Modeling simple trigeneration systems for the distribution of environmental loads

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Abstract

Integration of thermoeconomics and Life Cycle Analysis was carried out within the framework of an Environmental Management Information System. This combined approach identified where environmental loads were generated and tracked environmental loads throughout the system, allowing for a more precise understanding of operational activities. A trigeneration system was modeled, providing electricity, heat, and cooling to a building. The trigeneration system consists of a cogeneration module, auxiliary boiler, absorption chiller and electrical chiller. The trigeneration system model is flexible, as it allows electricity from/to the electric grid to be purchased/sold, and part of the cogenerated heat to be wasted. Umberto software is specifically designed to analyze the distribution of material and energy resources throughout a productive system. The software is based on Petri networks, double-entry bookkeeping and cost accounting, allowing the setup of complex systems and also a combined material, energy and inventory calculation. An assistant was built to include the tracking of emissions through the application of algebra and rules similar to those used in thermoeconomic analysis. It is possible to evaluate the environmental impact in terms of the consumption of natural resources and generation of emissions in the system, from the input of natural resources to the output of the final products. Network parameters were used to calculate the emissions associated with the operation of the system. The issue of allocating environmental loads was introduced and two scenarios for each operational mode were compared: the trigeneration system vs. a conventional energy supply system in which electricity was produced in a representative coal power plant. In this case the trigeneration system operated with significant reduction of the CO2 emitted into the atmosphere.

1. Introduction

Residential and tertiary sectors are responsible for more than 40% of final energy consumption in the European Community (Directive COM 2002/91/EC, 2002). The tertiary sector includes different types of buildings (hospitals, schools, hotels, etc.) with a great variety of uses and energy services (heating, cooling, and electricity). European research projects, such as CHOSE (2001), TRIGEMED (2003), and Summerheat (2008), concluded that there is a significant technical potential for the implementation of trigeneration in the residential and tertiary sector of countries in the Mediterranean area.
countries the need for heating is restricted to few winter months, limiting the application of cogeneration systems. There is, however, a significant need for cooling during the summer period. One solution is the use of absorption chillers for cooling. By combining cogeneration with absorption chillers (trigeneration), the energy demand can be extended into the summer months to match cooling loads. Advantages of trigeneration systems in buildings have been demonstrated in literature, as the improved use of fuel is associated with economic savings and sparing of the environment, since less fuel is consumed and consequently less pollution is generated (Maglorie et al., 2002; Chicco and Mancarella, 2008).

As sustainability-related issues such as energy consumption and environmental impact become a more integrated part of operational and long-term planning decisions in energy systems, simulation modeling and analysis tools are needed to aid in the decision making process.

Thermoeconomics is a potent tool for energy analysis and has been used to support the design, synthesis and operation of energy systems by providing crucial information not available through conventional analyses. Thermoeconomics combines economic and thermodynamic analysis with the purpose of revealing opportunities of energy and cost savings when designing and operating energy conversion systems (El-Sayed and Evans, 1970; Gaggioli, 1983; El-Sayed and Gaggioli, 1989; Lozano and Valero, 1993; Serra et al., 2009). The basic concept of thermoeconomic analysis is the energy cost, understood as the amount of energy resources consumed for obtaining a piece of equipment, a flow or a commodity. Hence, the cost of a flow in a plant represents the amount of resources that have to be supplied to the overall system to produce this flow. Unit costs are used by thermoeconomic cost accounting theories for rational price assessment, and allow us to follow the cost formation process throughout the system, from energy resources to final products. Thermoeconomic costs can be expressed in monetary or energy units.

The necessity of considering the environment as an additional design factor is an increasing demand due to the uprise of environmental conscience and the requirements to reduce the environmental impact of modern society. Life Cycle Analysis (LCA) provides a more global perspective of energy production and has the potential to fulfill the need for an adequate design tool for energy supply systems (Guinée, 2002). LCA is an objective process to evaluate the environmental loads associated with a product, process, or activity (Awasthi and Chauhan, 2011; Carvalho et al., 2011a,b; Turner et al., 2011). LCA also identifies and quantifies the use of mass and energy as well as the emissions to the environment, determining the impact of the use of resources and emissions, allowing for evaluation and implementation of strategies of environmental improvement. The life cycle or cradle-to-grave impacts include those resulting from extraction of raw materials, fabrication of the product, transportation or distribution of the product to the consumer, use of the product by the consumer, and disposal or recovery of the product after its useful life. Herein, the environmental cost of a flow represents the amount of environmental loads that have been generated in the overall system to produce this flow.

Thermoeconomic and LCA techniques are both based on the premise that all of the resources required for producing a good or service need to be accounted for. Thermoeconomics is usually applied to energy conversion systems and the limits of the system are those of the associated plant. However, there is no constraint that impedes widening the limits of analysis to include the well or the mine from where the natural resources were extracted. Thus, merging thermoeconomics and LCA methodologies provides a global perspective of a complex system via an integrated analysis of energy, economics and environment. Generally, the analyzed system in LCA is treated as a black box from which only its inputs and outputs are measurable, without further knowledge of the inner structure. Applying the philosophy of thermoeconomics to energy systems opens this black box and unravels the process of environmental burden formation, which is where the importance of combining thermoeconomics with LCA lies (Carvalho, 2011). Similar to the cost formation process in thermoeconomics, it will be possible to evaluate the process of formation of the environmental impact linked with consumption of natural resources and distribution of environmental loads throughout the system—i.e., from the input of natural resources to the output of final products.

