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Development of a tool based on thermoeconomics for control and diagnosis building thermal facilities

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A B S T R A C T

This work develops a software to control and diagnose building thermal facilities based on thermoeconomics. It is tested with the data obtained from three building blocks in the Basque Country (northern Spain) with the aim of detecting the potential energy saving points and mitigating environmental impacts. Some obstacles, solved, are related to the insufficient number of probes and the inherent errors of sensors. Besides, new methodologies for performing a thermoeconomic dynamic analysis are described. Apart from this, the inefficiencies of components are quantified, a dynamic cost calculation of all flows is done and different operation modes are discussed. The outcomes of operation modes are discussed and their exergetic, economic and environmental average unit cost are calculated. In such way, the intervention of the control system is analysed and the operation modes with lower and higher fuel consumption are detected. The results show that domestic hot water (DHW) production has an average value of 13.72 c€/kWh and heating of 12.92 c€/kWh; in addition, boilers have 1,587 MWh of real losses. Besides, the operating modes dynamic analysis opens a new research line for thermoeconomics applications. This information is a key fact for control optimization searching the high performance of buildings.

1. Introduction

In Europe, buildings are responsible for 40% of the final energy consumption, Ref [1], and 50% of the CO_2 emissions in the atmosphere, while in Spain, the tertiary sector represents 28% of the total energy consumption. Indeed, as justified in Ref. [2], most of the buildings that exist in the Spanish building stock show a poor energy performance profile.

1.1. Application of thermoeconomics to building energy supply systems

Therefore, due to such a great amount of energy consumption, many efforts are done to maximize the energy efficiency in buildings, focusing especially on retrofitting objectives, since new buildings are only a small percentage of the global building stock, Ref [3]. For example, in Ref. [4] a multi-objective optimization model for retrofitting the building envelope of a residential building is performed; in turn, energy retrofit technologies for small and medium-sized commercial buildings are analysed by using software developed in Ref. [5].

However, most of the energy-saving studies ignore the dynamic performance of the retrofitted systems during operation, Ref [6], and on its maintenance. After all, as concluded in Ref. [7], maintenance provides the wholesome functioning of a system at a much lower cost and possibly for a longer time. In the end, even if the design is optimal, structural components and equipment degrade during the use and, thus, extra costs arise. Consequently, it is necessary to check how the system is really performing and act according to the energy saving purposes. Therefore, energy efficiency studies should be focused also on maintenance and operation phases whether to the building envelope as well as to the building heating, ventilation and air conditioning (HVAC) systems.

Accordingly, in Ref. [8], for example, the behaviour of some historical buildings in Italy were analysed, focusing especially on the envelope for further refurbishment purposes. The proposed diagnosis approach needed a previous research and in-situ surveys for identifying the structure and the thermo-physical properties. HVAC systems, conversely, have to be constantly monitored since

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the energy behaviour of buildings totally depends on the environmental conditions and the user specific needs. Therefore, HVAC systems must be constantly adapting to the requirements at each moment. That is why Ref [9] concludes that the continuous monitoring and the complete comprehension of the key factors that influence the buildings' energy-use are required.

Although the number of installed sensors in buildings are increasing, there is a lack of database related to energy consumption of buildings. Accordingly, the work done in Ref. [10] gathers the available current data sets related to the building stock.

On the other hand, many studies are based on energy-behaviour evaluation. Unfortunately, such analyses do not allow quantifying the real losses (irreversibilities) that take place in the energy chain and, thus, they are not able to assess the potential for energy improvement; nevertheless, this can be easily rectified by using exergy analysis. Therefore, in order to truly analyze energy savings, the studies should be extended to the application of the Second Law of thermodynamics and not to remain merely in the basic issues of the energy balance, Ref [11].

Thermoeconomics allows, through the First and Second Law and the use of the concept of cost, to quantify the amount of natural resources consumed in a process and, therefore, to know how much a particular product costs in terms of consumed resources. It combines exergy analysis with economic analysis and allows assigning monetary costs (exergoeconomic costs) to the different flows, as well as to the irreversibilities, Ref [12]. Thus, it provides the necessary information that cannot be obtained with conventional energy analyses. It is the ideal tool for obtaining a cost distribution based on a rational parameter such as irreversibility (or exergy destruction). Then, from that information, optimization techniques can be applied for design, control or diagnosis, Ref [13].

In recent years, several works have been done related to the application of thermoeconomics on buildings. The most complete one can be the book entitled *Exergy Analysis and Thermoeconomics of Buildings*, Ref [14], which covers the analysis of building envelops and energy supply systems as well as their diagnosis and design. Besides, in Ref. [15], thermoeconomics is the key tool to locate the weak points and the energy saving potentials of an nZEB building located in Spain. Dynamic thermoeconomic application in a very complex HVAC&R system was solved in Ref. [16]. Moreover, critical analysis of thermoeconomic application in HVAC systems was done in Ref. [17] and, afterwards, refined in Ref. [18].

Nevertheless, there are scarce works related to the thermoeconomic analysis based on building systems real dynamic data. Indeed, as far as the authors know, this is the first work related to a dynamic software for system diagnosis and analysis under a thermoeconomic point of view, with real building data.

1.2. Objectives

The general objective of this article is to provide a software based on thermoeconomics, which can be a very helpful tool for the supervision of building thermal systems, searching their high performance and mitigating their environmental impact. For this, the software makes a rational cost-sharing analysis based on thermoeconomics (according to the SPECO and symbolic thermoeconomic guidelines), at each instant and for each operation mode. This software enables the user to know how much resources is consuming, at each time step, in order to cover the required demand. It has a double objective: (1) make the users aware of their consumption profiles (daily, monthly, etc.) by displaying an understandable cost-distribution based on thermoeconomics, and, (2) bring the technician a basis for further control or maintenance optimization applications.

The developed methodology is innovative, since the thermoeconomic analysis is for the first time applied with the real data acquired in real-time in a building thermal facility. This software is a versatile tool that only requires the common data from sensors, but provides essential information for a proper understanding of the cost formation process, which is variable because of the components interconnections as well as due to the dynamic behaviour of the system.

Nowadays, innovation in strategies for energy saving techniques is fundamental for societal development and is particularly interesting on buildings since the building sector has a great potential for energy savings.

In this way, by locating the areas of greatest irreversibility and/or detecting the anomalous components, it will be possible to intervene in the control to reduce the energy consumption of the buildings' thermal systems, making it work more efficiently and with minimum operating costs. This software is versatile enough to be incorporated into the management system of any type of HVAC&R system; the key fact is related to the definition of the thermoeconomic productive structure that is, at the same time, associated with the existing sensors and data acquirement system. Therefore, the more data there is, the more detailed the costs distribution will be. **DEFINITELY, THE** structure of the software is intended to be applied to any HVAC&R installation, although in each case it must be adapted according to the particular characteristics and the available sensors.

The paper is divided into 4 main sections: after this brief introduction of Section 1, Section 2 deals with the methodology used for programming the software. Section 3 describes the case study to implement the program and explains the main barriers and their solutions. The numerical results are shown in Section 4 and, in the last Section 5, conclusions and further discussion are presented.

2. Materials and methods

This section explains how to apply the software in building thermal facilities. Thus, the costs of the final products, as well as those of the internal flows are dynamically accounted for. The software combines Symbolic Thermoeconomics (ST) and SPECO approaches. On the one hand, ST, based on Structural Theory, provides the common mathematical formulae to describe the formation process based on the structure of the system, Ref. [19]; hence, it is used to make the so-called productive super-structure. On the other hand, SPECO approach gives a systematic and general methodology for defining the Fuels and Products of each component, Ref. [20].

2.1. Software caharacteristics

The software is able to adapt to the specific conditions of any building's energy supply system. The main program, developed in Matlab, solves a series of matrix equations filled with the data obtained from the facility's sensors. The workflow for a specific facility under study can be seen in Fig. 1:

The first two phases (system definition and numerical values)

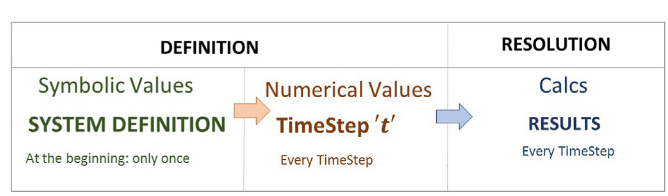

Fig. 1. Program main steps.

refer to the specific facility under study. The third phase, on the contrary, is based on a generic matrix mathematical resolution. Likewise, the system's definition is made once at the beginning, and data collection and results are extracted at each time-step.

