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## Article

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# First and second law analysis applied to building envelope: A theoretical approach on the potentiality of Bejan's theory



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## ABSTRACT

Especially in the last decade, efforts have been made in developing the sustainable building assessment tools, which are usually performed based on fundamentals of the First Law of Thermodynamics. However, this approach does not provide a faithful thermodynamic evaluation of the overall energy conversion processes that occur in buildings, and a more robust approach should be followed. The relevance of Second Law analysis has been here highlighted: in addition to the calculation of energy balances, the concept of exergy is used to evaluate the quality of energy sources, resulting in a higher flexibility of strategies to optimize a building design. Reviews of the progress being made with the constructal law show that diverse phenomena can be considered manifestations of the tendency towards optimization captured by the constructal law. The studies based on First and Second Principle of Thermodynamics results to be affected by the extreme generality of the two laws, which is consequent of the fact that in thermodynamics the “any system” is a black box with no information about design, organization and evolution. In this context, an exploratory analysis on the potentiality of constructal theory, that can be considered a law of thermodynamics, has been finally outlined in order to assess the energy performance in building design.

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## 1. Introduction

Heating, cooling and lighting appliances in building constitute more than one third of the world's primary energy demand (Acikkalp et al., 2014; Hepbasli, 2012). Energy is used in buildings throughout their whole lifecycles. Therefore, many aspects and stages of building development and utilization present various impacts on their energy and environmental performance: there include planning, design, construction and installation to test, commissioning, operation and maintenance. In the EU where buildings account for 41% of the total final energy use, efforts are ongoing to improve buildings energy efficiency and thereby reduce dependency on fossil fuels (Enerdata, 2012; European Commission Energy Efficiency Plan, 2011). Therefore, predicting energy consumption starting from the early stages of building design is important for energy and emissions reduction efforts. The majority of decisions in the building design process are taken in the early design stage. This delicate phase presents the greatest opportunity to obtain high energy performance. However, design decisions influence

different multidisciplinary aspects which are often in contrast. Ref. Echenagucia et al. (2015) illustrates an integrative approach for the early stages of building design aimed to obtain detailed information on energy efficient envelope configurations. Low-energy buildings (Tetty et al., 2014) are mainly achieved by increased use of materials such as insulation and glazing with improved transmittance-values to achieve better thermal performance and improved air tightness. Both the improvement of energy-efficiency standards and the deployment of low-energy buildings typically focus on reducing the energy use for building operation. Building energy assessment is usually performed based on fundamentals of the First Law of Thermodynamics, which is especially concerned on quantitative energy aspects (Goncalves et al., 2013). However, this approach does not provide an exhaustive thermodynamic evaluation of the overall energy conversion processes that occur in buildings, and a more robust approach should be performed. The exergy analysis (Yucer and Hepbasli, 2011; El Shenawy and Zmeureanu, 2013) is a useful method that combines First Law and Second Law perspectives and has been applied in many related engineering fields, such as building energy systems. Ref. Dovjak et al. (2015) illustrates the efficiency of some building interventions both from building and user point of view. With exergy analysis based on connective thinking approach, thermal exergy flows through the building envelope are analysed jointly with human body exergy balance. Reviews of the progress being made with the constructal

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law show that diverse phenomena can be considered manifestations of the tendency towards optimization captured by the constructal law (Bejan and Lorente, 2008). The studies based on First and Second Principle of Thermodynamics result to be affected by the extreme generality of the two laws, which is consequent of the fact that in thermodynamics the “any system” is a black box with no information about design, organization and evolution. In this context, the aim of the present paper is to outline a novel approach on the potentiality of constructal theory applied to access the energy performance in building design.

## 2. Energy analysis

In order to evaluate the amount of energy that has to be supplied, an energy balance with reference to the building envelope has to be set up, in the context of the first principle of thermodynamics. The demand side is calculated cumulating energy losses that have to be (fully or partly) compensated by energy gains. All heat flows including gains and losses are summed up to create the heating energy balance: the heat demand is equal to the sum of heat losses minus the sum of heat gains.

$$\Phi_h = (\Phi_T + \Phi_V) - (\Phi_S + \Phi_{i,o} + \Phi_{i,e} + \Phi_{i,L}) \quad [W] \quad (1)$$

where:

- $\Phi_h$  is the total heat power demand;
- $\Phi_T$  represents the transmission heat losses of the envelope;
- $\Phi_V$  represents the ventilation heat losses;
- $\Phi_S$  represents the solar heat gains through windows;
- $\Phi_{i,o}$  represents internal heat gains caused by occupants;
- $\Phi_{i,e}$  represents the internal heat gains caused by electrical appliances;
- $\Phi_{i,L}$  represents the internal heat gains caused by lighting power.

All the terms of Eq. (1) have been clearly described in Ref. Schlueter (2009); for sake of conciseness, only the energy losses will be here reported in explicit form.

The total transmission heat loss is given as follows:

$$\Phi_T = \sum (F_{x,i} * U_i * A_i) * (\theta_i - \theta_e). \quad (2)$$

$F_{x,i}$  is the temperature correlation factor, which is set according to the regulations to 1.0 for external walls and roofs and to 0.6 for walls and floors facing the ground (attics, unheated room, etc. are neglected). Indoor and outdoor temperatures, respectively  $\theta_i$  and  $\theta_e$ , are defined by the particular location of the building.  $U_i$  represents the thermal transmittance of the  $i$ -element (wall, window objects, etc.), which is multiplied by the respective area  $A_i$ . Finally, it is worth mention that in Eq. (2) heat bridges have not been contemplated.