Integration of thermoeconomics and LCA was carried out within the framework of an Environmental Management Information System (EMIS). EMIS are designed to detect, evaluate and prevent a wide range of environmental dangers and stresses. In more concrete terms, EMIS consist of computer programs that support management by collecting, documenting and evaluating all relevant data about an enterprise’s interaction with its environment and plan, initiate and control all activities related to environmental

**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>AB</td>
<td>auxiliary boiler</td>
</tr>
<tr>
<td>AC</td>
<td>absorption chiller</td>
</tr>
<tr>
<td>C</td>
<td>operation mode (followed by subscript)</td>
</tr>
<tr>
<td>CM</td>
<td>cogeneration module</td>
</tr>
<tr>
<td>COP</td>
<td>coefficient of performance</td>
</tr>
<tr>
<td>Ed</td>
<td>electricity demand</td>
</tr>
<tr>
<td>Ep</td>
<td>electricity purchased from the grid</td>
</tr>
<tr>
<td>Er</td>
<td>electricity input to electrical chiller</td>
</tr>
<tr>
<td>Es</td>
<td>electricity sold to the grid (cogenerated)</td>
</tr>
<tr>
<td>EM</td>
<td>environmental loads (followed by subscript)</td>
</tr>
<tr>
<td>ExC</td>
<td>example of operation mode (followed by subscript)</td>
</tr>
<tr>
<td>EC</td>
<td>electrical chiller</td>
</tr>
<tr>
<td>Fe</td>
<td>fuel for the cogeneration module (natural gas)</td>
</tr>
<tr>
<td>Fa</td>
<td>fuel for the auxiliary boiler (fuel oil)</td>
</tr>
<tr>
<td>L</td>
<td>loss node</td>
</tr>
<tr>
<td>MFN</td>
<td>Material flow networks</td>
</tr>
<tr>
<td>P</td>
<td>Purchase node</td>
</tr>
<tr>
<td>Pet</td>
<td>price of purchased electricity</td>
</tr>
<tr>
<td>pes</td>
<td>price of electricity sold to the grid</td>
</tr>
<tr>
<td>pea</td>
<td>price of fuel oil (for auxiliary boiler)</td>
</tr>
<tr>
<td>pec</td>
<td>price of natural gas (for cogeneration module)</td>
</tr>
<tr>
<td>Qd</td>
<td>heat distribution node</td>
</tr>
<tr>
<td>Qa</td>
<td>heat produced by auxiliary boiler</td>
</tr>
<tr>
<td>Qc</td>
<td>heat produced by cogeneration module</td>
</tr>
<tr>
<td>Qcc</td>
<td>heat internally consumed</td>
</tr>
<tr>
<td>q1</td>
<td>wasted heat</td>
</tr>
<tr>
<td>q2</td>
<td>heat input to absorption chiller</td>
</tr>
<tr>
<td>q3</td>
<td>heating demand</td>
</tr>
<tr>
<td>r</td>
<td>cooling node</td>
</tr>
<tr>
<td>Re</td>
<td>cooling produced by electrical chiller</td>
</tr>
<tr>
<td>Rq</td>
<td>cooling produced by absorption chiller</td>
</tr>
<tr>
<td>qil</td>
<td>cost of waste heat</td>
</tr>
<tr>
<td>s</td>
<td>sale node</td>
</tr>
<tr>
<td>Wc</td>
<td>electricity produced by cogeneration module</td>
</tr>
<tr>
<td>Wcc</td>
<td>electricity internally consumed</td>
</tr>
<tr>
<td>a'</td>
<td>efficiency (cogeneration module)</td>
</tr>
<tr>
<td>eta</td>
<td>efficiency (boiler)</td>
</tr>
</tbody>
</table>
Trigeneration is the combined production of heat, cooling and electricity from the same source of energy. The benefits of trigeneration arise from the comprehensive integration of the processes and technologies used to supply energy in all necessary forms to meet defined energy demand profiles. Trigeneration technologies have socio-economic and environmental benefits that relate to their efficient use of energy resources, typically resulting in the reduction of operation costs and in environmental benefits (reduced carbon emissions).

The technology behind trigeneration is fundamentally based on the coupling of a cogeneration module with an absorption chiller. The simple trigeneration system analyzed herein is complemented by the usual equipment present in a conventional plant: a hot water boiler and an electrical chiller (Lozano et al., 2009a). Both technologies are used to guarantee supply and also to avoid oversizing the cogeneration module and the associated absorption chiller. The idea is that the cogeneration module, jointly with the absorption chiller, satisfies the average thermal demand for heat and cooling, while the conventional units (boiler and electrical chiller) are utilized in an auxiliary way to make up for the demand peaks. Therefore, supply is guaranteed and the installation is reliable, since the existence of conventional equipment assures the satisfaction of the thermal demand (Lozano et al., 2009b).