2.2. Thermoeconomic dynamic program steps

To begin with, the exergy values of the flows (m_{MAX} flows) that interrelate the different equipment of the facility (n_{MAX}) must be determined. These values are obtained based on the available sensors and the thermodynamic properties. Thus, the accuracy of the results obtained is directly proportional to the number and accuracy of existing sensors.

In addition, the acquisition costs of each piece of equipment and the prices of the input resources (fuels, electricity …) must be specified. If prices vary, these values are updated continually.

2.3. Definition of the super-structure

The first step is to define a productive super-structure capable of representing all the operation modes of the system, as explained in Ref. [16]. As it is commonly known, the buildings thermal facilities continually modify their operation mode (by switching on or off and modulating the different equipment) to adapt to the consumers' needs. Because of this, the active components in each state varies continuously.

With all this in mind, each operation mode can be deduced from a global super-structure defined by the links between all components and the environment. Therefore, the goal is to create a generic super-structure that collects all the possible configurations. In this case, the particular productive structure will depend on the specific moment considered. Thus, each state will have a different formation cost, since it will be related to the flows which are activated in that state.

The innovative contribution of this software lies in the ability to account for the thermoeconomic costs of the system flows under dynamic conditions. The complexity, therefore, is related to the highly dynamic behaviour of building energy supply systems, which makes it difficult to evaluate the continuous deviation of the equipment with respect to the nominal operation mode, the instantaneous performance and the costs at each time step.

2.3.1. Productive structure definition

Cost allocation is based on the productive structure represented by a functional diagram that represents graphically the process of cost formation at each time step. It distributes the flows into Fuels, $\mathbf{F}$ [kWh] (the resources for performing a process in each component) and in Products, vector $\mathbf{P}$ [kWh] (the objective of the process in every component). The productive structure clearly shows how the product of one component is distributed and used as fuel in another component or as the final product of the installation, Ref. [14].

Accordingly, the m active flows, the n active components and the specific productive structure are extracted at each time step.

2.4. Definition of the active operation mode

The following step is to identify the active operation mode at each time-step. For this, the positions of 3-way valves (V3V) and pumps' states are detected, since those are the components that decide if a circuit is in operation or not.

2.5. Matrix resolution

This part performs the calculations at each time-step and returns the results. In this regard, there are three main steps, as shown in Fig. 2:

1. Data registration and treatment: real-time data processing and calculation of the thermodynamic properties.
2. Matrix calculations: calculations and thermoeconomic equations are solved each time-step.
3. Results storage: instantaneous results and trend charts are shown.

The matrix calculation is disaggregated into four stages: (1) definition of the specific productive structure activated at each time-step, (2) calculation of exergy costs, (3) calculation of exergoeconomic costs, and (4) calculation of exergoenvironmental costs.

2.5.1. Exergy costs calculation

Generally, the goal is to obtain the value of the unit exergy costs [kWh/kWh] of fuels $\mathbf{k}_\mathbf{F}^*$ and products $\mathbf{k}_\mathbf{P}^*$, and in this way, visualize how the unit costs increase as they move along the energy chain, from generation to consumption. Those values are calculated by applying the corresponding thermoeconomics equations, Ref [21]. As stated, the main reason for the increase in cost is the equipment inefficiencies. The exergy costs [kWh] of fuels $\mathbf{F}^*$ and products $\mathbf{P}^*$ are obtained by multiplying the unit costs by the corresponding fuel or product and account for the exergy required to achieve that flow.

$$\mathbf{F}^* = \mathbf{k}_\mathbf{F}^* \cdot \mathbf{F} \tag{1}$$

$$\mathbf{P}^* = \mathbf{k}_\mathbf{F}^* \cdot \mathbf{P} \tag{2}$$

2.5.2. Exergoeconomic costs calculation

An economic balance in every component concludes that the total cost of the products [€], $\mathbf{C_P}$, must be equal to the total cost of the resources, $\mathbf{C_F}$, plus the fixed costs of construction and acquisition, depreciation, operation and maintenance costs. The vector that contains the fixed costs of the active equipment in the production process is $\mathbf{Z}$ [€] and the exergoeconomic cost balances for the components are reflected by the following matrix equation:

$$\mathbf{C_P} = \mathbf{C_F} + \mathbf{Z} \tag{3}$$

On the other hand, economic costs of fuels and product $\mathbf{C_F}$ and $\mathbf{C_P}$, are obtained by multiplying the unit exergoeconomic costs of Fuels and Products of each equipment [€/kWh], $\mathbf{c_F}$ and $\mathbf{c_P}$, by the corresponding fuel and product, Ref. [11].

$$\mathbf{C_F} = \mathbf{c_F} \cdot \mathbf{F} \tag{4}$$

$$\mathbf{C_P} = \mathbf{c_P} \cdot \mathbf{P} \tag{5}$$

2.5.3. Exergoenvironmental costs calculation

A similar procedure is done to calculate the environmental impacts (exergoenvironmental costs) of the flows. The

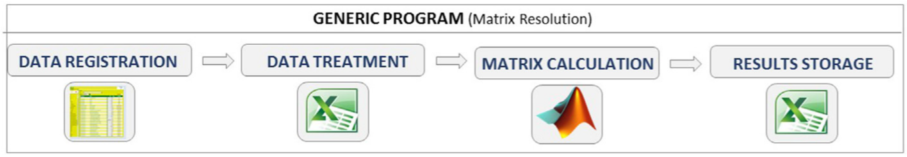

Fig. 2. Disaggregation of the generic program.

exergoenvironmental cost of a flow [impact/kWh] is the impact associated with the generation of that flow, expressed for example in Eco-indicator points per unit of time (due to resource consumption).[1] More information about combining thermoeconomics and Life Cycle Assessment (LCA) methods can be found in Ref. [22] and a detailed LCA is found in Ref. [23].

The properties and relationships in the exergoenvironmental analysis for each component maintain an analogy with those obtained in the exergoeconomic analysis, being $\mathbf{b_F}$ and $\mathbf{b_P}$ the unit exergoenvironmental costs of Fuels and Products of each piece of equipment [gCO_2/kWh] and therefore

$$\mathbf{B_F} = \mathbf{b_F} \cdot \mathbf{F} \tag{6}$$

$$\mathbf{B_P} = \mathbf{b_p} \cdot \mathbf{P} \tag{7}$$

2.6. Software results

The results are at each time-step displayed and saved to create trend charts. These charts depend on the objective of the analyst and, among others, the following charts can be shown:

- Average unit exergoeconomic costs in a day/week/month for the DHW, heating or cooling production (in energy or exergy).
- The same for the exergoenvironmental costs.
- Unit costs associated to a particular operation mode.
- Charts of exergy destruction and their costs for each equipment.
- Etc.

In this way, the irreversibilities are located and, what is more, the costs of those irreversibilities are quantified as well as the impact of each irreversibility on the rest of the system. That detects where to act in order to optimize the whole system. The results of this software allow understanding the cost formation process in both energy and monetary units, as well as in environmental units.

3. Case study

This software was implemented in the experimental facility we have available at the Laboratory for the Quality Control of Buildings in Vitoria-Gasteiz (Basque Country) [24].

Later, the software has been implemented in the centralized heating and DHW facility of three multi-dwelling buildings in the Basque Country (northern Spain). The facility is based on two 1300 kW/each natural gas boilers that supply the DHW and heating demands, see Fig. 3. Therefore, we will focus on the possible setbacks and complications that may arise during its implementation and how to resolve such incidents.

3.1. Description of the facility

Fig. 4 depicts a schematic picture of the facility: on the left, the generation equipment is located, followed by the distribution section, the storage and, finally, on the right, the final emission units are located (radiators for heating and faucets for DHW). The position of the sensors distributed in the different circuits is also illustrated; main equipment nomenclature appears also on Fig. 4.

Thus, these are the sensors located in this installation: 13 temperature sensors Pt 100 (with an uncertainty ± 0.3 °C) $\{T_i\}$; 4 electromagnetic flow meters (±0.1%) and 4 Kamstrup Multical 602 energy meters (±0.5%) to measure mass flow rates $\{m_i\}$; 6 SQL33 electro-valves (with leaks <0.1%) to get the opening percentage of valves $\{v_i\}$, 2 VZ08RE gas volumetric meters (±1%) for fuel consumption rates $\{F_i\}$ and pump status (on or off) $\{Bi_{0/1}\}$.

