Chapter 40
Building Thermal Exergy Analysis

Lorenzo Leoncini and Marta Giulia Baldi

Abstract The energy and environmental impacts due to energy consumption in the building sector are one of the main topics in the global energy field. A building is an energy system that uses energy sources in order to maintain its functionality and to ensure thermal indoor comfort for its occupants. Exergy analysis is a way to assess the impact of an energy system on the environment. This chapter introduces a model able to describe the interaction between a building and its surroundings from an exergetic point of view. The building is considered as a so-called black box, evaluating the exergy of overall energy and matter fluxes that cross the system boundaries. In this way it is possible to evaluate the exergy balance of the system and particularly the destroyed exergy. The exergy destruction percentage can be understood as a building environmental impact indicator. To illustrate the model and its operating suitability, an existing building was analyzed using the transient simulation software Trnsys. The modeling results show that about 95 % of the exergy used from the building is destroyed and that about 5 % is lost (transferred to the surroundings). This means that this building has very high impact. The model can be applied to assess the effectiveness of different building energy retrofit strategies. Through Trnsys modeling some conventional and advanced retrofit strategies, as well as on-site renewable energy utilization, are analyzed. The chapter presents the main analysis results, showing which of these strategies are able to reduce the building's exergy demand and, hence, the building's impact.

Keywords Exergy • Energy retrofit • Building impact • Transient analysis

1   Introduction

The energy and environmental impacts due to energy consumption in the building sector are one of the main topics in the energy field. A building is an energy system that uses energy sources in order to maintain its functionality and to ensure thermal

L. Leoncini (✉) • M.G. Baldi
Department of Industrial Engineering, University of Florence,
via di S. Marta 3, Florence 50139, Italy
e-mail: lorenzo.leoncini@unifi.it; marta.baldi@unifi.it

indoor comfort for its occupants. An exergy analysis is a way to assess the impact of an energy system on the energy sources and the environment [1–3].

Generally, an exergy analysis of an energy system is made to show how the system uses inlet energy to produce a "useful product" (for example, electricity in a power plant). In contrast, a building is designed for thermal indoor comfort, with functionality being the useful product. From this consideration it follows that a building exergy analysis does not necessarily address exergy destruction percentage minimization. Alternatively it could address building exergy demand minimization, as will be discussed in this chapter.

In a previous paper [4] the authors developed a model called the thermal exergy analysis of a building in order to describe the interaction between a building and its surroundings from an exergetic point of view. This model views a building as a black box, taking into account only the flows that cross the system boundaries. The model makes it possible to quantify the exergy inlet and outlet from a building, considering all energy and mass flows, and, hence, to quantify the destroyed exergy. The exergy destruction percentage can be understood as a building impact indicator. In addition, the building exergy demand, normalized with respect to a year of operating time and a square meter of floor area, can be understood as a similar indicator, as explained in [5].

We verified the model reliability under different values of the reference state temperature. This verification [6] revealed that variation in the reference state temperature does not significantly affect the building exergy analysis results. In particular, the exergy magnitude of the sun, fuels and grid electricity are such that, from an overall system point of view, the results are affected marginally by the thermal exergy interaction between a building and its surroundings.

The model can be applied to assess the effectiveness of different building energy retrofit strategies. Through Trnsys modeling some conventional and advanced retrofit strategies, as well as on-site renewable energy utilization, were analyzed. This chapter presents the main analysis results, showing which strategies are able to reduce the exergy destruction percentage, or the building exergy demand, and, hence, the building impact.

2   Building Exergy Analysis in the Literature

In the literature, exergy analysis in the building sector has been mainly applied at the component level rather than at the system level. Lohani and Schmidt present in [7] an energy and exergy study of various heating configurations for a residential building. The fueling devices modeled are a gas-fired condensing boiler, an electric air-source heat pump and an electric ground-source heat pump. The study was carried out splitting the energy chain from the primary sources to the building envelope into subsystems placed in series. For each subsystem were calculated the energy and exergy efficiencies. The analysis results show that most thermodynamic irreversibility happened in the conversion from primary sources to so-called low-temperature thermal energy. Among the fueling devices modeled, the electric ground-source heat pump allowed for the highest overall exergy efficiency.