A simplified formula captures the ventilation heat losses. The overall building volume  $V$  is multiplied by the air exchange rate  $n_d$ ; the specific heat capacity of air, assumed equal to  $0.34 \text{ Wh/m}^3 \text{ K}$ , is also taken into account:

$$\Phi_V = (0.34 * n_d * V) * (\vartheta_i - \vartheta_e). \quad (3)$$

## 3. Second law balance and exergy indicator

Under steady state conditions, energy balance of the building envelope can be synthetically described as follows:

$$\dot{Q}_{in} = \dot{Q}_{out} \quad (4)$$

where  $\dot{Q}_{in}$  [ $\text{W/m}^2$ ] is the thermal energy entering the building envelope and  $\dot{Q}_{out}$  is the rate at which energy flows out from the envelope into the outdoor space; all terms are expressed per unit

surface and unit time. The entropy balance corresponding to Eq. (4) turns out to be:

$$\frac{\dot{Q}_{in}}{T_r} + \dot{S}_g = \frac{\dot{Q}_{out}}{T_0} \quad (5)$$

where  $T_r$  is the temperature of indoor rooms and  $T_0$  is the outdoor temperature.  $\dot{S}_g$  is the entropy generation rate [ $\text{W/m}^2 \text{ K}$ ]. Multiplying by the outdoor temperature and substituting Eq. (4), the exergy balance equation is expressed as follows:

$$\left(1 - \frac{T_0}{T_r}\right) \dot{Q}_{in} + \dot{S}_g T_0 = 0. \quad (6)$$

The term  $(1 - T_0/T_r) \dot{Q}_{in}$  represents the exergy rate flowing into the building envelope surface which is totally consumed until the exergy flow reaches the external ambient.

The energy balance formulated in Eq. (1) does not take into account the thermodynamic considerations on the final energy usage of a system so that an exergy balance had to be performed in Eq. (6) in order to contemplate both quantity and quality aspects. In this context, a new performance indicator,  $\psi_i$ , based on exergy, is proposed:

$$\psi_i = \frac{Ex_{des,i}}{Ex_{req,i}} \quad (7)$$

where  $Ex_{des,i}$  is the exergy desired (output) and  $Ex_{req,i}$  is the exergy required (input) to perform a given task  $i$ . The required exergy is directly related to the thermodynamic state of the supplied energy source. According to Kotas (1995), exergy input associated to a given energy quantity can be calculated by the product between the quality factor of the source and the respective energy related:

$$Ex_{req,i} = F_{q,f} E_{f,i} + \sum_k F_{q,f,k} \frac{W_{el,k}}{\eta_{eg,k}} \quad (8)$$

where  $F_{q,f}$  is the quality factor of the fuel and  $E_{f,i}$  is the fuel energy supplied for the task  $i$ .  $F_{q,f,k}$  is the quality factor of the fuel source,  $k$  for the electricity production  $W_{el,k}$ . On other side, the assessment of the desired exergy is calculated as follows:

$$Ex_{des,i} = F_{q,i} E_{u,i} \quad (9)$$

where  $F_{q,i}$  is the quality factor for the desired task  $i$  and  $E_{u,i}$  is the useful energy required to perform the task  $i$ . The assessment of  $F_{q,i}$  is quite different from the quality factor of the source,  $F_{q,f}$ , since different exergy levels are involved for each task. Thus, in order to apply the exergy method, as illustrated in Ref. Gonçalves et al. (2012), it is important to split all the energy consumers according to their final use, defining a dead-state temperature and a required temperature for each application.

## 4. Discussion and concluding remarks: Constructal theory as a law of thermodynamics for building design optimization

The energy conservation Law has been here outlined with reference to the building system. Therefore, the exergy balance has been performed as a complementary method to estimate quantity and quality aspects on energy utilization. The extreme generality of the two laws are consequences of the fact that in thermodynamics the “any system” is a black box, i.e. a region of space without shape and structure. In other words, the two laws are global statements about the balance (or imbalance) of heat, work, entropy, etc. that flow into the black box. They say absolutely nothing about design and organization. The Constructal law was initially formulated by Bejan in 1996 (Bejan, 2000) as a principle of generation of

flow configuration: “For a finite-size flow system to persist in time (to live) it must evolve in such a way that it provides easier and easier access to the currents that flows through it”. The new research direction defined by the constructal law is documented in a growing literature, review articles (Reis, 2006; Bejan and Lorente, 2011) and books (Rocha et al., 2012; Bejan and Lorente, 2008). Reviews of the progress being made with the constructal law show that diverse phenomena can be considered manifestations of the tendency towards optimization captured by the constructal law. Ref. Bejan (2015) illustrates why the constructal law is even a law of thermodynamics but it is at the same time distinct and/or complementary to the other principles of thermodynamics. The first law accounts for a quantitative energy balance while the second law significance is linked to the irreversibility or entropy generation that prevents us from extracting all possible energy as work from various sources. The concept of quality of energy sources and energy conversion is at the basis of the exergy calculations here performed in Paragraph 3. It is worth knowing that the First and Second Laws of Thermodynamics do not say anything about the possible internal configurations: classical thermodynamics is not concerned with non-equilibrium flow systems. The time sequence of drawings towards optimal configurations is the phenomenon covered by the Constructal Law, which is now leading in many directions. In this context, the investigation aimed to enhance the building performance represents one of the most promising challenge for Bejan’s theory.

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