Environmental impacts evaluation of a Chinese building integrating three boundary conditions

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RESUME. Les conditions aux limites d'un bâtiment influencent directement les résultats de l'évaluation des impacts environnementaux. L'étude présentée vise à améliorer la méthode d'évaluation des impacts environnementaux des bâtiments en Chine, en intégrant trois conditions aux limites : le sol, le microclimat et le système d'arrière-plan considéré dans l' analyse du cycle de vie (ACV). Un modèle de pompe à chaleur couplée au sol (GCHP) a été intégré dans l'outil de simulation énergétique du bâtiment COMFIE pour considérer l'interaction entre le bâtiment et le sol. Une méthode de couplage de l'outil de simulation du microclimat Envi-met avec COMFIE a été proposée, en tenant compte des effets du microclimat, tel que l'effet d'îlot de chaleur urbain. La méthode ACV est améliorée en prenant en compte les spécificités du mix électrique chinois pour évaluer au mieux les impacts environnementaux. Les méthodes susmentionnées ont été appliquées à un immeuble à Wuhan, en Chine. Les émissions de CO_{2eq} *sont d'environ 76 kg/m*^{2}*.an et la consommation d'énergie primaire est estimée à 267 kWh/m*^{2}*.an.*

MOTS-CLÉS : Conditions aux limites, impacts environnementaux, simulation énergétique dynamique.

ABSTRACT. Boundary conditions of a building directly influence the evaluation results of its environmental impacts. This study aims at improving the method of evaluating the environmental impacts of the building in China, by integrating three boundary conditions: the ground, the microclimate and the background system considered in life cycle assessment (LCA). A ground coupled heat pump (GCHP) model is integrated into the building energy simulation tool COMFIE to consider the interaction between the building and the ground. A method of coupling the microclimate simulation tool Envi-met with COMFIE is proposed, considering the microclimate's effects, e.g. the urban heat island effect. The LCA method is improved with Chinese electricity production mix to evaluate the environmental impacts. Finally, the abovementioned methods are applied to a building in Wuhan, China. The CO_{2eq} *emissions are approximately 76 kg/m*^{2}*.year and the estimated primary energy consumption is 267 kWh/m*^{2}*.year.*

KEYWORDS: Boundary condition, environmental impacts, dynamic energy simulation.

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1. INTRODUCTION

Massive urban expansion in China leads to a high pressure on the environment such as energy consumption and CO_2 emissions. According to China Building Energy Use 2018 (Jiang et al. 2018), building energy consumption accounted for approximately 20 % of the total primary energy consumption in 2016 in China. The evaluation of related environmental impacts highly depends on the buildings' boundary conditions. To have a more precise evaluation of these impacts, more site-specific boundary conditions of the building should be taken into consideration, e.g. local electricity production mix, site-specific climate conditions and characteristics of the ground. In this paper, three boundary conditions are considered in the building energy simulation (BES) and its environmental impacts evaluation: the ground, the microclimate around the building, and the local electricity production mix in life cycle assessment (LCA).

As a boundary condition directly in contact with the building, the ground can serve as a heat source or a heat sink to supply heating or cooling, respectively in winter and summer. This procedure is accomplished by especially a ground coupled heat pump (GCHP) system in the urban regions in China due to the limited ground area. A vertical GCHP system mainly consists of a vertical ground heat exchanger (GHE), heat pumps (HP) and distribution units. The GHE is the component directly influenced by this boundary condition. The building's energy performance can be improved by using this system.

The second boundary condition is the local climate. In the urban areas, the urban heat island (UHI) effect is well-known and can be quantitatively described by the urban heat island intensity (UHII) (Yang et al. 2020), which is the urban air temperature minus the rural air temperature. As an essential boundary condition for BES, the accuracy of the weather file comprising of 8 760 hours of various climatic parameters such as air temperature and solar radiation strongly influence the simulation results (Tsoka et al. 2018). Existing BES tools mainly use the meteorological data collected from the rural areas such as the airport, which cannot reflect the urban's microclimate conditions. A weather input file considering the local microclimate of the building can yield a more accurate result of BES, especially in the urban areas where the UHI effects are observed.