Yildiz and Güngör describe in [8] a parametric methodology for assessing the exergy efficiency of a generic heating configuration. Through the application to an office building some factors are emphasized that directly affect energy consumption (and the exergy destruction), such as whether the boiler is installed indoors or outdoors, the thermal insulation of the distribution piping, the operating temperature of the fluid, and the temperature difference between the terminal and the room. The resulting overall exergy efficiency is about one order of magnitude smaller than the overall energy efficiency. In agreement with Lohani and Schmidt, Yildiz and Güngör also conclude that most of the thermodynamic irreversibility happens in the conversion from primary sources entering the boiler to low-temperature thermal energy entering the distribution piping.

Hepbasli [9] presents an extensive review of so-called low-exergy heating and cooling configurations. Also Hepbasli, as well as Lohani and Schmidt, splits the energy chain from the primary sources to the building envelope into subsystems placed in series. The calculations are made both under steady-state and transient conditions. Moreover, a comparative review of 20 air-conditioning systems is presented, both from a device-size point of view and a device-efficiency point of view. From this review emerges the suitability of the exergy analysis as a planning tool for air-conditioning systems, considering exergy as a sustainability parameter for the building sector.

Torío et al. [10] propose an exergy vision of renewable energy sources used for fueling building needs, starting from a critical review of the related exergy analysis presented in the literature. The review underlines that exergy analysis methodologies are diverse and sometimes in disagreement with each other. There is no shared characterization of the reference state. Also, there is no commonly shared definition of exergy efficiency; it is variously understood as being "simple" or "rational" or "universal" or "functional." These considerations lead to an exergy vision based on a distinction between technical boundaries and physical boundaries and between steady-state conditions and transient conditions. The aim of this vision is to define a shared methodological approach in order to make consistent the exergy analysis results.

Systematic studies of exergy analysis applications to whole building systems are reported in the ECBCS Annex 37 [11] and ECBCS Annex 49 [12]. The main topics are respectively low-exergy air-conditioning systems and exergy-efficient buildings and zones.

The Annex 37 study is set up to more levels: at the conceptual level, where exergy is explained as an analysis tool for energy systems; at the experimental level, where the building exergy balance is related to the human body's exergy balance through comfort indices; at the application level, where many low-temperature heating devices and high-temperature cooling devices are described in order to minimize the thermal difference between a terminal and a room and, hence, to minimize the exergy destruction related to heat exchange.

The Annex 49 study deepens the Annex 37 study, focusing on building exergy analysis methodologies and low-exergy building design strategies. The criteria for the reference state choice and characterization are discussed and formulas for

exergy calculations collected. Moreover, some applications of these concepts were presented, both at the building scale and at the district scale.

3   Thermal Exergy Analysis of a Building

We summarize here the main concept of the model in order to allow a better understanding of the computational model described in the following paragraph.

A building is an open thermodynamic system. It exchanges energy and mass flows with its surroundings. Each exchange is characterized by an associated exergy (thermomechanical or chemical) defined with respect to some reference state. The model does not consider the difference in pressure between system and surroundings and the wind kinetic exergy. Consequently, the air potential and kinetic exergy are not calculated.