From these data and the thermodynamic properties, the exergy rate E_i of each flow is calculated according to the following expressions:

- Heat flow: $E_{heat} = Q_{heat} \cdot \left(1 - \frac{T_0}{T_i}\right)$
- Mass flow: $E_{mass} = m_{mass} \cdot c_{P_{mass}} \cdot \left[(T_i - T_0) - T_0 \cdot ln\left(\frac{T_i}{T_0}\right)\right]$ [2]
- Fuel flow: $E_{fuel} = F_i \cdot f_i \cdot LHV$

Where $\left(1 - \frac{T_0}{T}\right)$ is the Carnot factor, T_0 and T_i are the ambient and the i –th flow temperatures respectively, c_P is the specific heat, *LHV* is the lower calorific value of the natural gas and f_i is its quality coefficient.

Therefore, as the analysis is based on the exergy rates calculated out of the real time measured data, it is affected by the sensor errors and uncertainties.[3] This fact highlights the necessity of having good quality measurement devices and reliable mathematical models.

3.2. Data acquisition

Data from sensors are stored in a MySQL database; and, by linking MySQL-Matlab-Excel environments, the software calculates the final and intermediate costs of all the flows.

The extracted data were analysed in order to debug the possible inconsistencies and to process the algorithm correctly, for the incoming continuous operation. After all, one of the biggest sources of error comes from the data acquired from the sensors, which must be previously treated. Indeed, as commented in Ref. [25], the quality of the meta-data in most databases is very poor.

[1] As doing LCA is out of the scope of this work, only CO_2 emissions of external resources are considered. If a LCA of the system were to be incorporated, it would be done in the same way as the acquisition/operation/maintenance cost of the equipment is included.

[2] The exergy values related to DHW demand are calculated with the net water temperature as a reference, that is.$T_0 = T_{55}$

[3] When two or more magnitudes are summed or subtracted, the absolute error is the sum of the errors of both magnitudes. The relative error of the product or the quotient of two magnitudes is equal to the sum of both relative errors. Therefore, the relative uncertainty of each exergy flow is calculated according to its formula and the sensor errors. A deep uncertainty analysis is out of the scope of this work because of the lack of space and in order to focus on the thermoeconomic software application.

Fig. 3. Two of the buildings to be supplied by the central heating and DHW facility (Biscay, Spain).

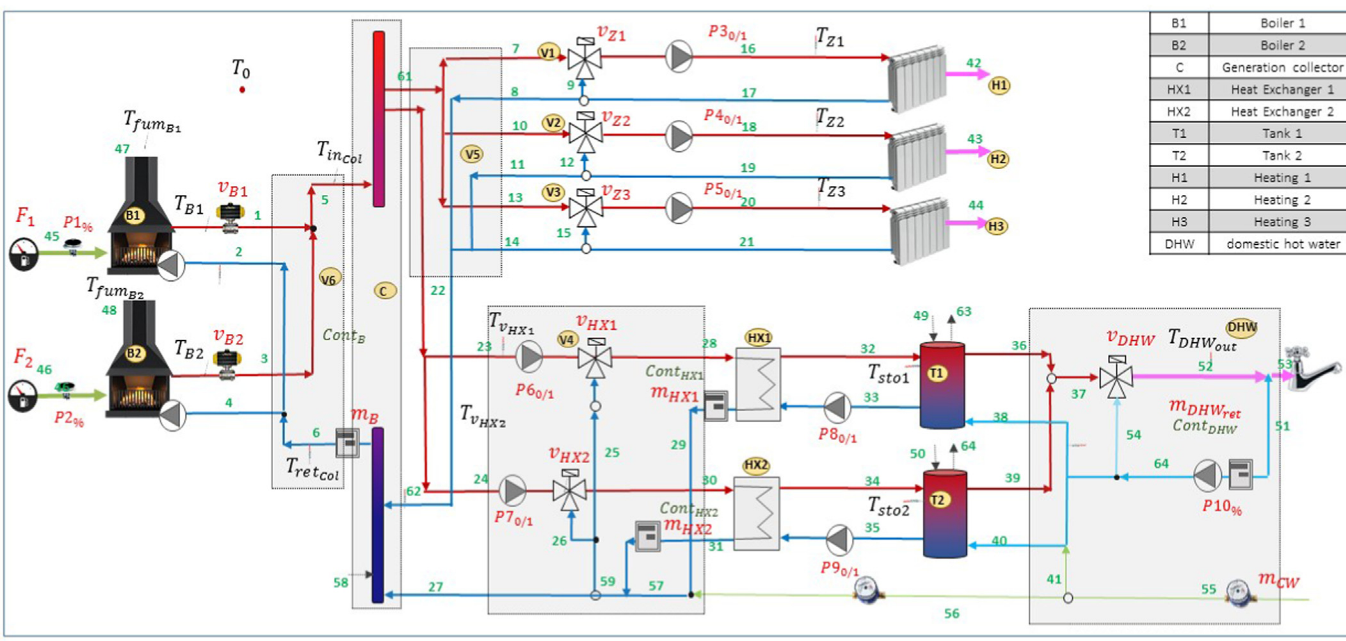

Fig. 4. Schematic of the installation, localization of the sensors and numbering of the flows.

3.3. Data treatment

Data from sensors were stored on the MySQL server from March 07, 2019 to the final date (February 06, 2020) and data dump is done every 30 s.

Then, the values were averaged every 5 min. A study period of 5 min was chosen as it was considered sufficient for the dynamic study to be performed, since 5 min is a time-step enough to allow the characterization of the dynamics of the different equipment, Ref [26].

3.4. Software inputs calculation

Likewise, in order to calculate the exergoeconomic costs of all the flows, it was necessary to deduce the mass flow rates and temperatures of those branches that do not have a sensor mounted.

3.5. Dynamic energy and exergy study

Once the temperature and mass flow rates are known, the energy and exergy rate of each flow is calculated and the analysis of the equipment is performed.

3.5.1. Energy analysis

This step is essential for checking the consistency of the numerical values. The most interesting value refers to the energy efficiency of each equipment, which is the quotient between the product and the fuel of the equipment (P_i/F_i). Accordingly, the fuel and product of each component are calculated following the flow classification that appears in Table 1, where each number refers to the energy flow listed in Fig. 4. Fuel flows are determined with numbers 45 and 46; heat flows are 42, 43 and 44; and the rest of the flows (except numbers 49, 50, 63 and 64) are mass flows. These last four flows are used to represent the variable productive structure of inertial tanks. After all, as developed in Ref. [27], special attention should be given to the inertial tanks (T1 and T2), since different products and fuels can appear depending on the conditions of the primary and secondary mass flow rates ($\dot{m}_p$, $\dot{m}_s$). Accordingly, all the possibilities should be incorporated into the generic productive structure of Table 1.

The example of the first T1 tank is depicted in Fig. 5, where the naming ΔH_p, ΔH_s and ΔH_{disc} is used to refer to the incoming primary energy, outgoing energy and discharged energy of the tank during the studied time-step respectively (the definition of each flow according to the numbering of Fig. 4 is incorporated in the lower left part). Consequently, new virtual-flows i_{st} and o_{st} are defined in order to determine all the charging and discharging possibilities.

Accordingly, the output flows numbered as 63, 64 correspond to the operation mode when the DHW tanks do not discharge and, hence, they accumulate thermal energy; in such cases, the 49, 50 incoming flows are null (see Table 1).

3.6. Exergy analisys

The next step consists in calculating the exergy of each flow. Now, the ratio between the product and the fuel is defined as exergy efficiency and the difference between the fuel and the product corresponds to the irreversibility of each component (exergy destruction plus exergy losses). In this study, there are no heat exergy losses since the limits of each component are considered to be at room temperature, so the heat exergy loss is null.

Exergy destruction quantifies the irreversibilities generated and is, precisely, the parameter on which the increase of exergoeconomic cost is based; that is, as the destruction increases, the cost of the product increases.

3.7. Application of thermoeconomics

After, thermoeconomic analysis is carried out.

3.7.1. SUPER-PRODUCTIVE structure

To build up the productive structure, each component is defined by a black box with an entering arrow, Fuel, and outgoing arrow, Product (Table 1). Sometimes the fuel of one component is, in turn, the product of another. For those situations, the same arrow joins both components. Other times, the equipment product is separated and combined with other outputs to create a specific fuel input. In order to illustrate those separations and those joints, "virtual" components (represented by rhombuses for bifurcations, and circumferences for joints, −m0 … m5− in Fig. 6) are used.

It is worthwhile to highlight that, usually, thermal systems in buildings are very close to sequential systems since a resource

Table 1
Definition of fuel and product in each piece of equipment.

