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Energy Procedia 62 (2014) 723 – 732

Energy Procedia

6th International Conference on Sustainability in Energy and Buildings, SEB-14

Thermal Exergy analysis of a building

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Abstract

Exergy analysis has been contemplated to evaluate the direct energy impact of a building on the environment. The authors' approach is to consider the building as a "black box" that needs exergy. The surrounding and the Environment are closed systems, in thermodynamic equilibrium between them. The building is transient open system. The paper is composed of two main sections: a description of the model and the application to a building. The aim is to analyze thermodynamic interaction building – surrounding in order to estimate the input exergy, loss and especially destruction exergy.
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Keywords: Exergy Model; Building Assessment; Energy Impact; Transient Simulation; Thermal Exergy; Black Box;

1. Exergy as environmental impact value

The anthropic action has an impact on the natural environment [1]. From a thermodynamic point of view the natural environment destroys its potential due to natural processes. The anthropic processes increase the destruction velocity of this potential [2]. The Man has always used materials and energy to build infrastructures, buildings and to ensure the functionality to the users.

Exergy is a thermodynamic potential measure of energy or material flux with respect to an equilibrium state assumed as the reference state. The choice of the reference environment is a function of the system analyzed. The reference environment must be directly available to the system and it do not changes its properties due to interactions with the system. An interaction occurs in relation to a difference of temperature, pressure, chemical composition, etc. Exergy allows to describe, using a single indicator, the contribution of thermal, chemical, physical,

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doi:10.1016/j.egypro.2014.12.436

etc. … of human - environment interactions [3].

Exergy shows the value of energy as work, and permits comparisons between energies which are different from Second Law point of view: it is defined as the maximum amount of work which can be ideally produced by a system as it comes to equilibrium with the reference environment [4,5]. In the real processes, exergy consumption is related to entropy production due to irreversibility [5]. So the exergy takes into account the entropy increase in the environment due to the natural and anthropic process.

Exergy destruction is a good measure of the impact of a system on its surroundings, but it has some limitations: it fails to account for non-thermodynamic effect [6]. Exergy can be considered a property of the interactions between the open system and its surrounding [7].

Nomenclature

B	Exergy, kWh
b	Specific Exergy, $kWhkg^{-1}$
U	U-Value, $Wm^{-2}K^{-1}$
T	Celsius, °C
ρ	Density, kgm^{-3}
λ	Conductivity, $Wm^{-1}K^{-1}$
cp	Specific heat, $Jkg^{-1}\ K^{-1}$
$\dot{v}$	Volumetric Flow Rate, m^3h^{-1}
$\dot{m}$	Mass Flow Rate, kgs^{-1}
cv	Control Volume
B_{TM}	Thermomechanical Exergy
B_{CH}	Chemical Exergy
B_{PH}	Physical Exergy
B_{KN}	Kinetic Exergy
B_{PT}	Potential Exergy
P	Pressure, Pa

2. Building impact on the environment

Buildings interact with environmental context and energy infrastructure and so it is non-neutral on the environment. These interactions occur according two patterns. The first one is based on the distinction between overall impact and energy impact. The Energy Impact accounts all energy fluxes (as fuel, air, water etc.) that provide to the energy requirement of the building during its useful life. The second one is based on the distinction of building phases, in life cycle sense: the construction and disposal phases and the useful life phase. The building energy need during its life cycle is both direct and indirect. Direct energy need is for construction, operation, rehabilitation and disposal. Instead indirect energy need is for the material production used in its construction and rehabilitation.

Currently the energy performance measures the building energy efficiency, through assessing the amount of direct energy that a building uses during its useful life. The calculation of the building energy performance is only a part of the complex evaluation of the environmental building impact (Fig.1). The authors limit this paper to dissertation of building direct energy impact.