The flow diagram in Fig. 40.1 illustrates the model concept. The building is treated as a black box: the mass and energy flow inlets are necessary to maintain its functionality and to ensure indoor comfort for the occupants. The model takes into account, for a standard building, the energy and mass flows illustrated in Fig. 40.2.
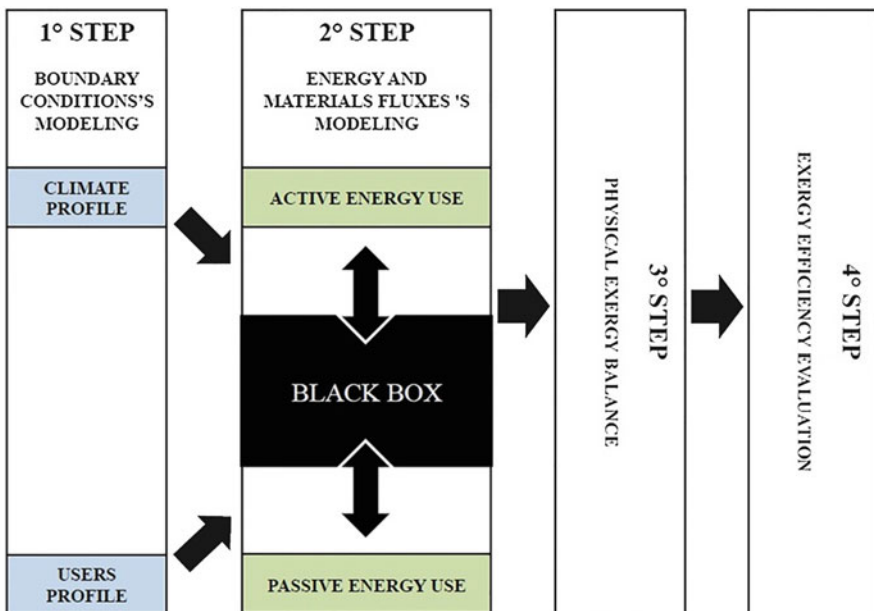
Active energy use refers to the devices fuelled from energy carriers.
Passive energy use refers to the sun radiation incident on the building envelope.

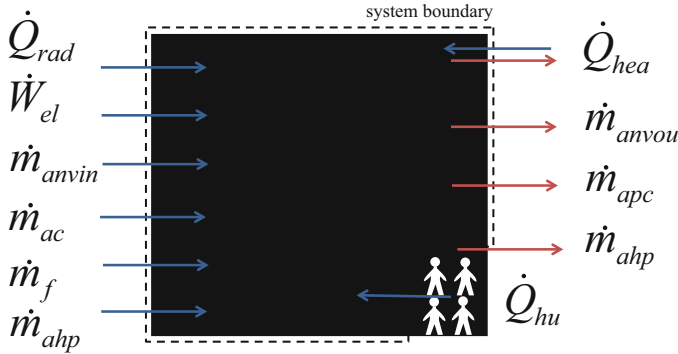**Fig. 40.1** Thermal exergy analysis of a building model concept

Fig. 40.2 Energy and mass flows considered for a sample building

4 Computational Model of a Sample Building

The sample building is a multiunit linear apartment buildings located in Florence, Italy. It was built in the 1980s, applying the building technologies typical of that time period. The building can be considered as being representative of Italian urban neighborhoods built in the period 1960–1980, mostly composed of multiunit linear apartment buildings. Consequently, this building is suitable for the model aim, which is to present an assessment method applicable to any generic building.

The external walls are composed of reinforced concrete having internal insulation in glasswool, the internal walls are made of plastered brick, the slabs of "predalles" plates, and the windows of a single-layer glaze and an aluminum frame.

The building is equipped with a central heating system, fueled by a gas-fired condensing boiler. Each apartment has a single domestic hot water (DHW) production system, fueled by an electric boiler. Originally the building was devoid of cooling systems. Recently each apartment has been equipped with an air-condensed cooling device, of a split type, which makes it possible to control the indoor temperature year round. The heating set-point temperature is 20 °C, and the cooling set-point temperature is 26 °C. The DHW production temperature is 45 °C.

The building was modeled through the transient simulation software Trnsys [13]. The geometric and thermal properties were drawn using a T3D plugin [14] for SketchUp [15], as shown in Fig. 40.3.

In the Trnsys model, the calculation time step was set at 1 h and the calculation time period at 1 year. The hourly weather data were taken from the test reference year (TRY) for the city of Florence, available from the EnergyPlus database [16].

The user profiles are described using some hourly schedulers taken from a benchmark tool developed by the US Department of Energy [16]. These schedulers feature separately the effects of occupants, lighting, and appliances. These schedulers are also used to describe DHW consumption.