One of the tools for evaluating environmental impacts is LCA. It is a tool used for the quantitative assessment of materials, energy flows and environmental impacts of a product or a system throughout its life (i.e. cradle to grave) from raw material acquisition, processing, manufacturing, use and finally its disposal or recycling. As another boundary condition, LCA evaluates the environmental impacts by using a life cycle inventory (LCI) database, including a background system which is sensitive to the region and other local elements (e.g. local electricity production mix).

The dynamic energy simulation of a building can be performed using the BES tool COMFIE (Peuportier and Blanc-Sommereux 1990) and its environmental impacts can be evaluated using the LCA tool EQUER. These two tools are integrated in the software PLEIADES. This study mainly presents a method to more accurately evaluate the environmental impacts by considering the abovementioned boundary conditions in China, using PLEIADES. This method is applied to a case study located in a business district in Wuhan, China and the results are presented and discussed.

2. CASE STUDY

Wuhan, the capital city of Hubei Province, China, is located in the eastern part of Jianghan Plain and the middle reaches of Yangtze river. The location of Wuhan in China and the remote sensing image of Wuhan is shown in Figure 1 (a) and (b) (Huang et al. 2019). The studied building for energy performance simulation is situated on the intersection between Zhongbei road and Donghu Xi road of Wuchang District, with latitude of 30° 32' and longitude of 114° 20'. This area is a business and commercial center, mixed with many recently built high-rise office, commercial and residential buildings and old buildings, as shown in Figure 1 (c). This area lies south by east with an angle of 20°. The heating and cooling of the whole block is supplied by a GCHP heat pump system. The simulated high-rise building is the unit 2 of the #2 building in Haishan Jingu (HSJG) block. HSJG consisting of 1 office building (#1) and 3 residential buildings (#2, #3 and #4) is a project integrating housing, offices and shopping. The overall effect plan and a photo of HSJG block is shown in Figure 1 (d). The simulated residential building #2.2 consists of 34 floors with an average height 3 m for each floor in HSJG. The area of the building is around 12 500 m^2.

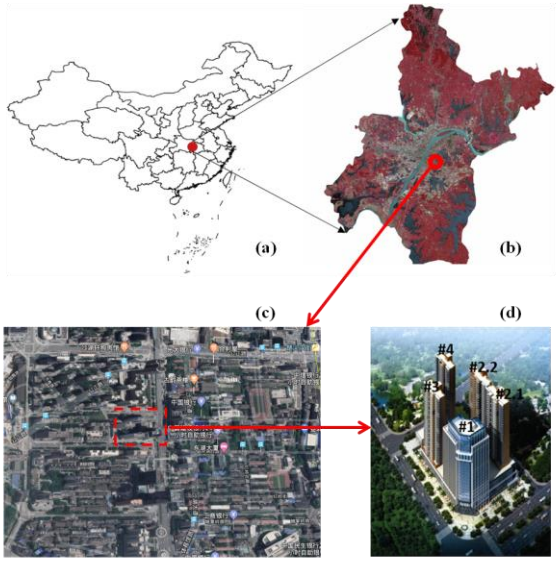


Figure 1: (a) Location of Wuhan in China (Huang et al. 2019), (b) remote sensing image of Wuhan (Huang et al. 2019), (c) surrounding area of the studied building and (d) studied residential building block HSJG

3. METHOD

3.1. INTEGRATION OF GCHP IN COMFIE

To consider the effect of the ground, a model of GCHP was developed and integrated into COMFIE. Then this whole model was applied to the case study to improve its building energy performance by changing the design parameters of GHE. In this study only the heating is considered.

The whole model consists of several sub-models. With the heating load calculated by the building model (COMFIE), the heat distribution model determines the inlet and outlet fluid temperatures of the distribution system, which correspond to the outlet and inlet fluid temperatures of the condenser. The outlet fluid temperature and the heat flow of the condenser are then transferred to the HP model as inputs. The HP model calculates the energy exchanged in the evaporator and the inlet and outlet fluid temperatures of the evaporator, as well as the compressor work and coefficient of performance (COP) of the heat pump. The energy exchanged in the evaporator is equal to the heat extracted from the ground, which is an input for the GHE model (a square borehole field). For the GHE model, we use the finite line source model (Zeng, Diao, and Fang 2002) of a single borehole and employ the Duhamel's superposition principle (Hellström 1991) to the whole filed to obtain the ground temperature responses (G-function) of the field. By using the G-function calculated by Matlab (which could be solved in only 4 seconds and 1 minute for a 26 × 26 boreholes field for a simulated time of 1 year and 20 years on a standard computer), the GHE model calculates its outlet fluid temperature which is compared to the inlet fluid temperature of the evaporator calculated by HP model. An iterative process is performed here for these temperatures to converge. At each timestep of the simulation, a balance point between different systems is achieved to describe the overall system performance. It should be noted that this GCHP model does not increase noticeable.