Building Direct Energy Impact on the environment includes two complementary analysis: energy and exergy ones. The second one is able to solve some problems present in the first one. At the same time the exergy analysis application as an evaluation parameter allows a complete thermodynamic assessment of a building energy use, because it accounts the potential of the energy carriers that cross the system boundary and their degradation, in addition to the energy conservation equations [8].

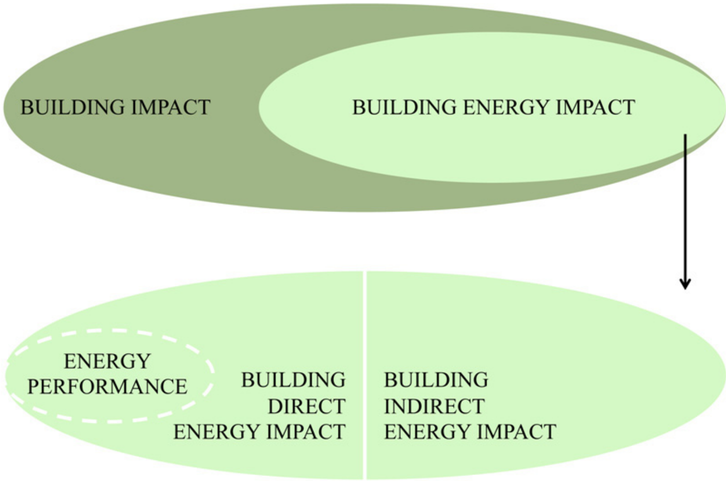

Fig. 1. Building Impact scheme

3. Equations

In Literature there are numerous studies about exergy analysis of energy systems at the building scale. A typological review of air-conditioning systems, currently employed for building indoor control, and their energy and exergy efficiencies, is proposed in [9]. A methodological review of air-conditioning technologies fuelled from renewable sources, interpreted by an exergy point of view, is proposed in [10].

Both reviews take up and develop a model of exergy analysis of energy systems proposed by Schmidt in [11]. The model is based on division of energy chain: from primary energy source via building services to building envelope. The steps in energy flow are: transformation of primary energy, generation, storage, distribution, emission and control, indoor air, building envelope. The sectors are considered in series among them. Each of them receives an exergy input from the sector placed upstream and provides an exergy output to the sector placed downstream. The irreversibility due to energy conversion and transport, or to temperature differences, determines the exergy destruction of each sector and the corresponding exergy efficiency.

An example of the use of this model is presented in [12], in order to compare the energy and exergy efficiency of different thermal generation technologies that fuel a heating system. The Schmidt's model shows that exergy efficiency of air-conditioning systems currently employed for building indoor control is poor when compared to its energy efficiency, and then that a high exergy destruction takes place in these systems. The decomposition of the energy chain in sectors allows to locate the causes of exergy destruction and thus to identify among different energy retrofit strategies one that allows a better overall building efficiency. An exergy analysis model similar to that is presented in [13].

4. Thermal Exergy model

Many authors, as Adrian Bejan [14], George Tsatsaronis [15], Tadeusz Kotas [16] and others, wrote of exergy to provide a congruent and coherent quantification of the quality of energy. Mechanical and electrical energy forms can be ideally converted into each other with maximum efficiency. They are other quality energy form, as internal, chemical and thermal energy that cannot be converted into high quality energy form without irreversibility.

Building is an open thermodynamic system: it exchanges with the environment energy and material fluxes. Each exchange has an associated exergy (thermomechanical and/or chemical) defined with respect to a reference environment (1). Thermomechanical exergy is composed from physical, kinetic and potential exergy (2).

$$B = B^{TM} + B^{CH} \tag{1}$$

$$B^{TM} = B^{PH} + B^{KN} + B^{PT} \tag{2}$$

At this stage of model advancement, the chemical exergy of fuels is approximated to their lower heating value. According to [17] the error is of a few percentage points, compared to an analytical determination. This approximation allows to describe the reference environment via only temperature and pressure properties. In coming papers the model will consider analytically the chemical exergy of fuels. The reference environment model will account the chemical composition of air.