Fig. 40.3 Building drawing in T3D plugin for SketchUp

The core building model is the Trnsys Type 56 (multizone building model, with thermally coupled zones). The model reads and processes the TRY weather data through the Trnsys Type 15-3. Moreover, the model describes the ground thermal properties using Trnsys Type 77.

The following flows, respectively inlet and outlet from the black box, were taken into account:

- Natural gas for the heating system; electricity for the cooling devices, DHW production boilers, lighting, and appliances; supply water to DHW production; air for ventilation, for combustion, and for the condensation of the cooling devices.
- Hot water from DHW consumption; air for ventilation and from the condensation of the cooling devices; products of combustion.

The heat exchange through the building envelope serves as the energy flow inlet and outlet. Moreover, the solar radiation incident on the building envelope (only the absorbed amount) and the energy emitted by the occupants, lighting, and appliances were taken into account.

The exergy of each flow or heat exchange was calculated using the standard formula for exergy analysis.

5 Building Energy Retrofit Configurations

The actual building configuration, called Setting 0, was described in the previous paragraph. In this configuration the the system's annual exergy inflow is 496,323 kWh, and the annual exergy outflow from the system (that is, transferred

to the surroundings) is 22,414 kWh. The ratio between these two indicates that the exergy destruction percentage is around 95 %, and so the building in the actual configuration is very high impact.

Eight different building configurations, called Settings 1 to 8, involving both conventional and advanced energy retrofit strategies, were analyzed using the Trnsys transient model. The purpose of the analysis was to assess which of these strategies would allow for system enhancements, both from a relative point of view, that is, the exergy destruction percentage, and from an absolute point of view, that is, the building exergy demand. The main features of each building configuration are described in what follows:

- Setting 1: application of a thermal insulation to the whole building envelope. The walls' thermal transmittance falls from 0.642 to 0.242 W/m^2K, the roof thermal transmittance from 1.427 to 0.250 W/m^2K, and the glazing thermal transmittance from 2.83 to 1.4 W/m^2K.
- Setting 2: installation of mechanical ventilation systems (one for each apartment) in place of natural ventilation. We implemented a combination of air handler devices (such as heat recovery units and variable-flow-rate fans) and control logics to activate the heat-recovery function in winter and the free cooling function in summer only when suitable for the heating/cooling consumption reduction.
- Setting 3: this configuration is the sum of Settings 1 and 2.
- Setting 4: installation of an electric air-source heat pump that fuels the central heating system, in place of the gas-fired condensing boiler.
- Setting 5: this configuration is the sum of Settings 1 and 4.
- Setting 6: this configuration is the sum of Settings 1, 2, and 4.
- Setting 7: installation on the building roof of solar thermal and photovoltaic devices. The photovoltaic field is fully connected. Instead the solar thermal field is split up into four subfields, for the following reason. The produced thermal energy fuels four semicentralized DHW production systems. These systems are obtained linking the actual individual boilers in four clusters, one for each apartment group connected to the same stairwell. Each system has a solar technical room located on the building roof, equipped with its own water thermal storage and control system. The produced electrical energy fuels the building's needs when consumption is greater than production and is fed to the grid when production is greater than consumption.
- Setting 8: this configuration is the sum of Settings 1, 2, 4, and 7.

The resulting exergy values, both for single flow and for the sum of inlet and outlet flows, for each analyzed building configuration are summarized in Table 40.1.