3.2. COUPLING A MICROCLIMATE MODEL AND COMFIE

The simulation of buildings' energy performance requires a yearly file containing hourly values of meteorological data. To have a more accurate evaluation of the environmental impacts, the microclimate should be considered. In this study, the microclimate simulation tool Envi-met is used and we focus on the influence of the site-specific air temperature (the UHI effect). However, as a complex dynamic numerical microclimate model, the simulation using Envi-met for a one day period requires a heavy calculation load (around one day in our study). It is not possible to obtain the hourly microclimate effects for one year with our existing computer resource. Thus, a method which can generate the hourly microclimate's effects appropriately in reasonable simulation time is proposed:

1. One representative day of the representative week (extreme hot/cold week for summer/winter and average week for spring/autumn, directly given in EnergyPlus Weather (EPW) file) is chosen using Matlab: extreme hot day in summer (ex-summer), extreme cold day in winter (ex-winter) and average days in spring (av-spring) and autumn (av-spring), by the criteria that the root mean square error is the smallest for 24 hours compared to the average of each hour of the representative week;
2. Then these four representative days are simulated using Envi-met to obtain the local microclimate parameters and the UHIIs;
3. The hourly UHIIs are obtained with linear interpolation for 24 hours between each two representative days, using Matlab;
4. The air temperature of the site-specific weather file is generated by adding the hourly UHII to the original weather file (Energyplus weather (EPW) file in this study), in Matlab.

In BES, a building is usually modelled and simulated considering the orientations and heights. In the urban areas in China, the buildings are dense and high-rise. The temperature profile might be rather different in the different orientations, as well as along the height. The most accurate simulation should consider these differences. In order to perform a detail investigation on the UHI effect on the building energy performance, the temperature profiles of four different orientations along different heights (depending on the zone definition) are generated from Envi-met. The temperature profiles are inputted in the weather tool Meteocalc (which is integrated in PLEIADES) and corresponding site-specific weather files are generated and then used by COMFIE for building energy simulation. The whole coupling method is shown in Figure 2.