In this paper the authors assess only thermomechanical exergy of energy and material fluxes. Specifically, the model does not consider the difference of pressure between system and environment and kinetic exergy of wind. For this reason, the authors not calculate kinetic and potential exergy.

Building is a control volume. The authors define the rate of physical exergy exchanged from building excluding mechanical exergy (3).

$$\frac{dB_{cv}}{dt} = \sum_j \left(1 - \frac{T_0}{T_j}\right)\dot{Q}_j - \dot{W}_{cv} + \sum \dot{m}_i b_i - \sum \dot{m}_e b_e - \dot{B}_D \tag{3}$$

The model structure is very similar to that of a standard energy analysis. In comparison to energy (energy is a function of the state of the considered matter only), exergy is a function of the state of the considered matter and of the common components of the environment [18]. The flow diagram in Fig.2 represents the logic in the exergy Model.

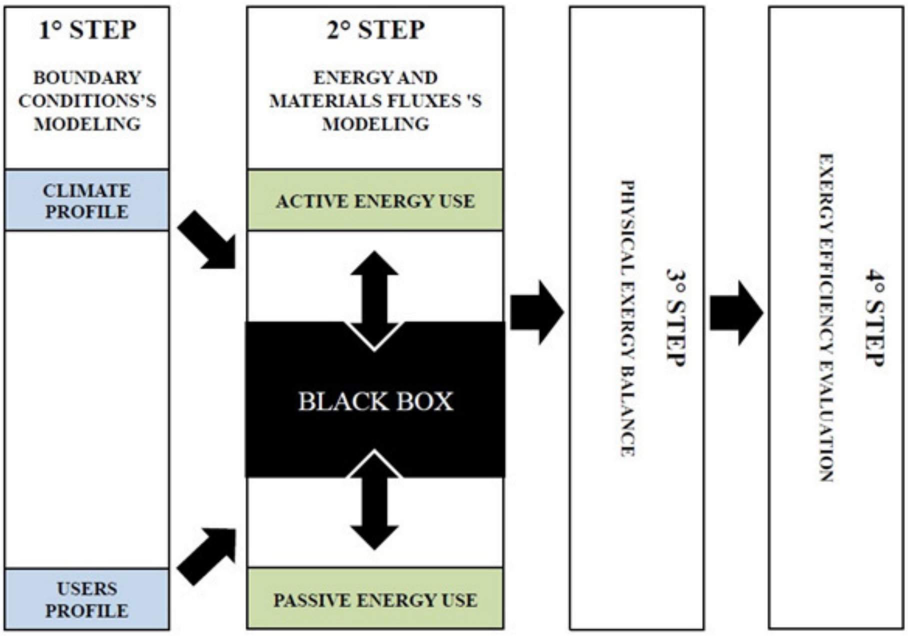

Fig. 2. Process flow of analysis according to the Model

4.1 Thermodynamic system and boundaries definition

The model calculates fluxes' exergy in and out system boundary. The authors' approach is to consider the building as a "black box" that needs exergy. The internal operational mode of the building is analyzed through a standard energy balance.

Physically the system includes the indoor air and the materials that make up the buildings, but human body is not a part of the system. It is considered as an open thermodynamic system that is not in thermodynamic equilibrium with the surrounding and continuously utilizes and converts energy. The authors consider the virtual infinitesimal surface of external wall as the system boundary. The system temperature T_S during the period of heating is 20°C.

4.2 Surrounding and Environment

The system's surrounding refers to everything is not included in the system, but it borders with system boundary. It is an immediate physical space.

The term environment applies to some portion of the surrounding, the intensive properties of each phase of which are uniform and do not change significantly as a result of any process under consideration (Fig. 3). The environment is regarded as free of irreversibilities. All significant irreversibilities are located with in the system and its immediate surroundings. Internal irreversibilities are those located within the system. External irreversibilities reside in the immediate surrounding. [19]. In this paper the irreversibilities of the surrounding are not considered. The surrounding is considered as a closed system and the environment as a closed system in thermodynamic equilibrium with the surrounding. The building is a transient open system.