	PRODUCTIVE STRUCTURE				
	FUEL	PRODUCT		FUEL	PRODUCT
B1	45	1–2	HX1	28–29	32–33
B2	46	3–4	HX2	30–31	34–35
C	5–6	(61–62)+(22–27)	T1	(32–33)+49	(36–38)+63
V1	7–8	16–17	T2	(34–35)+50	(39–40)+64
V2	10–11	18–19	H1	16–17	42
V3	13–14	20–21	H2	18–19	43
V4	22-27 + 58+56	(28–29)+(30–31)	H3	20–21	44
V5	61–62	(7–8)+(10–11)+(13–14)	DHW	(36–38)+(39–40)	(53-63-55)+56
V6	(1–2)+(3–4)	5–6			

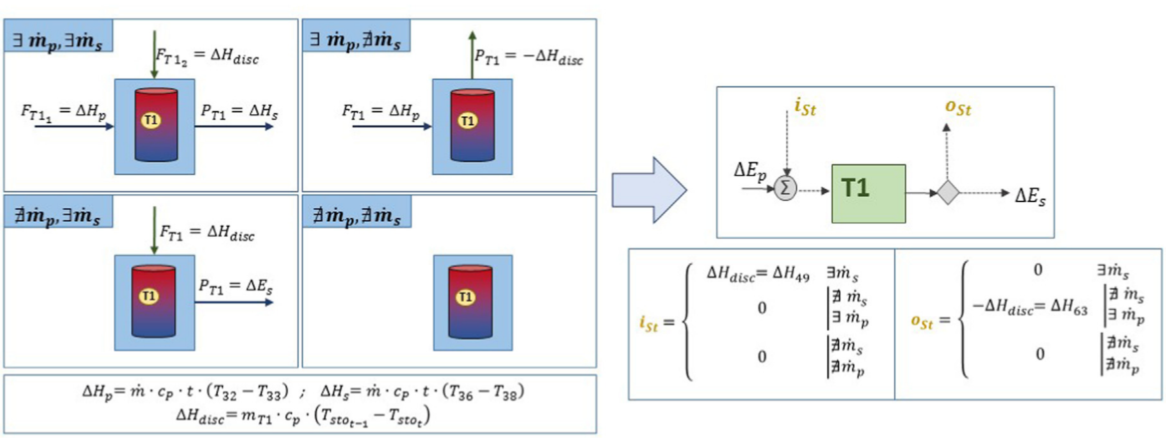

Fig. 5. Possible configurations of T1 according to mass flow rates and generic productive structure.

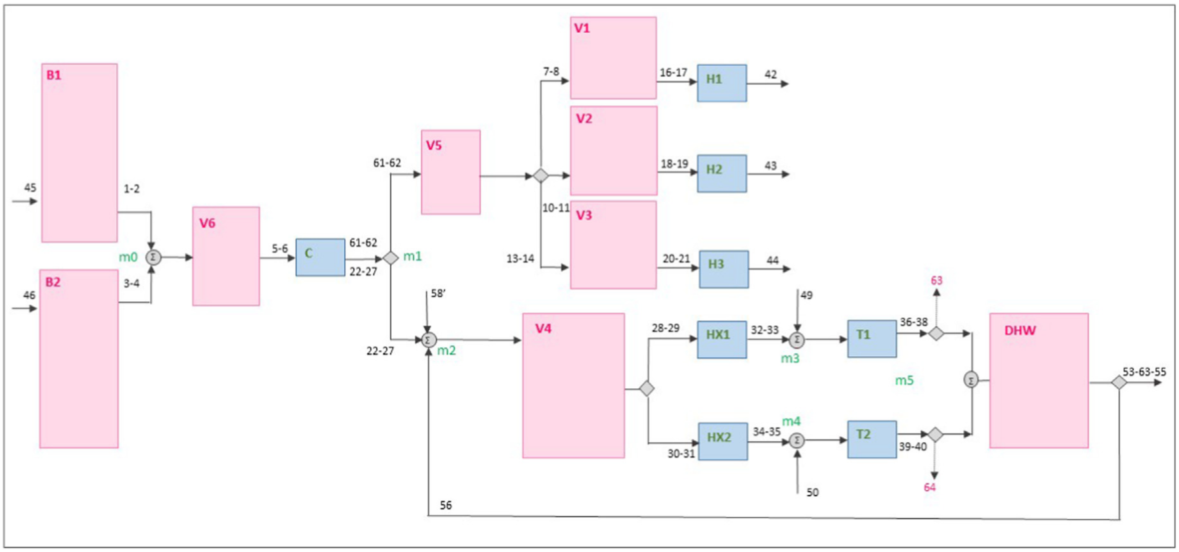

Fig. 6. Super-productive structure of the installation.

enters to the generator and energy transforms sequentially until it arrives to the terminal components (heaters and taps). Therefore, there are far from complex systems with recirculations and bifurcations, such as those of industrial sector. Consequently, the productive structure is many times easy to define and the difficulty arises when the dynamic states have to be represented, which is precisely one of the aims of this work. Following this procedure, the generic productive structure of the system, represented in Fig. 6, is built.

In addition, the flows entering directly from outside (external resources) are defined according to their nature, see Table 2 i.e., electricity, water inlet, natural gas, etc. Accordingly, those flows are directly linked to its corresponding quality factor [−], specific economic cost [c€/kWh] and environmental impact [gCO_2/kWh].

Furthermore, in the absence of external assessment, the exergy unit cost of the external fuel is equal to one. If, conversely, previous external assessment has being done and k_F^* has being calculated, the specific exergetic cost is included.

Additionally, the output flows are classified into two categories:

Table 2
External resources entering the super-structure.

	External Resources		
	F0	Type	Ext.Val.
inlet 1	45	4	1
inlet 2	46	4	1
inlet 3	58′	0	1
inlet 4	49	0	1
inlet 5	50	0	1
Resource Type			
0			–
1			electricity
2			water inlet
3			natural gas
4			gasoil
5			biomass
6			other
External valuation			
NO			1
YES			value

final products (heating flows, 42, 43, 44 and DHW flows, 53-63-55) or residues. For more information on residues, read Ref. [28] and Ref. [29]).

3.8. Operating modes

As stated above, the productive super-structure must be able to represent all the operating states of the installation by isolating and cancelling the deactivated equipment at each time-step. To achieve this goal, each piece of equipment is linked to a characteristic flow, such that, when that flow has a null value, the equipment is deactivated. This is a very sensitive step since it can occur that, when a component is disabled, the called “islands” are generated, since they de-virtualize the entire structure as new external flows − which are not previously defined − are added.

Fig. 7 reflects this concept of “island” when the operating mode is such that boiler 1 (B1), the three-way distribution valve of zone 1 (V1) and the DHW 1 heat exchanger (HX1) are deactivated. Three different situations are encountered:

- By turning off boiler B1, the heat generation continues operating thanks to the fuel input to the second boiler B2. Therefore, hot water continues to reach the hydraulic compensator and from there continues on to the distribution circuits. In this case, no island is generated.
- When heat exchanger HX1 is deactivated, no hot water enters to the accumulation tank T1. It may happen that, at the same time, DHW demand exists so the tank needs to discharge the accumulated hot water to cover such demand. Therefore, the tank would bring hot water from the external resource flow 49; hence, its productive structure is properly defined. In this case, the generated island is a “logical island”, as the tank is fed from an already defined external flow.
- When the valves V1 of Zone 1 for the heating distribution circuit are turned off, there may still be heat at the H1 terminals, so heat continues being extracted. In this way, H1 equipment is operating alone, considering the incoming fuel of H1 as an “external resource flow”. In this case, an “illogic island” is generated, since the fuel of H1 is not defined as an external resource input.

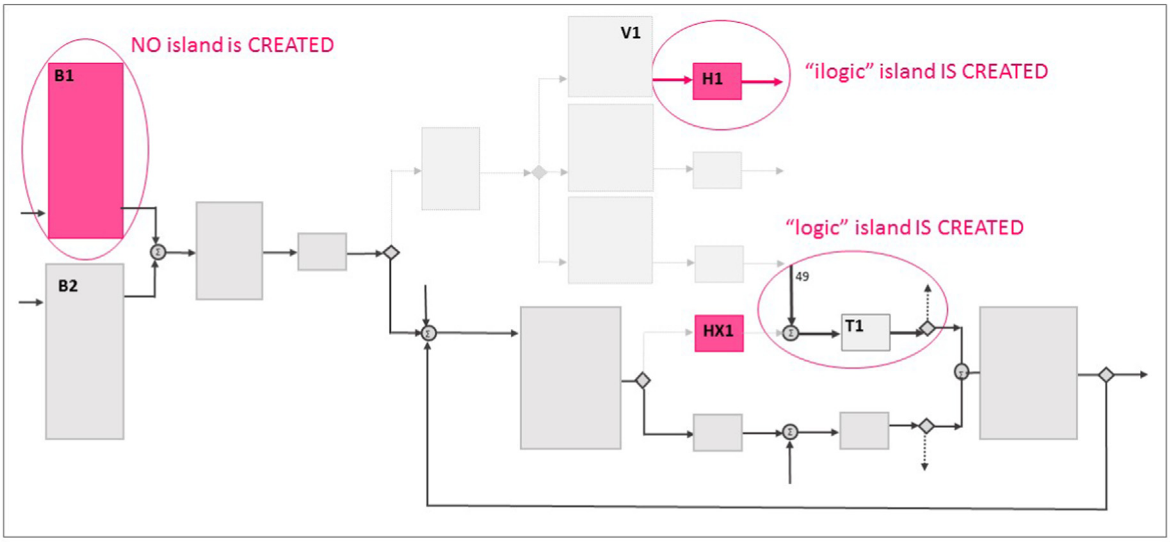

Fig. 7. Example of possible "isolation of component" and production of "islands".