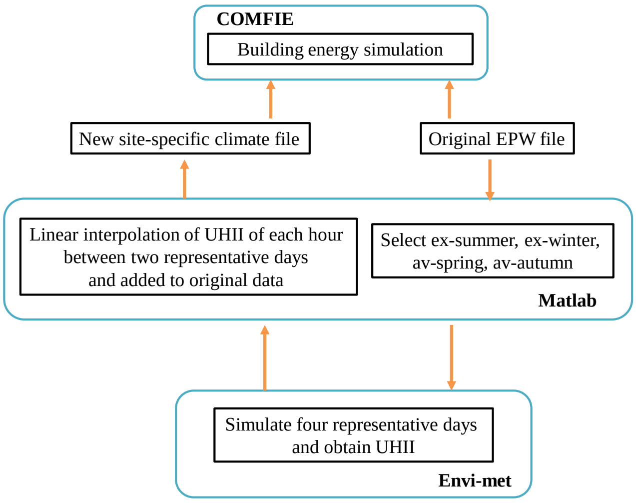


Figure 2: Method of coupling microclimate tool with the BES tool

3.3. LCA IN CHINA

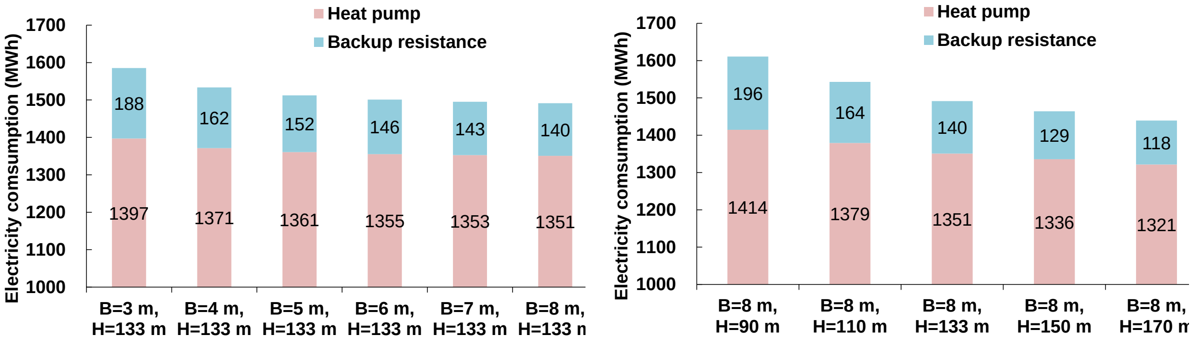
The environmental impacts evaluation of the studied case is performed using EQUER. In China no available life cycle inventory database can be used for building sector in this study, thus the Swiss database Ecoinvent was used to analyze the environmental impacts. Ecoinvent database is an international database with consistent and transparent LCI data containing the areas of agriculture, energy supply, transport, biofuels and biomaterials, bulk and chemicals, construction materials, packaging materials, basic and precious metals, metals processing and electronics as well as waste treatment. In EQUER materials, processes and equipments widely used in the building sector are adapted for LCA from Ecoinvent database.

The production share of the electricity is an essential element in LCA because it strongly influences the environmental impacts. In this study, the average annual China electricity production mix is used for LCA. The evolution of the electricity production mix during the last decade is considered to compare the environmental impacts. In this paper, as a first step, the annual electricity production mix in 2011 in China is studied: coal 78 %, hydro power: 15 %, nuclear 2 %, natural gas 2 % and other energies 3 % and the transmission loss is 9 % (National Bureau of Statistics of China 2012). In 2019, it evolved to: coal 63.3 %, hydro power: 17.4 %, nuclear 4.6 %, natural gas 3.2 % and other energies 11.5 %. The environmental impacts of this evolution will be studied afterwards. In the energy sector, there are four main consumptions to be considered: heating (COP = 3.1), cooling (COP = 3.9), domestic hot water (COP = 3 and distribution loss = 2 %) and specific electricity (grid loss = 9 %). The heating, cooling and domestic hot water are provided by the GCHP system. The specific electricity is supplied by the electricity grid. The water leakage is set as 20 %, and the hot and cold water consumptions are set as 40 liters/day/person and 100 liters/day/person.

4. RESULTS

4.1. BOUNDARY CONDITION 1: GCHP

The studied block HSJG uses a large-scale borehole field, thus the proposed model was applied for the whole HSJG, instead of only the building #2.2, to improve the whole block's energy performance, for different boreholes' spacings (the distance between two boreholes), B (from 3 m to 8 m, H = 133 m), and various borehole depths, H (90 m, 110 m, 133 m, 150 m and 170 m, B = 8 m). The electricity consumptions of the heat pump and the backup resistance (which supplies heating when the heat pump cannot provide enough power) are shown in Figure 3. For H = 133 m, the electricity consumption of the heat pump decreases with B. The decrease becomes smaller when B gets larger. The same trend is found in the backup resistance as well. The total electricity consumption of B = 8 m is 1 491 MWh, which is 94 % of B = 3 m. For B = 8 m, larger H values show better performances. The total electricity consumption of H = 90 m is 1 611 MWh; the heat pump and the backup resistance consume 1 415 MWh and 196 MWh, respectively. The electricity consumption decreases with H, and similarly, a larger reduction is observed for small H values. For H = 170 m, the total electricity consumption is reduced by 10 % compared to H = 90 m. Although larger B and H values show a better performance, larger land area and higher initial investment costs are required to install the GHE. The proposed model can help the designers to achieve a balance between performance and cost.