Trigeneration systems have wide range of applications: single residential applications (Wang et al., 2008), industry (Colonna and Gabrielli, 2003), or buildings (Marimón et al., 2011).

2. Structure and operation

The purpose of the trigeneration system (Fig. 1) was to meet the demand of different energy services (electricity, $E_d$; heating, $Q_h$; and cooling, $Q_c$) of a consumer center. Fig. 1 shows a diagram of the analyzed trigeneration system, with internal and product flows. The simple trigeneration system consists of the following productive units: a cogeneration module $CM$ (providing heat, $Q_h$, and electricity, $W_h$), an auxiliary boiler $AB$ (providing heat, $Q_h$), an absorption chiller $AC$ (providing cooling, $Q_c$, and driven by heat, $Q_h$) and an electrical chiller $EC$ (providing cooling, $Q_c$, and driven by electricity, $E_d$).

Table 1 presents the technical parameters of the simple trigeneration system. Efficiency coefficients were obtained from equipment catalogs and consultations with manufactures. For each equipment, $P_{nom}$ is the nominal capacity (power of its main product). Taking the cogeneration module as an example, electricity is the main product and $P_{nom} = W_{c\ nom} = 350$ kW. To produce $W_{c}$ kW of electricity, $F_{c} = (1/n_{a})W_{c}$ kW of natural gas will be consumed, recovering $Q_{p} = (a_{0}/a_{w})W_{c}$ kW of heat. It was considered that the efficiency coefficients were constant and independent from the production $P < P_{nom}$ of the equipment.

Demands were always met either by the productive units of the trigeneration system or with the help of purchased electricity from the electric grid ($E_{p}$). The possibilities also existed that a fraction ($Q_{p} > 0$) of the cogenerated heat could be wasted, and the electricity...
could be sold to the market \((E_t)\), \(F_t\) and \(F_s\) refer to the fuel utilized by the cogeneration module and the auxiliary boiler, respectively. Environmental loads were generated in the cogeneration module, which operates on natural gas and in the auxiliary boiler, which operate on fuel oil. When electricity was purchased or sold from/to the electric grid, environmental loads were also considered.

The minimal operation \(\text{CO}_2\) emissions of the system were evaluated by a linear programming model, as explained in section 2.3. The model was applied to very different demands of energy services and the results show how different the operation modes for a simple trigeneration system can be. A greater sophistication of the optimization model, using non linear production restrictions taking into account how ambient conditions affect capacity and efficiency coefficients and binary variables limiting both the minimum load of the equipments and the on/off status, would provide more precise results but, generally, the achieved conclusions would still prevail.

The approach presented in this paper can be used for whole system design by considering, in the optimization model and analysis methodology, the life cycle environmental loads of the system: a) the environmental loads embedded in the selected equipment for the plant and b) the environmental loads associated with the operation of the plant. In this paper, only the second part (b) was studied: the minimization of the environmental loads associated with the operation of a previously dimensioned trigeneration system. Minimization of environmental loads associated with the whole system should also be considered as an obligatory prior step of project and design methodologies for new trigeneration systems (Carvalho et al., 2011a,b).

2.2. Environmental loads of fuels and electricity

**SimaPro (2008)** is a specialized LCA tool, one of the most widely used LCA softwares, used by major industries and consultancies, through to research institutes and universities, and was utilized to calculate the impact associated with the operation of the system (consumption of resources). This was possible because SimaPro includes several inventory databases with thousands of processes and several well-known impact assessment methods. The system interacted with the economic environment (market) through the purchase of natural gas, fuel oil, and electricity from the grid, as well as through the sale of cogenerated electricity to the grid.

LCA analyzes the environmental impacts associated with a process or product from 'the cradle to the grave', which begins with the gathering of raw materials from the earth to create the product/service and ends at the point when all materials are returned to the earth (SAIC, 2006).

### 2.2.1. Natural gas

Natural gas was characterized by utilizing the related emissions of combustion of natural gas, from the IDEMAT database (IDEMAT, 2001), and the total aggregated system inventory for a natural gas consumer in Spain, from the Ecoinvent database (Ecoinvent, 2007). The \(\text{CO}_2\) emissions associated with the consumption of natural gas in Spain were obtained by utilizing SimaPro, calculated as \(\text{EM}_\text{fc} = 0.272 \text{ kg CO}_2 \text{ per kWh of consumed natural gas.}\)

### 2.2.2. Fuel oil

Fuel oil was characterized by an inventory module (extraction, production at refinery and transportation from refinery to an average European end user) and related emissions of controlled burning, from the Ecoinvent database. The \(\text{CO}_2\) emissions associated with the consumption of fuel oil were obtained by utilizing SimaPro, calculated as \(\text{EM}_\text{fa} = 0.305 \text{ kg CO}_2 \text{ per kWh of consumed fuel oil.}\)

### 2.2.3. Electricity

The \(\text{CO}_2\) emissions associated with the local electricity were also calculated by SimaPro, utilizing the Ecoinvent database and considering that all electricity originated from a single-fuel representative coal power plant (\(\text{EM}_\text{ep} = 1.020 \text{ kg CO}_2/\text{kWh}\)).