The system operates within the surrounding. Air, land and water are part of the surrounding. The air is defined at constant pressure P_0 and with a temperature T_{0h} variable hour by hour obtained by data set from Test Reference Year. The temperature of water and land are defined respectively T_W and T_G constant.

4.3 Energy Fluxes

A building must maintain essential indoor conditions in order to be benefited by users, using exergy for space heating, hot water preparation, lighting and appliances.

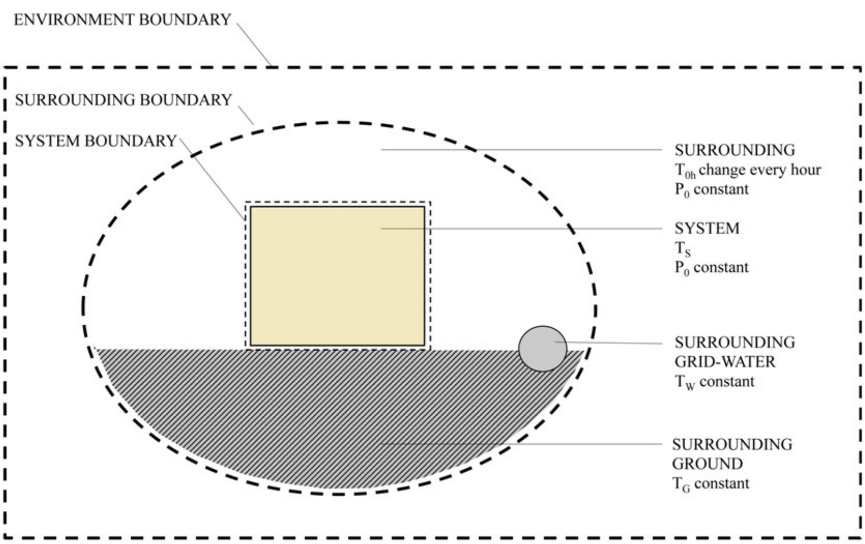

Fig. 3. Model Scheme

The solar radiation flux includes only solar fraction that effectively enters into the system: the fraction absorbed

The input fluxes considered are both material and energy: solar fraction incident on the external surface of the building envelope, heat flux through the building envelope, air flux for natural ventilation, fuels for the central heating system, electricity for both the electric boilers for the domestic hot water production systems and the artificial lighting equipment and plug & play appliances, cold water for sanitary use taken from the aqueduct, human thermal energy from occupant's metabolism.

The solar radiation flux includes only solar fraction that effectively enters into the system: the fraction absorbed by the opaque surfaces and that one absorbed or transmitted by the transparent surfaces. The heat flux is exchanged by conduction through the building envelope with the surrounding air or with the ground. The human body is not a part of the system. The air flux refers to input air needed for ventilation and fuels combustion.