The criterion established for the deactivation of the equipment has been based on the existence or not of the fuel of the component; that is, if the fuel is zero, that equipment is considered to be off. To avoid the so called "illogical islands", corrections are introduced in the software.

4. Numerical results

The numerical results for the studied period, averaged on an hourly basis, are shown below .[4] Therefore, thermoeconomic dynamic data is given on a real case study, for the first time, based on a novel thermoeconomic versatile software. These data is very useful for system deep analysis and diagnosis.

As a whole, the registered diesel oil consumption for this period rises to 177,434 L and is used to generate the heating and DHW demands of the 319 dwellings. The unit cost of diesel oil has been considered to be 9.43 c€/kWh, with a lower heating value of 10.18 kWh/L. The energy efficiency of the installation, considered in its entirety, is 79%, while its exergy efficiency is 7%.

4.1. Thermoeconomic dynamic analysis

This subsection deals with the results of thermoeconomics dynamic application.

4.1.1. Exergy dynamic costs

Fig. 8 shows the unit exergy costs, $k^*_{F,i}$ and $k^*_{P,i}$, of the fuel and product of the main equipment.

The exergy cost analysis of the facility provides an image of the cost allocation throughout the system. These values allow us to detect, among other things, the following two key facts for future modifications and optimizations of the installation, components or control intervention:

- The increment in the unit cost between the required resources and the product obtained in any i -th component ($k^*_{p,i} - k^*_{F,i}$); that is, the cost due to exergy destruction.
- The irreversibilities accumulated until reaching the i -th component ($k^*_{F,i}$). Therefore, this parameter indicates where and how the components interrelate in terms of costs and allows for improvements and optimization of control.

As it can be checked, the unit exergy cost of the boiler's fuel is equal to 1 since diesel oil is an external resource. The cost of the boiler's product, conversely, rises to ~ 7 meaning a low exergy efficiency of $\sim 1/7 = 14\%$.

As we are advancing in the energy chain, the unit exergy costs rise due to the encountered irreversibilities, and so the heating and DHW unit costs at the end of the energy chain are the highest ones.

4.2. Exergoeconomic dynamic costs

The values of investment, operation and maintenance costs of each piece of equipment are required to calculate the exergoeconomic costs. Accordingly, the left part a) of Table 3 shows the investment cost of each piece of equipment according to the data obtained from the project. The right part b) shows the prices and the gCO2/kWh emitted by the external resources. These data are taken from the official Spanish document of Ref. [30].

For this study, an annual effective interest rate of 0.05 and 20 years of useful life were assumed.

The results of the unit costs at every 5 min of the fuel ($\mathbf{c_F}$) and product ($\mathbf{c_P}$) for the components B1 and H1 are shown in Fig. 9. In addition, the costs of the products have been divided into those due to the consumption of external resources ($\mathbf{c_p^e}$) and those due to the fixed costs ($\mathbf{c_p^z}$) of investment, and other costs of operation and maintenance.

The exergoeconomic unit cost of heating is much more variable than the boiler's product cost since it totally depends on the active productive structure at each time-step, as justified in Section 5. That is, it depends on the activated components at each time-step while the boiler only depends on itself, as there are no upstream components. The total average values of the final products are shown in Table 4, whereas the average values of exergoeconomic unit costs of intermediate equipment products are in Table 5.

[4] Internet connexion was lost during one month so a gap is shown in the graphics.

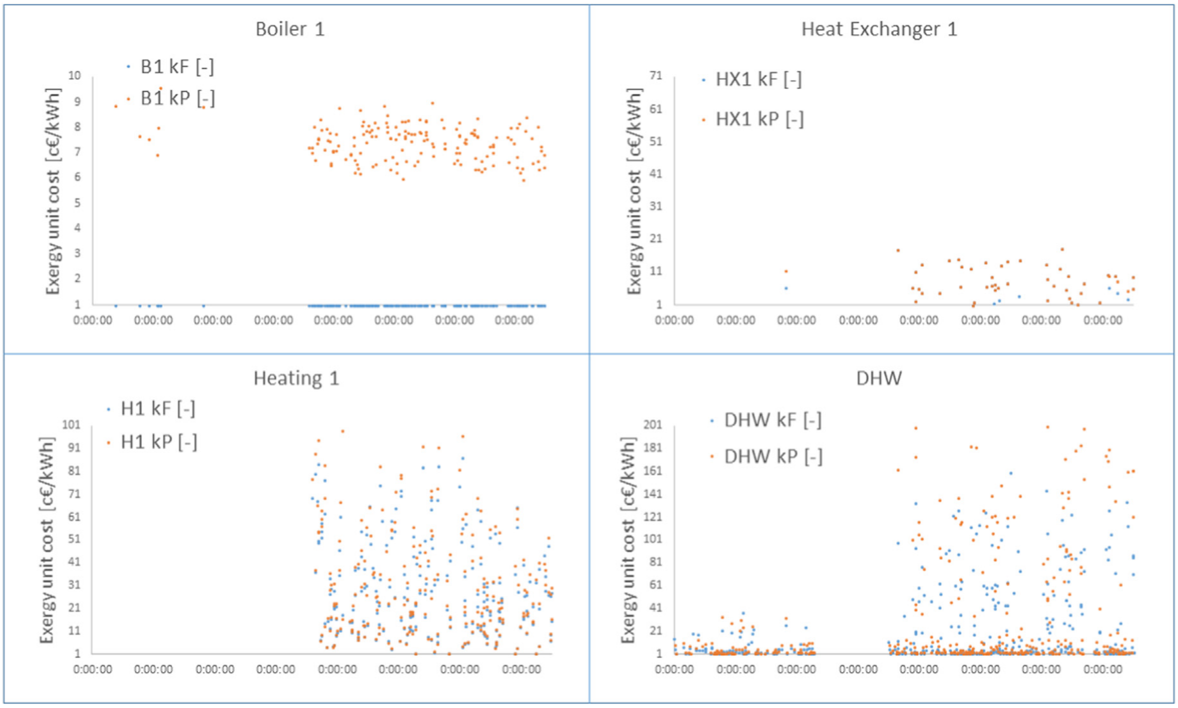

Fig. 8. Exergy dynamic unit costs of fuel and product of generators and terminal equipment.

Table 3
a) Investment costs of equipment and b) external resource prices and CO_2 emission factors.

ACQUISITION COST			
B1	37,608 €	HX1	325 €
B2	37,608 €	HX2	325 €
C	65,069 €	T1	5,539 €
V1	2,753 €	T2	5,539 €
V2	2,753 €	H1	14,140 €
V3	2,753 €	H2	14,140 €
V4	2,427 €	H3	14,140 €
V5	0 €	DHW	976 €
V6	6,120 €		
Cost	**[c€/kWh eN]**	**[g CO2/kWh eN]**	**Quality Factor**
Electricity price	21.81	649	1
water inlet [€/m3]	0.5197		–
natural gas	5.274	204	1.04
diesel oil	9.43	287	1.04
Biomass	4.1	0	1.03

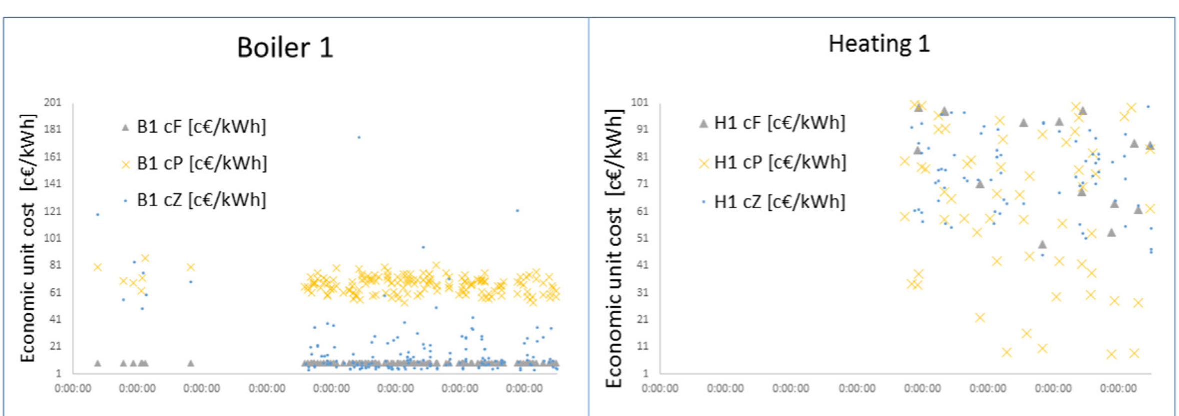

Fig. 9. Exergoeconomic unit costs of fuel and product of B1 and H1.