Table 40.1 Calculation results

Setting	0	1	2	3	4	5	6	7	8
Flow	Exergy (kWh)	Exergy (kWh)	Exergy (kWh)	Exergy (kWh)	Exergy (kWh)	Exergy (kWh)	Exergy (kWh)	Exergy (kWh)	Exergy (kWh)
Natural gas	241,854	134,728	205,928	100,481	0	0	0	251,691	0
Airflow for fuel combustion	0	0	0	0	0	0	0	0	0
Electricity for cooling	7073	7348	3965	3009	7073	7348	3009	4925	2475
Electricity for heating	0	0	0	0	79,049	44,448	33,053	0	33,742
Airflow for chiller condensation	0	0	0	0	0	0	0	0	0
Airflow for heat pump evaporation	0	0	0	0	0	0	0	0	0
Water for DHW use	665	665	665	665	665	665	665	665	665
Electricity for DHW production	83,833	83,833	83,833	83,833	83,833	83,833	83,833	30,682	30,682
Heat flow from people	2309	2309	2309	2309	2309	2309	2309	2309	2309
Electricity for lighting and appliances	62,598	62,598	62,598	62,598	62,598	62,598	62,598	29,273	29,273
Solar radiation	97,558	80,627	97,558	80,627	97,558	80,627	80,627	92,848	76,719
Airflow for ventilation	0	0	0	0	0	0	0	0	0
Heat inflow through building envelope surfaces	432	393	781	841	432	393	841	412	809
Annual amount of exergy inlet	496,323	372,502	457,638	334,364	333,518	282,222	266,936	412,805	243,324
Products of combustion	1374	801	1161	591	0	0	0	1402	0
Airflow necessary from chiller condensation	857	909	426	316	857	909	316	568	258
Airflow from heat pump evaporation	0	0	0	0	2774	1535	1147	0	1176
Water from DHW use	7865	7865	7865	7865	7865	7865	7865	7865	7865
Airflow for ventilation	3390	3472	2527	2746	3390	3472	2746	3363	2699
Heat inflow through building envelope surfaces	8928	4842	8877	4816	8928	4842	4816	9173	4852
Annual amount of exergy outlet	22,414	17,889	20,856	16,335	23,814	18,623	16,891	22,372	16,850
Exergy destruction (%)	95.48	95.20	95.44	95.11	92.86	93.40	93.67	94.58	93.08

6 Results and Discussion

From a relative point of view, that is, considering the aim of exergy destruction percentage reduction, the analysis results show values ranging from 92.86 % in Setting 4 to 95.48 % in Setting 0. The paradox of these results is that whatever energy retrofit strategy leads to an exergy destruction percentage (slight) increase respect to the actual configuration. This configuration, that is, one having the highest energy demand, would seem to be exergetically more suitable. The apparent tradeoff between energy demand and exergy destruction percentage, that is, between energy analysis and exergy analysis, can be overcome by changing perspective from a relative to an absolute one.

We underline that, as mentioned at the beginning of the chapter, a building is not designed to produce something useful but to provide thermal indoor comfort and functionality. So a building exergy analysis will not necessarily address how to reduce the exergy destruction percentage. Alternatively, it could address the building exergy demand reduction.

From an absolute point of view, that is, considering the aim of building exergy demand reduction, the analysis results show that the actual configuration has the maximum exergy requirement. Instead, Setting 8, the one with the lowest energy demand, has the minimum exergy requirement. In this way the alignment between energy analysis and exergy analysis is restored. All building configurations bring exergy savings with respect to the actual configuration. The saving values range from −7.79 % (Setting 2) to −50.97 % (Setting 8).

The ratio between the Setting 0 inlet exergy and the Setting 8 inlet exergy is around 2:1. The ratio between the Setting 0 outlet exergy and the Setting 8 outlet exergy is around 1.3:1. From these ratios we get the following consideration: energy retrofit strategies affect inlet flow exergy values rather than outlet flow exergy values because the former have high exergy while the latter have low exergy.

On the basis of the analysis, we can look at a building as an intrinsic exergy destroyer. We determined that the main reasons for this quality of being a destroyer lie in the high exergy magnitude of the sun, the fuels, and the grid electricity compared to the low exergy magnitude of the thermal exergy interaction between a building and its surroundings.

To extend the model from the building scale to the district scale we refer to the methodologies presented by Balocco et al. [17] and Balocco and Grazzini [18]. In the first work the extended exergy analysis method is applied to evaluate the sustainability of an urban area. The applied methodology provides a single thermodynamic environmental criterion for the selection of technological alternatives, strategies, and designs that produce lower environmental impacts. In the second work some thermodynamic indicators are introduced that are useful for energy planning in urban areas and for defining the scenarios of integrated low-environmental-impact energy strategies and actions in an urban area.