The evaluation of \(\text{CO}_2\) emissions in a representative coal power plant was utilized as an example here, in order to illustrate the application of the proposed methodology. Carvalho (2011) analyzed other environmental indicators as well as other types of power plants, and different national electricity mixes. Using coal power plants, different operation modes of the system appear when varying the energy services demands. This allowed for a clearer and complete validation of the proposed methodology.

### 2.3. Optimal operation modes

A linear programming model was solved in order to obtain the optimal operation mode from an environmental viewpoint. The environmental analysis considered that the only significant variable environmental loads were electricity, natural gas and fuel oil. No environmental burden was associated with the waste of cogenerated heat, i.e., \(\text{EM}_\text{f}\) = 0. The objective function to be minimized was the operation variable emissions (in kg \(\text{CO}_2/\text{h}\)):

\[
\text{Operation variable emissions} = \text{EM}_\text{fc}F_c + \text{EM}_\text{fa}F_a + \text{EM}_\text{ep}E_p
- \text{EM}_\text{f}E_s + \text{EM}_\text{q}Q_l
\]  

(1)

Cogenerated electricity sold to the grid was considered to have the same environmental load as that of electricity purchased from the grid (\(\text{EM}_\text{ep} = \text{EM}_\text{ep}\)). The concept of avoided emissions is presented as the emissions avoided elsewhere with the production of electricity by the cogeneration module, consequently avoiding the purchase of electricity from the grid.

Equation (1) was subject to restrictions of capacity limit and equipment efficiency as well as balance equations, previously presented in Lozano et al. (2009a). Results were obtained by utilizing the modeling language and optimizer Lingo (2008). Lingo is a commercial software package for solving optimization problems that uses the branch and bound solver to enforce any integer restrictions contained in a model. The advanced capabilities of Lingo such as cut generation, tree reordering, advanced heuristic and presolve strategies were used as needed.

Given the energy demands to be satisfied, according to the different operation modes, Lingo solved the previous model and determined the feasible operation mode with the minimum operation variable emissions.

The resulting feasible operation states could be classified into nine different operation modes, based on the values of purchased electricity \((E_p)\), sold electricity \((E_s)\), auxiliary heat \((Q_a)\) and waste heat \((Q_l)\). These operation modes corresponded to different demand of the energy services of the consumer center and are shown in Table 2.

A summary of results (demand, flows, and hourly cost) obtained with Lingo for four examples ExC1, ExC3, ExC7 and ExC9 that corresponded to different operation modes \((C_1, C_3, C_7, \text{ and } C_9)\) is presented in Table 3. For each different example, the minimum

### Table 1

<table>
<thead>
<tr>
<th>Technical/equipment</th>
<th>Efficiency coefficient</th>
<th>Nominal capacity (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cogeneration module</td>
<td>(a_h = W_h/W_i = 0.35)</td>
<td>(W_{\text{nom}} = 350)</td>
</tr>
<tr>
<td>Auxiliary boiler</td>
<td>(a_h = Q_h/Q_i = 0.40)</td>
<td>(Q_{\text{nom}} = 400)</td>
</tr>
<tr>
<td>Absorption chiller</td>
<td>(COP_h = R_h/Q_h = 0.625)</td>
<td>(R_{\text{nom}} = 250)</td>
</tr>
<tr>
<td>Electrical chiller</td>
<td>(COP_c = R_c/F_c = 5.0)</td>
<td>(F_{\text{nom}} = 250)</td>
</tr>
</tbody>
</table>

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**Table 2.** Technical parameters of the simple trigeneration system.
emissions of satisfying the energy service demand of the consumer center was reached in a different operation mode, which exchanged energy flows with the environment and utilized the productive capacity of the installed equipment. Table 3 shows the energy flows obtained and the operation variable CO₂ emissions.

### 3. Environmental management information system

#### 3.1. Umberto software for material and energy flow analysis

Software support for Material Flow Networks (MFN) must meet a number of requirements. For instance, the software must be capable of modeling complex production processes from different fields of application, such as chemistry or engineering, and must offer flexible data management for updating and extending the model. Different ways of data interpretation and display must also be supported. The Umberto software, which entered the market in the mid-1990s, was the first suite of programs that tried to meet these goals. Umberto software is a powerful and user-friendly family of operating systems and meets software ergonomic standards (Wohlgemuth et al., 2006).

The inclusion of environmental information on the usage and consumption of resources into Umberto allowed for the evaluation of the distribution of the environmental loads associated with each flow of the system. Additionally, integrated models of energy flows facilitated a better understanding of the assignment of environmental and economic costs to the internal and final products of the trigeneration system.

The modeling of material flows in multi-stage production systems initially focused on absolute flows of companies and supply chains. The objective is to trace the material flows within different companies within a value chain. In MFN, the term material refers to substances and energy, meaning there is virtually no distinction between substances and energy. Based on the concept of material flow networks, the powerful calculation algorithm of Umberto allows for the determination of all material and energy flows in the system under study.