Table 4
Total and average unitary costs of final product.

	UNITARY COSTS	ENERGY	TOTAL COSTS	ENVIRON. C.
	[c€/kWh] en	[MWh]	[€]	[gCO2]
Heating 1	12.39	283	35,070 €	1066
Heating 2	13.44	151	20,294 €	616
Heating 3	13.09	284	37,204 €	1130
DHW	13.72	545	74,789 €	2273

The first column contains the average unit exergoeconomic costs [c€/kWh] of each main product per unit of energy, the second portrays the energy consumption during the study period [MWh], whereas the third column represents the total exergoeconomic costs [€]. The fourth column displays the grams of CO_2 generated during the operation period to cover each demand [gCO_2]. The following conclusions can be obtained.

- The average unit cost of heating for the three buildings is 12.97 c€/kWh (referring to energy).
- The DHW average energy unit cost is 13.72 c€/kWh. This cost considers the entire route taken to generate hot water from the mains (water network), that is, from the combustion in the boilers and the distribution to the heat exchangers, the storage in the tanks and, finally, mixing with the cold mains' water to finally obtain the DHW at the required temperature.
- DHW is consumed continuously throughout the year while heating is only turned on during the heating period.

Table 5
Total average values for main equipments.
•Regarding unit exergoeconomic costs, it is verified that as the equipment at the end of the energy chain (DHW and H1-2-3) is reached, costs increase, due to the energy degradation that takes place until reaching the final products.

	EFFICIENCIES		REAL LOSSES	UNIT COSTS
	Energy	Exergy		
	[%]en	[%]ex	[MWh]	[c€/kWh en]
B1	90%	14%	868	9.40
B2	90%	14%	719	9.40
C	48%	43%	311	10.50
HX1	82%	71%	12	10.70
HX2	93%	91%	9	8.10
T1	81%	19%	23	13.10
T2	84%	23%	42	9.70
H1	85%	98%	1	12.40
H2	85%	92%	2	13.40
H3	85%	96%	1	13.10
DHW	76%	79%	12	13.70

4.3. Exergoenvironmental dynamic costs

For the exergoenvironmental analysis, only the CO_2 emissions and the impact of external resources [gCO_2/kWh] have been considered. The unitary environmental costs corresponding to the fuel and product of B1 and H1 are shown in Fig. 10. Like exergy and exergoeconomic costs, the vector $a_F - a_P$ represents the environmental impact due to the exergy destruction in every piece of equipment; that is, due to technological inefficiencies and limitations. Also, the specific impact of the resource of the i-th component (a_{Fi}) takes into account the cumulative impacts until the generation of such fuel.

In analogy with the exergoeconomic unit costs, similar conclusions can be obtained from exergoenvironmental analysis but now on an environmental unit basis [gCO_2/kWh].

4.4. Total averaged costs

As we know, the total averaged costs of the fuel and product of any *i*-th component, whether in exergy, economic or environmental units, are obtained simply by multiplying the unit costs by the total exergy flows. The relevant values are the unit and the total costs of the product at the end of the energy chain, i.e. those of heating (Heating 1-2-3) and domestic hot water (DHW), see Table 4.

One needs to remember that, the total cost of heating and DHW is the same, whether you calculate it based on exergy (thermoeconomic approach) or in the conventional way (NG cost + amortization) −since the cost is conservative-. Cost distribution along the system, conversely, will vary, i.e. the unit costs related to heating branches and the ones related to DHW, which depend on de F/P definitions. Thermoeconomics approach allows making an internal cost distribution of all the processes of the system. Therefore, the sum of the unit costs, calculated by either of the two methods, multiplied by the respective productions is the total cost; and that sum must be the same.

4.5. Analysis of losses

Table 5 contains the average values of energy and exergy efficiency, the irreversibility and the product unit exergoeconomic cost of each of the main units of equipment. The following conclusions can be extracted:

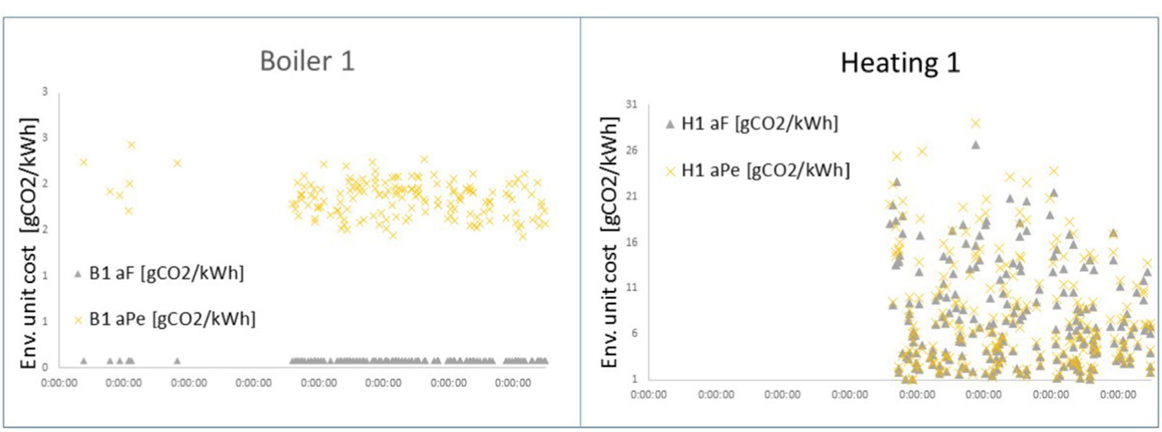

Fig. 10. Exergoenvironmental unit costs of fuel and product of B1 and H1.

- Combustion equipment (boilers) has a very low average exergy efficiency, of 14%, because they transform an energy with high potential (diesel oil) into a thermal energy (hot water at 80 °C) of limited utility.
- Something similar happens in the accumulation tanks. Although they are thermally very well insulated (that is, they hardly have heat losses, featuring energy efficiencies of 81% and 84%), they have great irreversibilities, because they mix hot flows with cold flows coming from the network and that is why they feature exergy average efficiencies of 19% and 23%.

Fig. 11 summarizes the evolution of the averaged exergoeconomic costs through the facility: it starts in the boilers (B), then the collector (C), separating on the heating and DHW branches (V4-5), entering heat exchangers (V-HX), going through storage tanks (TH) and ending in the terminal equipment (DHW-H). The costs are referred to as per unit of exergy, since the trend is better visualized in this way. As you can appreciate, the full line reflects the evolution of the unit heating cost, whereas the grated line refers to the unit DHW cost.

5. Analysis of control strategies

Another outcome of this software implementation is the ability to analyze the control strategies of the facility, in order to detect those configurations that minimize operating costs based on the current demands at any time.

With the data acquired from the software, the following information is obtained:

- The most repeated operating modes and their activation frequency.
- The average exergy, economic and environmental unit costs related to each operation mode.

These values show how costs are distributed over time and they help to identify the most effective operation modes for the implementation of control strategies.

5.1. Analysis of operation modes

Due to the intervention of the control system, there are various combinations of components working at each moment (called operating modes, OpMods). According to Figs. 6 and 21 components can be working together, so different combinations of those components can arise to adapt to the specific thermal conditions of the facility; for example, only DHW demand exists or only one boiler could be turned on to cover the heat requirement.

Fig. 12 plots the number of components that are switched on in different OpMods and the frequency of those component combinations. As we can see, 4 components are turned on at a higher rate than any other combination or category (29%), and, in addition, there are some combination of components that never occur (for example, 1 component is never active on its own).