7 Conclusions

This chapter introduces a model capable of describing the interaction between a building and its surroundings from an exergetic point of view. The building is treated as a black box, evaluating the exergy of overall energy and matter fluxes that cross the system boundaries. In this way it is possible to evaluate the exergy balance of the system and particularly the destroyed exergy. The exergy destruction percentage can be understood as a building environmental impact indicator.

To illustrate the main model concept and its operating suitability, an existing building was analyzed using the transient simulation software Trnsys. The modeling results show that around 95 % of the exergy used in the building is destroyed and that around 5 % is lost (transferred to the surroundings). This means that this building has a very high impact.

However, all the building's retrofit configurations bring exergy savings with respect to the actual configuration. The saving values range from −7.79 % (Setting 2) to −50.97 % (Setting 8). Looking at the building as an intrinsic exergy destroyer, we conclude that the building energy retrofit can be used to reduce its exergy demand.

In relation to the building design, the exergy approach leads to applying fueling solutions that use a low-exergy energy carrier or to improving the efficiency of the generation devices that use a high-exergy energy carrier. Moreover, the approach leads to a recommendation to install solar photovoltaic or thermal systems in order to take advantage of the electrical or thermal conversion of solar radiation incident on the building envelope. In general, the exergy approach enables building designers to assess their design choices from a perspective of exergy demand minimization, that is, from a perspective of system impact on the environment.

References

1. Romero JC, Linares P (2014) Exergy as a global energy sustainability indicator—a review of the state of the art. Renew Sustain Energy Rev 33:427–442
2. Simpson AP, Edwards CF (2011) An exergy-based framework for evaluating environmental impact. Energy 36:1442–1459
3. Caliskan H (2015) Novel approaches to exergy and economy based enhanced environmental analyses for energy systems. Energy Convers Manag 89:156–161
4. Baldi MG, Leoncini L (2014) Thermal exergy analysis of a building. Energy Procedia 62:723–732
5. Leoncini L (2014) Analisi degli scenari energetici europei e sviluppo di un criterio di valutazione exergetica del sistema edificio. PhD Thesis, Università degli Studi di Firenze
6. Baldi MG, Leoncini L (2015) Effect of reference state characteristics on the thermal exergy analysis of a building. Energy Procedia 83:177–186
7. Lohani SP, Schmidt D (2010) Comparison of energy and exergy analysis of fossil plant, ground and air source heat pump building heating system. Renew Energy 35:1275–1282
8. Yildiz A, Güngör A (2009) Energy and exergy analyses of space heating in buildings. Appl Energy 86:1939–1948

9. Hepbasli A (2012) Low exergy (LowEx) heating and cooling systems for sustainable buildings and societies. Renew Sustain Energy Rev 16:73–104
10. Torío H, Angelotti A, Schmidt D (2009) Exergy analysis of renewable energy-based climatisation systems for buildings: a critical view. Energy Build 41:248–271
11. ECBCS ANNEX 37 (2004) Heating and cooling with focus on increased energy efficiency and improved comfort. Guidebook to IEA ECBCS Annex 37 low exergy systems for heating and cooling of buildings
12. ECBCS ANNEX 49 (2011) Low exergy systems for high-performance buildings and communities—Annex 49 Final Report
13. Transient System Simulation Tool [Internet]. www.trnsys.com
14. Transsolar [Internet]. www.transsolar.com
15. Sketchup [Internet]. www.Sketchup.com
16. Office of Energy Efficiency & Renewable Energy [Internet]. http://apps1.eere.energy.gov
17. Balocco C, Papeschi S, Grazzini G, Basosi R (2004) Using exergy to analyze the sustainability of an urban area. Ecol Econ 48:231–244
18. Grazzini G, Balocco C (2000) Thermodynamic parameters for energy sustainability of urban areas. Solar Energy 69:351–356