy demand during operation mainly due to the reduced demand for heating and cooling energy. In Scenario 2, Model B results in a saving of 926 $kWh/m^2_{NIA}a$ or 31.3 % of the primary energy demand compared to Model A, after 50 years. The system technology in Model B requires more embodied energy for production in Scenario 2 as it is the case in Scenario 1, but the reduction in the useful energy demand is so much greater than in Model A, so this extra expense is rapidly offset. If renewable energy, such as district heating with a primary energy factor of 0.11 [29] is also used for the climate-unadapted building, the primary energy savings of the passive design compared to the climate-unadapted one are significantly lower, at only 290 $kWh/m^2_{NIA}a$. This shows that, not only the construction method but also the type of energy production plays a significant role in the potential energy savings of climate-adapted versus unadapted designs.

6. Results and Discussion

Table 6 clearly shows a reduction in energy demand in the passive building compared to the climate-unadapted one. The requirements of air-hygienic comfort are fulfilled in both buildings. Thermal comfort, using the same setpoint for room air temperature according to the workplace directive, is about 3 % better in the passive office building than in the climate-unadapted one. To enable a clear comparison, it should be noted that this is an average value for four double offices on the second floor.

Table 6. Primary energy demand (PE), raw material demand (RM), CO_2 content, daylight factor (DF), window area assessment (WA), and daylighting assessment (DLS).

	PE (Sc 1) [$kWh/m^2_{NIA}a$]	PE (Sc 2) [$kWh/m^2_{NIA}a$]	PPD [%]	CO_2 [ppm]	DF [%]	Evaluation WA	Evaluation DLS
Model A	2,939	2,960	91.3	<1000	8.0	too big	3.5[a]
Model B	2,292	2,034	94.7	<1000	2.5	right	3.3[b]

[a] Average evaluation of daylighting for perforated facades (1 = very poor; 5 = very good)
[b] Average evaluation of daylighting for all-glass facades (1 = very poor; 5 = very good)

In Scenario 2, the potential energy savings for the passive building are significantly higher than in Scenario 1, with otherwise unchanged values. This is due to the use of environmental heat rather than conventional fossil fuels. In Scenario 1 using the same system technology results in energy savings, but it is also dependent on the energy source. For this reason, it is very important to use renewable energy in addition to make structural climate adaptations. It is above all important to use sustainable, natural and well recyclable building materials. This study only compared a steel and glass facade with a tamped clay facade. It should be borne in mind that although clay is a natural building material that requires little energy in production, it is of limited supply. Further investigations of different buildings and building materials are needed for a final evaluation. As mentioned above, visual comfort comparison, since this would require either an active survey in two real-world buildings or special lighting simulations. Acoustic comfort is also neglected, as it is not directly dependent on climate.

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