The specific OpMods related to each combination can also be obtained from this analysis. As an example, and due to the lack of space, only the combinations of 15 active components (occurring during 2% of the time) are shown in Fig. 13. As seen, the following can happen:

- (15. A) B1—B2—C—V1—V2—V3—V5—V6—H1—H2—H3-DHW-m1-m3-m4) Both boilers (B1, B2) are turned on to cover the heating demand of the three branches (H1, H2, H3). DHW is discharged directly from both tanks (during 30% of the 2% of global time).

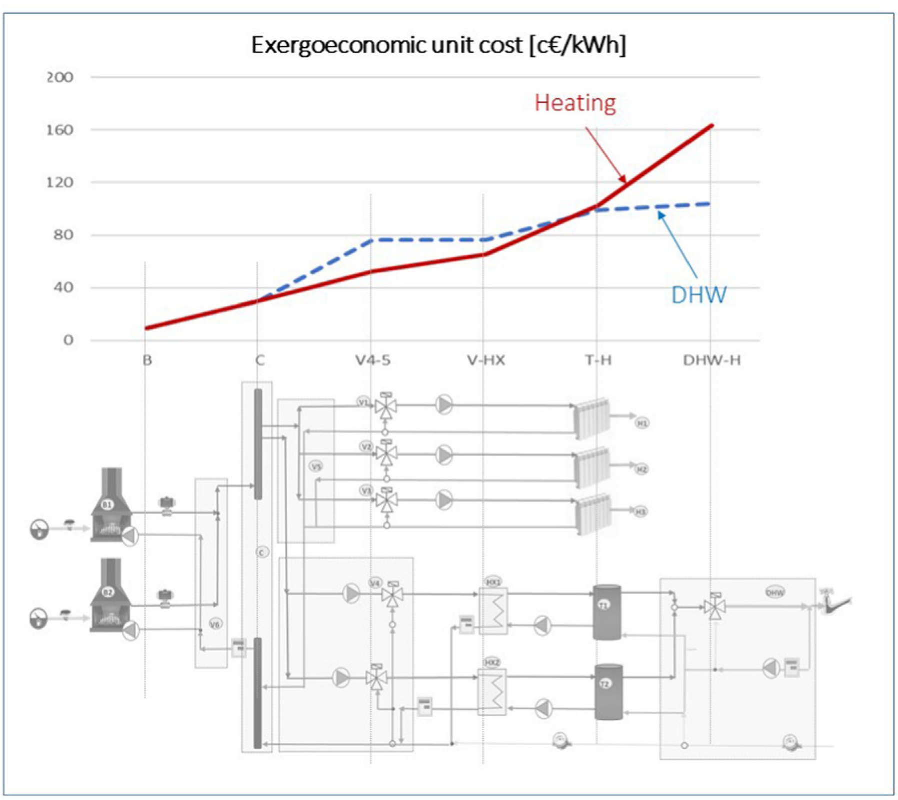

Fig. 11. Exergoeconomic unit cost evolution.

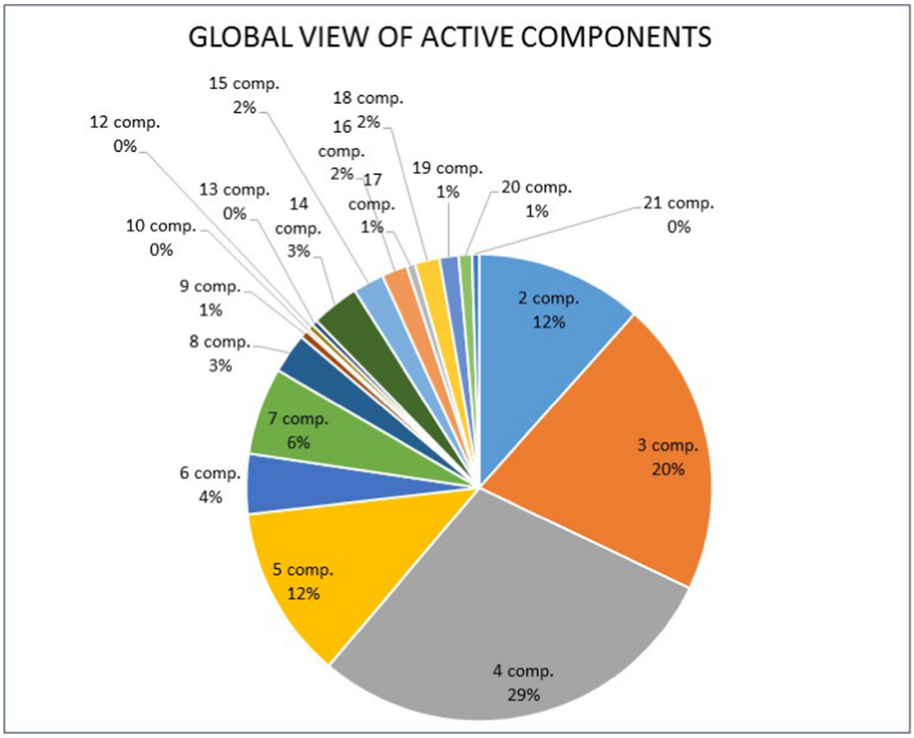

Fig. 12. Quantity of components activated in each OpMods and its frequency.

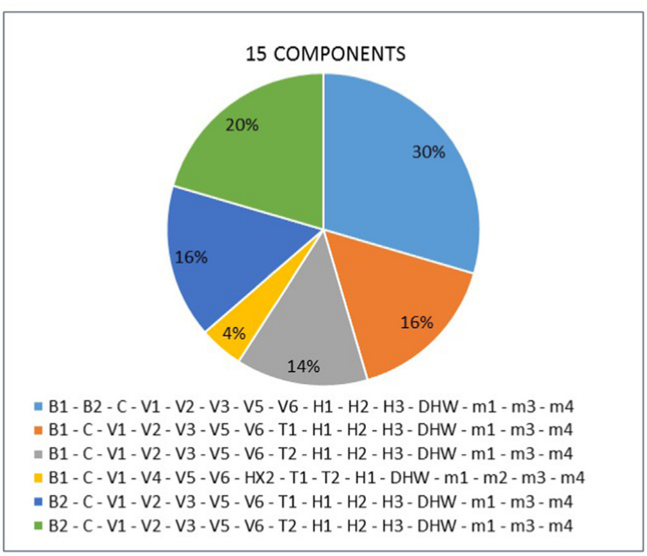

Fig. 13. of activation according to 15 active components.

- (15. B) B1—C—V1—V2—V3—V5—V6-T1-H1-H2-H3-DHW-m1-m3-m4) Only boiler 1 (B1) is turned on to cover the demand of heating of the three branches (H1, H2, H3). Tank 1 (T1) is charged with the residual heat of the secondary circuit and DHW is discharged from both tanks (m3, m4) (16%).
- (15. C) B1—C—V1—V2—V3—V5—V6-T2-H1-H2-H3-DHW-m1-m3-m4) The same as 15. B, but now T2 is charging instead (14%).
- (15. D) B1—C—V1—V4—V5—V6-HX2-T1-T2-H1-DHW-m1-m2-m3-m4) Only boiler 1 (B1) is turned on to cover the demand of the first branch of heating (H1). Tank 2 is charged through the heat exchanger 2 (HX2) and DHW is discharged from both tanks (5%). Fig. 14 represents this specific OpMod.
- (15. E) B2—C—V1—V2—V3—V5—V6-T1-H1-H2-H3-DHW-m1-m3-m4) This is similar to the 15. B condition but now the second boiler B2 is active (16%).
- (15. F) B2—C—V1—V2—V3—V5—V6-T2-H1-H2-H3-DHW-m1-m3-m4) This operation mode is similar to 15. C, but now B2 is turned on (20%).

5.2. Average costs of operation modes

The next step assigns the average unit costs (exergy, economic and environmental costs) to each operation mode. Due to space, only the results associated with 15 components active are shown, with all the possible OpMods configurations (15. A to 15. F) and are shown in Table 6. Besides, in this table only the exergy/exergy costs, exergoeconomic costs and exergoenvironmental costs related to the main product of the facility are gathered i.e. the three heating demands (H1,H2,H3) and the DHW demand (DHW).

Some conclusions are extracted:

- When the two boilers are turned on (15. A) the value of exergy, exergoeconomic and exergoenvironmental unit costs of heating demand are higher compared to the OpMods in which only one boiler is activated (15. B,15. C,15. E, 15. F). This is because the irreversibilities of both boilers are taken into account.