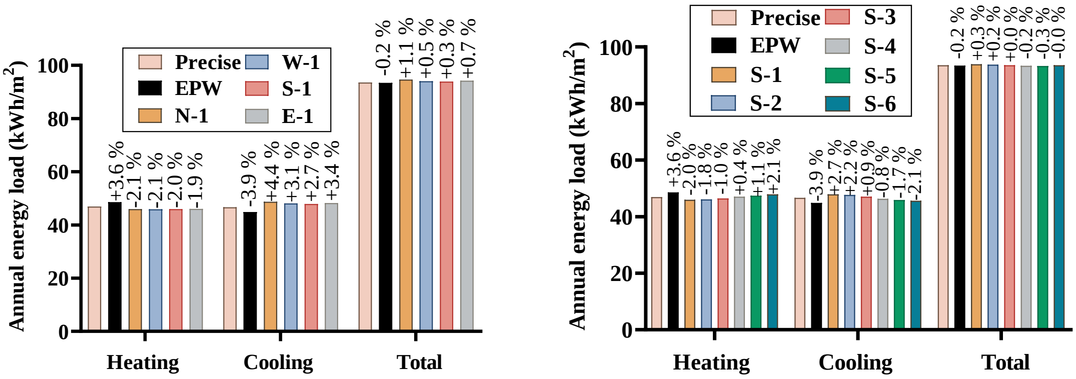


(a) **(b)**

Figure 3: Electricity consumptions of the heat pump and the backup resistance for (a) different B and (b) different H

4.2. BOUNDARY CONDITION 2: MICROCLIMATE

The air temperature was simulated for 4 orientations (N, W, S, E) and 6 different heights (1: 3 m, 2: 12 m, 3: 31 m, 4: 59.3 m, 5: 82.4 m, 6: 103 m) and the corresponding meteorological files were generated. The simulation results using these files were compared to including the original EPW and the precise simulation (each zone calculated by the weather file of its corresponding orientation and height). The yearly average UHII at the height of 3 m was estimated to be 0.45 °C (considering the average of four orientations). Figure 4 (a) shows the simulated annual loads of different orientation at 3 m. Compared to the precise simulation, the EPW shows a larger heating load of 3.6 %, a smaller cooling load of 3.9 % and a smaller total energy load of 0.2 %. The orientation slightly affects the heating load, but has a larger influence on the cooling load. For the total energy load, the north has the largest difference of 1.1 % and the south has the smallest of 0.3 %. In general, the accuracy of the orientation is: south > west > east > north. The influence of different heights is illustrated in Figure ***4*** (b). It can be inferred that compared to the precise simulation, the difference of the heating load increases from – 2.0 % to + 2.1 % and the cooling load decreases from + 2.7 % to – 2.1 % with the height. S-3 shows a better accuracy in evaluating the heating and cooling load, with a + 0.4 % and – 0.8 % difference. The height has a minor influence on the total load, with a maximal difference of ± 0.3 %. Compared to the EPW, the differences of heating load and cooling load can reach to – 5.4 % and + 6.9 % for S-1. The EPW did not consider the UHI effect, overestimating the heating load of 3.6 % and underestimating the cooling load of 3.9 %, however the total load was accurately predicted.



(a) **(b)**

Figure 4: Energy loads for (a) different orientations at 3 m and (b) different heights for south

4.3. BOUNDARY CONDITION 3: CHINA ELECTRICITY PRODUCTION MIX

The environmental impacts per m^2 per year of the studied building with a life span of 80 years were evaluated, as illustrated in Figure 5. It emits nearly 76 kiloton CO_{2eq} and consumes nearly 960 000 GJ of primary energy over 80 years, corresponding to 76 kg/m^2.year and 267 kWh/m^2.year. The use stage generates the most of the environmental impacts among the four stages: in 10 of the 12 impacts (except non-radioactive waste and odor), more than 87 % of each is caused during use stage. In this building, among all components in the construction stage, the wall is the main source for environmental impacts. The heat pump system consumes nearly 16 % of the total primary energy and emits almost 10% of the total CO_{2eq}. The specific electricity consumption causes nearly over 50 % of 11 indicators in the use phase.