According to Wohlgemuth et al. (2006), the most attractive feature of MFN is the possibility to combine the calculation of eco-balances for an industrial plant with an analysis of material flows associated with goods products or services. An eco-balance refers to the consumption of energy and resources and the pollution caused by the production cycle of a product. An advantage of the MFN approach resides in its gradual modeling approach, starting from a very basic model of few processes with simple specifications, the model can be extended step by step to include further processes, sites, more complex specifications, costs, etc. (Viere et al., 2010).

Umberto software allows for the visualization of processes, units and flows, carrying out mass and energy balances and analyzing from an environmental point of view the emissions generated. Petri Nets, double-entry bookkeeping, and cost accounting are the basis of Umberto software, allowing the setup of complex systems and also a combined material, energy and inventory calculation. Umberto models consist of places, transitions, and arrows (directed graphs).

##### 3.1.1. Places

An important function of places is that they delimit the system from its environment; they are points of contact with the world. The inputs of the simple trigeneration system (Fig. 4, light gray circles) were the consumption of fuel by the cogeneration module (Pₐ) and auxiliary boiler (Pₐ), and the electricity purchased from the grid (Pₑ).

The outputs of the system (dark gray circles in Fig. 4) were the demands of electricity (Eₑₐ), heat (Qₐ), and cooling (Qₐ). Freedom was available to the consumer to decide how the system operated: wasting heat permitted the operation of the cogeneration module to match the demand of the consumer center and the sale of surplus cogenerated electricity permitted to realize profit. Therefore two more outputs of the system were waste heat (Qₐ) and the cogenerated electricity sold to the grid (Eₑₐ).

The place “Environmental loads” accounted for the environmental loads originating from the consumption of natural gas and fuel oil, and from the purchase or sale of electricity. The two “Environmental loads” outputs seen in Fig. 2 are duplicate places. If an arrow leads to a place far away, the graphical display might become incomprehensible. Therefore the “Environmental loads” place was duplicated and the copy was positioned in the vicinity of transition P. All emissions go into the atmosphere, but Umberto software tracks the contribution of each transition to account for its share of emissions.

##### 3.1.2. Transitions

Each piece of equipment was modeled as a transition. A slightly more complex but more flexible method to specify transitions was

### Table 2

<table>
<thead>
<tr>
<th>Operation modes</th>
<th>Yes purchased electricity</th>
<th>No purchased electricity</th>
<th>No purchased electricity</th>
</tr>
</thead>
<tbody>
<tr>
<td>No sold electricity</td>
<td>Yes auxiliary boiler</td>
<td>C₁</td>
<td>C₄</td>
</tr>
<tr>
<td>No sold electricity</td>
<td>No auxiliary boiler</td>
<td>C₂</td>
<td>C₅</td>
</tr>
<tr>
<td>Yes sold electricity</td>
<td>No waste heat</td>
<td>C₃</td>
<td>C₆</td>
</tr>
<tr>
<td>No sold electricity</td>
<td>No auxiliary boiler</td>
<td>No waste heat</td>
<td>No auxiliary boiler</td>
</tr>
</tbody>
</table>

### Table 3

Energy flows and variable CO₂ emissions.

<table>
<thead>
<tr>
<th>Operation mode</th>
<th>ExC₁</th>
<th>ExC₃</th>
<th>ExC₇</th>
<th>ExC₉</th>
</tr>
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<tbody>
<tr>
<td>C₁</td>
<td>465.50</td>
<td>323.00</td>
<td>215.65</td>
<td>119.00</td>
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<tr>
<td>C₄</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C₇</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C₉</td>
<td></td>
<td></td>
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</tbody>
</table>
loads of internal software. The assistant performed calculations of environmental based on thermoeconomics, an assistant was created in Umberto with greater input monitor of Umberto software was used to model the system to be carried out easily. The assistant was validated with economic costs (correctly reproducing thermoeconomic cost results published in Lozano et al. (2009a,c). By changing ‘market prices’ to ‘environmental loads’, the assistant turned to an environmental perspective, giving the assistant flexibility to support calculations regarding environmental loads or economic costs.

Balances were formulated in each transition and external resources used in the production process were valued by the environmental burden caused. Applying the condition of cost conservation to each transition yields:

**Equipment**

\[
CM : \quad EM_{e_{\text{C}}} = EM_{w_{\text{C}}} + EM_{q_{\text{C}}}
\]

\[
AB : \quad EM_{q_{\text{A}}} = EM_{q_{\text{A}}}
\]

\[
AC : \quad EM_{q_{\text{A}}} = EM_{q_{\text{A}}}
\]

\[
EC : \quad EM_{e_{\text{C}}} = EM_{e_{\text{C}}}
\]

**Branching and merging points**

\[
S : \quad EM_{w_{\text{C}}} = EM_{w_{\text{C}}} + EM_{q_{\text{C}}}
\]

\[
P : \quad EM_{w_{\text{C}}} = EM_{w_{\text{C}}} + EM_{w_{\text{C}}}
\]

\[
L : \quad EM_{q_{\text{C}}} + EM_{q_{\text{C}}} = EM_{q_{\text{C}}}
\]

\[
R : \quad EM_{q_{\text{C}}} + EM_{q_{\text{C}}} = EM_{q_{\text{C}}}
\]

**3.2. Environmental cost accounting**

As previously mentioned, thermoeconomic analysis (cost accounting) can be combined with LCA, and both techniques can be integrated into an EMIS. In the particular case of Umberto, it was necessary to build an assistant to integrate the philosophy/methodology utilized in energy cost analysis (thermoeconomics) with the evaluation of environmental loads. The concept of cost can involve different magnitudes, for example, environmental loads. Environmental costs can be understood as a category of cost (according to the consumption of natural resources and generation of environmental loads in order to obtain a flow). For the implementation of the environmental allocation method based on thermoeconomics, an assistant was created in Umberto software. The assistant performed calculations of environmental loads of internal flows and products after network calculation. The input monitor of Umberto software was used to model the system with greater flexibility, allowing modifications in operation modes to be carried out easily. The flows that defined each operation mode were established in the input model, and then Umberto software calculated the remaining flows.