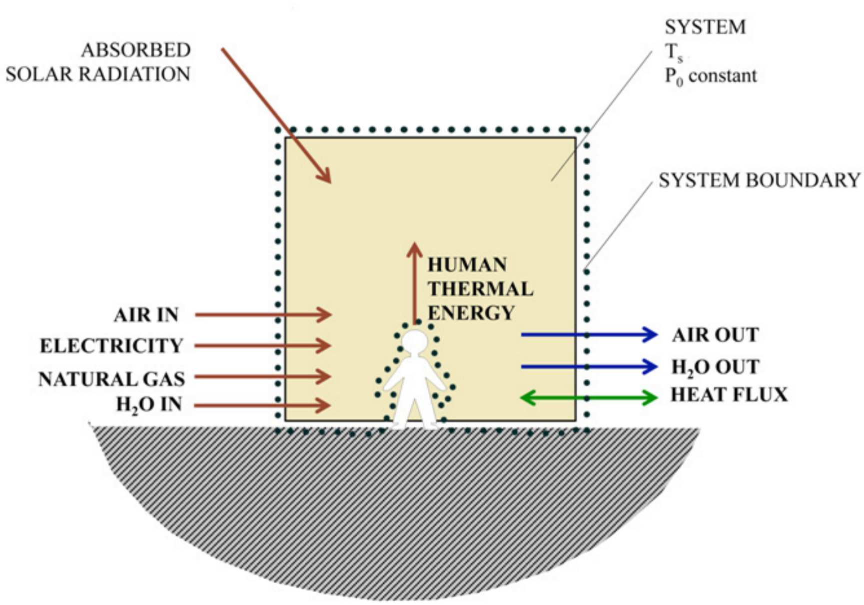

Fig. 4. Building Model Fluxes

The output fluxes considered are: exhaust air of combustion; hot water for sanitary uses, air flow for natural ventilation and heat flux exchanged by conduction through envelope with the surrounding air or with the ground. The model assesses the heat flux as a bidirectional flux.

The complexity of fluxes scheme may depend on building complexity, but in general for a standard building is as described in Fig.4. This paper take in account a standard building.

Currently, buildings require mostly low quality energy carriers for thermal uses at low temperatures and nowadays their energy demand is mainly satisfied by high quality energy sources. The model becomes significant when comparing the "Actual State" with the "Varied State". The main energy saving interventions can improve the building envelope, and redesign the individual energy systems or build and district-heating plants. They will reduce the exergy destroyed by the building.

The method allows the designer to compare different design solutions considering both the quantity and the quality of energy.

5. Computational Model

The model "black box" previously described has been used for the analysis of energy fluxes in an existent building. The overall analysis objective is to verify the model functionality. The specific aim is to evaluate exergy destructed and lost.

The analyzed building (Fig. 5) is a multi-unit residential building; it was built in the 80s. It is located near Florence, Italy. The vertical structure is composed from reinforced concrete walls, the external one also from interior insulation in glass wool. The horizontal structure is composed from predalles slabs. The windows are composed from double glazing and metal frame. The thermal data of building components (U-value) are reported in Table 1. The Building geometrical and thermal model is modelled by T3D plugin (www.transsolar.com) for SketchUp (www.sketchup.com).

Fig. 5. Building's geometrical and thermal model

Table 1. U-value of building components

Building component	U-value ($Wm^{-2}K^{-1}$)
External wall	0.642
Wall between apartments and stairs	3.431
Wall between cellars and ground	3.608
Internal wall	3.271
External floor	1.486
Internal floor	1.481
Ground floor	1.822
External roof	1.427
External window (glaze)	2.830
External window (frame)	10.900

The building has a central heating system, fuelled from a gas device. Each apartment has a domestic hot water production system, fuelled from an electric boiler. There isn't an air conditioning system.

The building was modeled using the transient simulation software TRNSYS (www.trnsys.com), setting one hour as calculation time step and one year as calculation time period. The climate data set are taken from Test Reference Year for the city of Florence (http://apps1.eere.energy.gov). The user time profile for domestic hot water production is taken from the literature [20]. The user time profile for artificial lighting is assumed constant throughout a year, due to the complexity of modeling the relationship between natural lighting and artificial lighting inside the building. The subsequent development of the computational model will also take account of this relationship.

The building heat exchanges were modeled using the TRNSYS Type 56 (multi-zone building model, with not thermally coupled zones). The climate data set from Test Reference Year have been read and processed by using the Type 15-3 (data format EPW). The ground's thermal property were described using the Type 77, assuming an annual average temperature of the soil T_G equal to 14.2 °C, density ρ_G of 3 200 kgm^{-3}, conductivity λ_G of 8.72 $Wm^{-1}K^{-1}$ and specific heat cp_G of 0.84 $kJkg^{-1}K^{-1}$.

The annual overall results are given by a combination of hourly partial results. The resulting values are reported in Table 2, distinct for each flux in the input and output (loss) from the system.