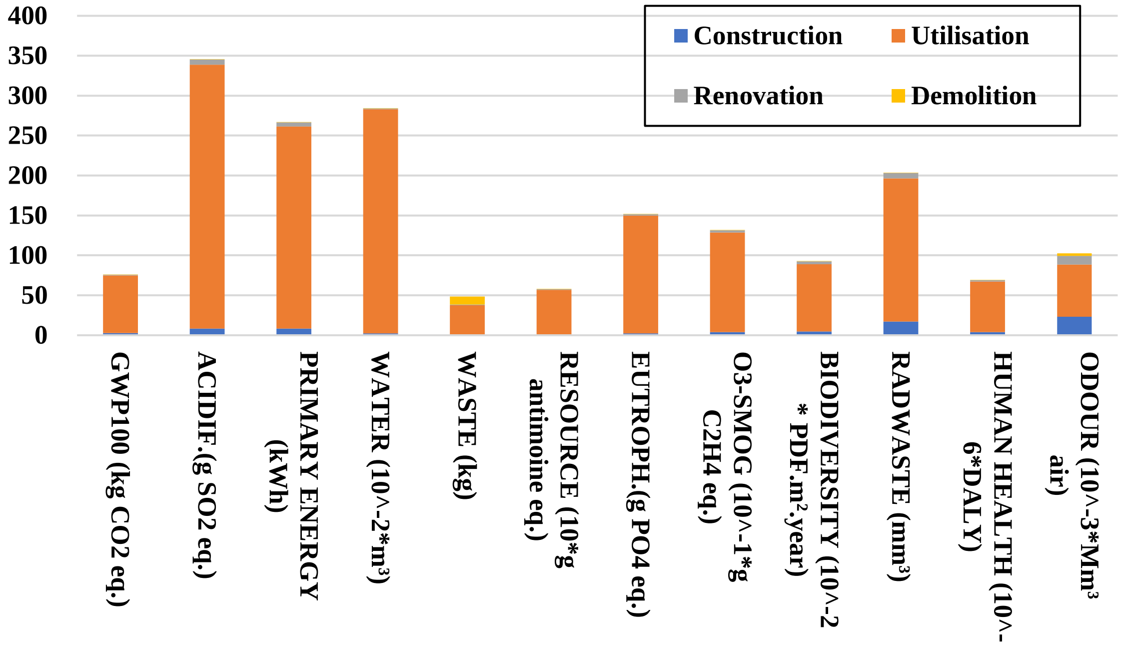


Figure 5: Environmental impacts per m^2 per year of the studied building over a life of 80 years

5. CONCLUSIONS AND PERSPECTIVES

The urbanisation in China brings various environmental loads such as energy consumption and CO_2 emission and some urban climate phenomena e.g. the heat island effect. One of the energy efficient systems widely used for the buildings in Chinese urban areas is the ground coupled heat pumps. When using the LCA method evaluating the environmental impacts of a building, the local electricity production mix is essential. In order to have a more accurate evaluation of the environmental impacts of the building in China, this work presents a method accounting for these three boundary conditions: the ground, the microclimate and the local electricity production mix in LCA.

A GCHP model is integrated into the BES tool COMFIE. The whole model is used to improve the HSJG block's energy performance by designing the parameters of the borehole spacing B and the borehole depth H. The results show that the average COP increased with both B and H. The total electricity consumption of B = 8 m, H = 133 m is reduced by 6 % compared to B = 3 m, H = 133 m. The proposed model is beneficial to evaluate the energy performance of a building in contact with the boundary condition of the ground.

The weather input file directly influences the building energy simulation results. A method of coupling the microclimate tool Envi-met and COMFIE is proposed, including a method to generate the weather input file accounting for the UHI effect. The site-specific weather files are generated and simulated in COMFIE. The results show that if considering the UHI effect, the heating load can decrease by 3.6 % and the cooling load can increase by 3.9 %, but the total energy load slightly changed, compared to the regional climate file (usually corresponding to rural areas).

By applying the average annual Chinese electricity production mix in LCA, the environmental impacts of the building are evaluated. The CO_{2eq} emissions are approximately 76 kg/m^2.year and the estimated primary energy consumption is 267 kWh/m^2.year. The use phase generates the most of the environmental impacts among the four stages in its life span.

The present work regarding the ground and the microclimate only considers the energy consumption. In the future work, the evaluation of environmental impact indicators will be studied. The LCA results are based on only changing the electricity production mix for energy use in the buildings, thus the next step is to contextualize the materials’ environmental impacts according to e.g. the Chinese electricity production mix.

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