Umberto offers several interfaces to other programs, one of which allows the specification of transitions. In combination with complex algorithms it can embed sub-models into MFN that have been developed outside of Umberto. This can be done through a script written in any of the languages supporting Microsoft’s Active Scripting Architecture. The new functions and extensions were implemented within the menu structure, utilizing structural language XML with code/logic J#. XML was chosen because it is human-legible and reasonably clear, easy to create, and the user has the advantage of acting independently of software (data can be moved through software upgrades and even to different software products). J# was used basically for its text highlighting abilities and because it uses Microsoft’s Common Language Runtime. The assistant was an application that collected data of the calculated flows to carry out cost accounting. The assistant was necessary because Umberto calculates flows and costs simultaneously, and the implementation of thermoeconomic equations required the flows to be previously calculated.

The assistant was validated with economic costs (correctly reproducing thermoeconomic cost results published in Lozano et al. (2009a,c). By changing ‘market prices’ to ‘environmental loads’, the assistant turned to an environmental perspective, giving the assistant flexibility to support calculations regarding environmental loads or economic costs.

Balances were formulated in each transition and external resources used in the production process were valued by the environmental burden caused. Applying the condition of cost conservation to each transition yields:

\[
CM : \quad EM_{e_{\text{C}}} = EM_{w_{\text{C}}} + EM_{q_{\text{C}}}
\]

\[
AB : \quad EM_{q_{\text{A}}} = EM_{q_{\text{A}}}
\]

\[
AC : \quad EM_{q_{\text{A}}} = EM_{q_{\text{A}}}
\]

\[
EC : \quad EM_{e_{\text{C}}} = EM_{e_{\text{C}}}
\]

\[
S : \quad EM_{w_{\text{C}}} = EM_{w_{\text{C}}} + EM_{q_{\text{C}}}
\]

\[
P : \quad EM_{w_{\text{C}}} = EM_{w_{\text{C}}} + EM_{w_{\text{C}}}
\]

\[
L : \quad EM_{q_{\text{C}}} + EM_{q_{\text{C}}} = EM_{q_{\text{C}}}
\]

\[
R : \quad EM_{q_{\text{C}}} + EM_{q_{\text{C}}} = EM_{q_{\text{C}}}
\]

Considering that the operation state of the plant was known, then all energy flows, environmental loads for fuel and electricity, and environmental load entailing waste heat were also known. Here it was considered that \( EM_{q_{\text{A}}} = 0 \) because the objective was to assess all environmental loads to useful final products. \( EM_{q_{\text{A}}} = 0 \) does not mean an absence of environmental impact, but that there was no environmental burden associated with the act of wasting heat. Consequently, there were 12 unit environmental loads of internal flows and final products to be calculated: \( EM_{w_{\text{C}}} \), \( EM_{q_{\text{C}}} \), \( EM_{e_{\text{C}}} \), \( EM_{e_{\text{C}}} \), \( EM_{q_{\text{C}}} \), \( EM_{q_{\text{C}}} \), \( EM_{q_{\text{C}}} \), \( EM_{q_{\text{C}}} \), \( EM_{q_{\text{C}}} \), \( EM_{q_{\text{C}}} \), \( EM_{q_{\text{C}}} \), \( EM_{q_{\text{C}}} \). As
the system was described using 9 equations with 12 unknowns, 3 auxiliary equations were needed.

It was considered that the unit environmental load of several flows obtained from a homogeneous flow was the same. Applying this rule to branching points $P$ and $Q$, two auxiliary equations were obtained:

$$P: \quad EM_{er} = EM_{ed} \tag{11}$$

$$Q: \quad EM_{fr} = EM_{qd} \tag{12}$$

This means that the environmental loads assessed to the electricity internally consumed in the electrical chiller ($EM_{ed}$) and the electricity provided to the consumer center ($EM_{ed}$) are the same. The environmental loads assessed to the heat internally consumed in the absorption chiller ($EM_{qd}$) and the heat provided to the consumer center ($EM_{qd}$) follow the same rule.

The third auxiliary equation must define how the environmental loads generated in the cogeneration module are attributed to its products: heat and electricity. Allocation is a very important issue when apportioning environmental loads to multiproduct systems, to ensure each party is credited with their appropriate share. Research on allocation of emissions and environmental burdens will allow the environmental benefits of co- and tri-generation technologies (adequately designed and operated) to be better understood and exploited (Rosen, 2008; Abusoglu and Kanoglu, 2009; Carvalho, 2011).