Table 2. Annual partial and total exergy fluxes in and loss from the system

Fluxes	Exergy (kWh)
natural gas	170 982
cold water for sanitary use	715
electricity (electric boilers)	83 833
human thermal energy	3 265
electricity (lighting and appliances)	88 946
solar radiation	97 558
air flux for natural ventilation	0
heat flux through the building envelope	458
Overall annual exergy fluxes in input in the system	445 759
air from gas combustion	3 199
hot water for sanitary uses	2 320
air flux for natural ventilation	9 116
heat flux through the building envelope	7 451
Overall annual exergy fluxes in output (loss) from the system	22 086

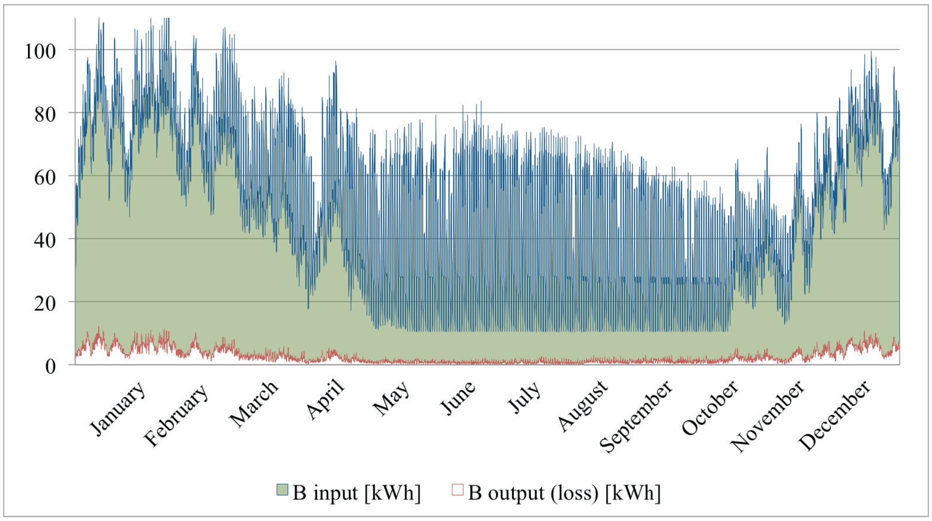

Fig. 6 Hourly exergy input and loss profiles

The results show that the overall annual exergy input is 445 759 kWh and that the overall annual exergy loss is 22 086 kWh. The difference is exergy destruction $\dot{B}_D$ equal to 423 673 kWh, referred to a year of the building useful life phase. The results are given from the assembly of the hourly exergy input and loss profiles, as shown graphically in Fig. 6.

The results show that about 95% of the exergy used from the building is destroyed and that about 5% is loss (transferred to the surrounding). The model described above can thus be used also to evaluate the exergy efficiency of a building.

The thermal exergy model previously described could be employed in order to compare different solutions of energy retrofit. The comparison among different system solutions will be analyzed in next papers.

6. Conclusion

The model described in this paper differs from the model proposed by Schmidt the building is considered as a "black box " and the overall exergy fluxes in input and in output from the system are evaluated. The model also differs because considers not only the energy fluxes but also the matter fluxes that are functional to building needs previously defined.

The model does not allow to carry out the exergy analysis of individual components that make up the system, but it allows to compare different building energy configurations. The "black box" approach is in line with the need of set up a suitable model for the future extension of the exergy analysis scale, in order to extend the evaluation from the building to the district. The scale extension will develop in subsequent work steps.

The authors' choice to call "thermal exergy analysis of a building" the model described, is due main some reasons. The first is to extend the concept of "building energy assessment" from a First Law to a second Law point of view. The second is to design a concept of "building energy impact on the environment through a sequence of steps, the first of all is "Thermal exergy analysis".

The next step will be to integrate the model taking in account also the chemical composition of fuel and of surrounding.

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