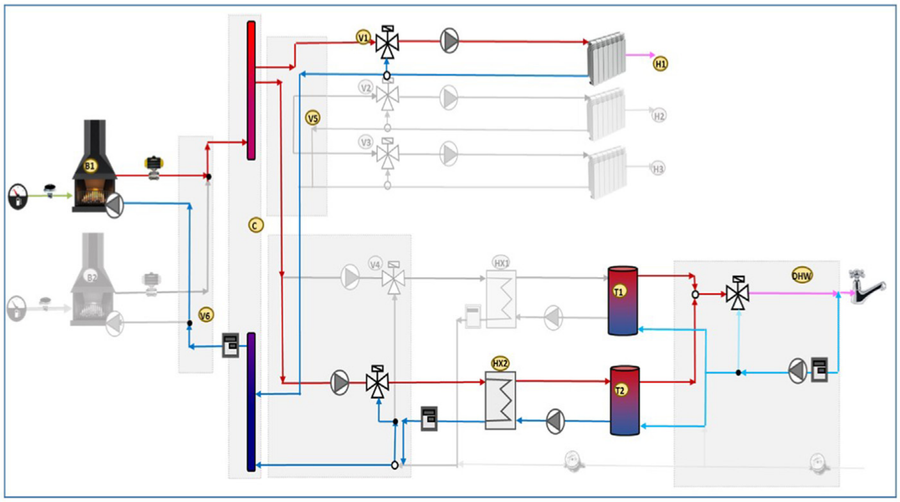

Fig. 14. Representation of (15. D) B1−C−V1−V4−V5−V6-HX2-T1-T2-H1-DHW-m1-m2-m3-m4 operation mode.

Table 6
Average data corresponding to 15 active components.

		MEAN VALUE 15 COMP.					MEAN VALUE 15 COMP.			
		H1	H2	H3	DHW		H1	H2	H3	DHW
15.A	**Exergy [kWh/h]**	52.72	31.05	37.65	20.13	**Exergoeconomic costs [c€/kWh]**	698.0	713.1	705.6	80.3
15.B		61.07	33.59	35.01	16.02		437.4	487.5	462.5	95.6
15.C		45.86	27.93	34.36	19.25		506.0	590.6	548.3	87.0
15.D		19.40			19.16		338.8			1421.1
15.E		51.55	30.83	35.33	11.87		387.9	423.4	405.7	156.7
15.F		60.96	34.26	41.02	15.84		407.9	412.7	410.3	117.5
15.A	**Exergy costs [kWh**	60.56	59.33	59.94		**Exergoenv. costs [gCO2/kWh]**	15.70	15.33	15.51	
15.B		35.72	37.82	36.77	0.09		9.18	9.73	9.46	
15.C		40.89	46.09	43.49	0.14		10.40	11.76	11.08	
15.D		16.59			92.11		4.12			22.75
15.E		26.94	28.00	27.47	0.06		7.28	7.57	7.43	
15.F		29.22	27.23	28.23	0.05		7.85	7.31	7.58	

•DHW demand exists during the six OpMods (15. A-15. F), since the exergy value is positive. Nevertheless, except for the 15. D OpMod, the demand is taken directly from the tanks without turning on the heat exchanger circuit. That is why the exergoenvironmental costs of those situations are null[5]. The exergoeconomic costs are related to the **Z** [€] fixed cost of the production process. The exergy costs, conversely, are less than unity since heat is taken "for free" from the storage tanks.[5]

However, this situation must not be misinterpreted, since charging such storage tanks has a cost that has been considered in previous operation modes. Therefore, even if in these OpMods, DHW generation is free of cost at this moment, it has previously been paid for it. Therefore, this aspect is discussable and another more appropriate way to determine the energy efficiency of the operation modes connected with this phenomenon is still open to research.[6]

[5] Remember that the exergy of net water is equal to 0 since the reference temperature is precisely its temperature. So no impacts are connected with the net water flow.

[6] Maybe, the charging or discharging flows should be linked, somehow, with an external valuation different to 0 (see Table 2). In such case, the cost of heat storage can be connected with a percentage of gasoil consumption (something similar to what happens with residues cost distribution, were each residue cost is associated with the other productive components according to the residue distribution ratios).

•The cost of DHW increases significantly in the 15. D OpMod, because the heat exchanger circuit (and, therefore boilers) is turned on to cover the DHW demand. In that situation, only the first branch is demanding heating.

6. Conclusions and discussion

The conclusions and the future perspectives offered by this dynamic thermoeconomic software in building thermal systems are here below developed; since, as said, it is a novel and pioneering tool for thermal system maintenance and diagnosis.

6.1. Conclusions

This work defines the procedure for the application of a thermoeconomic dynamic software in a heating and DHW facility of three building blocks in the Basque Country (northern Spain).

The biggest difficulties encountered are related to the analysis and filtering of the data obtained from the sensors. As all the thermoeconomic results are dependent on the quality of the data, it is necessary to have precise and well-calibrated probes. Some hypotheses and considerations have been made in order to avoid illogical results before applying the thermoeconomics software.

Based on the data acquired and the assumptions included, exergy, exergoeconomic and exergoenvironmental costs (taking into account only the CO2 emitted associated to the external resources) in real time were dynamically calculated. The relevant values are the unit and the total costs of the product at the end of the energy chain (DHW production has an average value of 13.72 c€/kWh and heating of 12.92 c€/kWh) and the global CO_2 emissions during the study period sums 5,085 gCO_2. As a whole, the final costs of the useful product are mainly due to the irreversibilities along the system, and consequently, efforts should be made to reduce those irreversibilities, Ref [31]. The components with less exergy efficiency are boilers (with an average value of 14% and with 1,587 MWh of real losses).

Besides, with the data acquired from the software, (1) the most repeated operating modes and (2) the average exergy, economic and environmental unit costs related to each operation mode are calculated. These values show how costs are distributed over time and help to identify the most effective operation modes for the implementation of control strategies. Nevertheless, this aspect is discussable and a new research-line is opened.

This study serves as a pioneering example in the implementation of a software based on thermoeconomics for the analysis of thermal installations in buildings. The main goal is to foster energy savings and to reduce costs and decrease environmental impacts, an objective that is commonly pursued by the society as a whole.

6.2. Discussion

Thanks to the software, a dynamic image of flow-costs distribution along a heating and DHW installation in the different operation modes is obtained. It is necessary to highlight that costs are obtained through a productive structure (which is subjective and is related to the experience and purpose or the analyst) which interconnects all the components according to the distribution ratios, unit exergy consumptions of each equipment and external resources (extracted from the available data). Therefore, this information is very useful for doing a sensitivity analysis of the system, since after all, when a parameter of a component varies, its unit exergy consumption varies so that the costs connected with that component also change. In other words, the deviation of the operating conditions from the design can be expressed by the deviations of the equipment performance and the exergy recirculation ratios. Each variable has a different weight/impact in the cost of each flow that can be obtained through thermoeconomic analysis.

The knowledge of internal costs of a system allows studying each component separately. Nevertheless, the components are not isolated but they are interacting with the rest of equipment. Because of that, the global optimum does not necessarily correspond to the local optimum of each subsystem separately. Besides, it may happen that, in certain conditions, a deviation from the local optimum of an individual component causes a better operation of the system as a whole.

Apart from that cost interconnections, due to the dynamic nature of the system, any operation mode is strictly linked to the previous situation, so that, the cost of that situation depends on the previous condition. Therefore, it can be said that the time dimension needs also to be incorporated. Therefore, optimization needs to be dynamically done considering all the inertial aspects of the system.

6.3. Further lines of research

Until this point, the software developed detects the operating modes in which the consumption of resources used to obtain DHW or heating are higher. Likewise, the more favourable operating mode for reducing the consumption of resources can be detected. Next step will deal with the implementation of control objectives, through optimization algorithms, considering all the variables present in the super-structure as well as the time-dimension. It is a huge challenge that we are wondering to undertake.

In short, the main goal is to reduce the irreversibilities by erasing the avoidable ones. This commitment may be obtained through the appropriate control strategy or by equipment modification.

As a summary, this new software is devoted to the maintenance and diagnosis practices along the useful life of a thermal system. On the one hand, this approach detects the components with the higher irreversibilities that increment the cost along the energy chain. On the other hand, it allows accounting the effects (in terms of cost increment) that one component's irreversibility produces in the rest of equipment. After all, the software is based on a dynamic super-productive structure, which is a key-structure that interrelates the processes and the flows of the whole system. In addition, as thermoeconomics is dynamically implemented, the operation modes that minimize the costs can be detected and analysed under an exergy point of view. New control strategies can be adapted according to the results of this software.

Author statement

Ana Picallo-Perez: Writing – original draft, Data curation, Conceptualization, Formal analysis, Methodology, Software, Validation **José M Sala-Lizarraga**: Writing- Reviewing and Editing, Conceptualization, Methodology, Formal analysis, Visualization, Investigation. **Luis Portillo-Valdes**: Data curation, Conceptualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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