Umberto software supports the consideration of different approaches to the allocation issue, and even supports the use of scripts to attach complex rules or models to a transition. However, the issue of allocation was not addressed in depth in this paper. A deep discussion on the allocation of environmental loads is presented in Carvalho (2011). Different allocation methods of environmental loads to electricity and heat products (third auxiliary equation for the cogeneration module with its productive environment).

Fig. 3. Control volume accounting for the interaction of the cogeneration module with the environment.

However, the main issue found during the utilization of such simple methods focused on the immediate products of the cogeneration module, $Q_c$ and $W_c$, not accounting for possible different destinations or uses of $Q_c$ and $W_c$ nor for the interaction of the cogeneration module with its productive environment.

Since traditional solutions to the problem were unsatisfactory, the authors proposed an innovative allocation method in Carvalho et al. (2010), which was implemented in Umberto software through the aforementioned assistant, allocating emissions to the consumed products of the cogeneration module ($W_c$ and $Q_c$), in proportion to the emissions generated by their alternative production:

$$EM_{qcc} = EM_{qa} \frac{EM_{ep}}{EM_{ep}} \tag{13}$$

$EM_{ep}$ being the environmental loads corresponding to electricity purchased from the electric grid, and $EM_{qa}$ the environmental loads associated with the heat produced in the auxiliary boiler ($EM_{qa} = EM_{qa}/\eta_{qa}$). Equation (13) could be applied directly to all operation modes, as it was previously established that $EM_{ep} = EM_{ep}$.

The choice of such control volume allows the benefits of selling electricity and the inefficiency of wasting heat to be both distributed between heat and electricity internally consumed.

When considering different equipment, activities, and options included in the trigeneration system, the assignment of unit costs should rather consider the products of the cogeneration module that were consumed ($W_c$ and $Q_c$). In this way, as shown in Fig. 3, the emissions associated with the operation of the cogeneration module, the sale of electricity to the grid, and waste heat ($EM_{qc}F_c - EM_{qa}E_c + EM_{qa}Q_c$) were distributed between heat and electricity internally consumed ($EM_{qc}W_c$ and $EM_{qc}Q_c$).

4. Results and discussion

Based on the flow quantities entered in the input monitor (energy demands and environmental loads associated with operation), the system calculated the flows of the entire network using the transition specifications. For comparison, a reference system (Fig. 4) was created, in which all energy demands were satisfied in a conventional way (electricity was purchased from the grid for $E_d$ and $R_d$, and $Q_d$ was satisfied by an auxiliary boiler). Table 4 shows the emissions for the trigeneration and conventional systems.

Umberto software provided the overall amount of emissions associated with the operation of the trigeneration system. It was verified that trigeneration technology reduced significantly the kg of CO2 emitted into the atmosphere. Table 5 shows the unit environmental loads associated with the operation of the simple trigeneration system for all operation examples.

Fig. 4. Conventional system.
Comparison of emissions between examples ExC1 and ExC3 gave indications on what occurred when some heat was wasted. EMwq and EMwqc increased their value in ExC3, reflecting the inefficiency of wasting heat, and consequently, EMq had a higher value. EMqd presented a lower value in ExC3, promoting the consumption of waste heat.

The comparison between examples ExC1 and ExC7 gave indications on the behavior of the system when electricity was sold to the grid. In ExC7, EMwq presented a higher value and EMwqc presented a lower value than in ExC1. The sale of electricity with lower emissions (but evaluated as having higher emissions) consequently lowered the cost of EMwq. The benefits of the sale of electricity were positively reflected on the values of EMw and EMwqc, and ultimately on the final emissions of Ed, Qd, and Rd, which were lower.

In ExC9, EMq presented increased reflecting the waste of heat, but with sale of electricity, EMq was still environmentally sounder than EMep. The sale of electricity benefited all final energy services, resulting in lower emission values when comparing ExC1 and ExC9. Internal flows too, were lower in ExC9. When comparing ExC7 and ExC9, it could be seen that EMep had a lower value, resulting in a lower value for EMq which could promote consumption of otherwise wasted heat. EMwq and EMwqc had increased values which were translated into higher emissions for EMq and EMw. The benefits as well as the penalties of the system were reflected in all energy services produced in the cogeneration module.

Table 4 shows the breakdown of energy resources and CO2 emissions assessed to final products (electricity, heat and cooling demands). Umberto provided the emissions associated with the consumption of each energy service, and the origin of the emissions, tracking the contributions of electricity purchased from the grid, and fuels of the cogeneration module and auxiliary boiler.

Umberto software uses diagrams to display materials, energy and final products (electricity, heat and cooling demands). Fig. 5 shows the contributors to the environmental loads of the electricity demand (Ed), which is satisfied by the generation of electricity in the cogeneration module (operating with fuel Fc) and is complemented by the purchase of electricity from the grid (Ep).

Fig. 6 shows the contributors to the environmental loads of the heat demand (Qd). The cogeneration module generates heat (operating with fuel Fc) and is complemented by heat produced by the auxiliary boiler Qa (which operates with fuel Fa).

Fig. 7 shows the contributors to the environmental loads of the cooling demand Rd. Electricity purchased Ed from the grid and electricity generated Wc by the cogeneration module contribute to operate the electrical chiller. The auxiliary boiler operates on heat produced by the cogeneration module (Qc) plus heat produced by the auxiliary boiler (Qa).

It is important to highlight the fact that the integration proposed in this paper (LCA and thermoeconomics into an EMIS) supports consideration of any environmental indicator, i.e., Eco-indicator 99 points, ozone layer depletion values (kg eq CFC-11 into air).

Table 4

<table>
<thead>
<tr>
<th></th>
<th>ExC1</th>
<th>ExC3</th>
<th>ExC7</th>
<th>ExC9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>kg CO2/h</td>
<td>642.12</td>
<td>466.53</td>
<td>453.18</td>
</tr>
<tr>
<td>Trigeneration</td>
<td>kg CO2/h</td>
<td>465.50</td>
<td>323.00</td>
<td>215.65</td>
</tr>
</tbody>
</table>

Table 6

<table>
<thead>
<tr>
<th></th>
<th>Ep (kWh)</th>
<th>Fc (kWh)</th>
<th>Fa (kWh)</th>
<th>CO2 (kg CO2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ExC1</td>
<td>88.89</td>
<td>622.72</td>
<td>–</td>
<td>260.05</td>
</tr>
<tr>
<td>ExC3</td>
<td>50.00</td>
<td>700.56</td>
<td>–</td>
<td>241.55</td>
</tr>
<tr>
<td>ExC7</td>
<td>400.32</td>
<td>299.44</td>
<td>250.00</td>
<td>157.70</td>
</tr>
<tr>
<td>ExC9</td>
<td>400.32</td>
<td>115.17</td>
<td>–</td>
<td>108.89</td>
</tr>
</tbody>
</table>

Fig. 5. Emissions associated with the consumption of Ed in example ExC1.
ecotoxicity values (kg eq triethylene glycol into water and soil), etc.

Information shown in Tables 5 and 6 and Figs. 5–7 allows for the study of the distribution of consumed resources, of the cost formation process, and the generation of environmental loads throughout the productive system.

This study emphasized the importance of integrating environmental information (obtained with the application of LCA techniques) and the philosophy of thermoeconomic analysis in Environmental Information Management Systems. Such integration was easily accomplished through an assistant implemented in Umberto. The assistant facilitated the registration and tracking of environmental impacts generated in each piece of equipment as well as the assessment of environmental loads to each output and internal flow, with the possibility of considering different approaches to the allocation issue. This combined approach allowed for a more precise understanding of operational activities.

International markets are increasingly seeking an indication of environmental performance and the carbon emissions associated with products and services. The responsibility exists to ensure long term ecologically sustainable production, particularly in changing climatic conditions. From an environmental viewpoint, the purpose of installing a trigeneration system was to provide a reduction in the amount of environmental loads produced to attend a consumer center, which was achieved here.

5. Summary and conclusions

A trigeneration system was modeled in Umberto software, with the flexibility to purchase/sell electricity from/to the electric grid. The possibilities of wasting part of the cogenerated heat and operating an auxiliary boiler also existed. The network was calculated for specific energy service demands, identifying where emissions were generated, and tracking the emissions throughout the system. This study case concentrated on the issue of climate change and therefore considered the emissions of CO₂. Flow analysis of individual production steps specific to operation made it possible to study the operational activities more precisely.

This paper demonstrates that LCA can and has been formally combined with thermoeconomic analysis. The result is an ability to take thermoeconomics and LCA — and their tradeoff relationships — into account in product/process design decision making. This combined approach was integrated into an EMIS, identifying where environmental loads were generated and tracked their distribution to the final products of trigeneration systems. In an attempt to address the ongoing debate, an innovative environmental allocation method was proposed.

The allocation proposal for trigeneration systems considered that environmental loads of the cogeneration module were distributed among the consumers of the final products, resulting in overall reduced emissions derived from the combined production. Such reductions were evaluated in proportion to the emissions associated with obtaining heat and electricity separately via conventional systems. The assistant developed also provided Umberto with the capability of calculating economic costs. A potent tool was obtained for energy, economic, and environmental analysis, to study the distribution of resources throughout productive systems as well as the formation process of costs and environmental loads.

Effective environmental related strategies connect the reduction of emissions with a system’s operational strategy (consumption of resources). Therefore the usage of EMIS with double input from thermoeconomics and LCA tools could be promoted to (1) analyze the distribution of material and energy resources throughout a productive system; (2) serve the numerical registration and interpretation of environmental effects; (3) calculate unit economic costs and study the cost formation process; (4) identify the most environmentally beneficial among competing technologies; and (5) allow an emission-efficient economy to develop.

By incorporating environmental information on the usage and consumption of resources into Umberto software, the approach of material flow networks gave insight on the environmental loads associated with each flow of the system. Thus, the consumers of a productive system can be made aware of the environmental loads associated with the consumption of each product (either internal or final). This information can be very useful for the introduction of strategies oriented to changes and improvements in the design and operation of productive systems as well as in consumption patterns and resource conservation, contributing to the development of a more sustainable economy.

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