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# Modeling a simple trigeneration system: Environmental costs

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**Abstract:** Directive COM 2002/91/EC recognized the importance of buildings in the consumption of energy, helping promote a stable framework for the support of cogeneration in the European Union. Cogeneration and Trigeneration can provide substantial benefits from economic, energetic, and environmental viewpoints. The Umberto software is used to model a trigeneration system providing electricity, heat, and cooling to a building, revealing important relevant structures and flows. The software's basis rests on Petri networks and double-entry bookkeeping and cost accounting, allowing the setup of complex systems and also a combined material, energy and inventory calculation. Umberto software is an Industrial Environmental Management Information System, specifically designed to analyze the distribution of material and energy resources throughout a productive system. Each piece of equipment is modeled as a transition (indicating material or energy transformations) and is specified utilizing user-defined functions (technical production coefficients and generation of emissions). Network parameters were used to calculate the emissions associated with the operation of the system. From the perspective of Material Flow Networks, arrows are viewed as accounts of material and energy flows, and places keep track of all relevant stocks. Costs are understood as the amount of emissions generated (according to the consumption of resources) in order to obtain a flow. The issue of allocating environmental costs is introduced and two scenarios for each operational mode are compared: the trigeneration system vs. a conventional energy supply system.

**Keywords:** Trigeneration; Material Flow Analysis; Environmental costs; Umberto Software.

## 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).

In Mediterranean 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, which efficiently recover "waste" heat to cooling energy. By combining cogeneration with absorption chillers (= trigeneration), the energy demand can be extended into the summer months to match cooling loads.

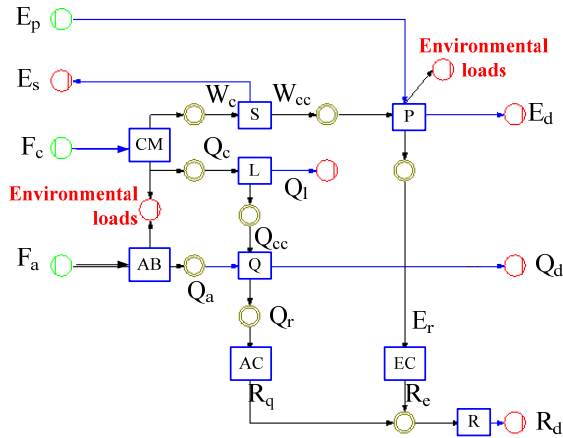
As sustainability-related issues such as energy consumption and environmental impact become a more integrated part of operational and long-term planning decisions, simulation modeling and analysis tools are needed to aid in the decision making process. Material

Flow Analysis (MFA) has become an important instrument to support environmental protection and sustainable development. Often, a special approach, Life Cycle Assessment (LCA), is put on the same level as MFA; LCA is a tool that provides global perspective of environmental loads [Guineé, 2002]. LCA is an objective process to evaluate the environmental loads associated with a product, process, or activity, identifying and quantifying the use of mass and energy as well as the emissions to the environment. LCA also determines the impact of the use of resources and emissions, evaluating and carrying out strategies of environmental improvement.

This study modeled a simple trigeneration system with Umberto<sup>1</sup> software [2006], incorporating environmental information on the consumption of resources. Typically, analysis on environmental loads concentrates on the system's input and output of energy and materials; no analysis of the internal operations/processes takes place. Umberto software is specifically designed to analyze the distribution of material and energy resources throughout a productive system. Here costs are understood as the amount of emissions generated (according to the consumption of resources) in order to obtain a flow (or commodity). Hence, the cost of a flow represents the amount of emissions that have been generated in the overall system to produce this flow. The issue of allocating environmental costs (emissions) is introduced and two scenarios are compared: the trigeneration system vs. a conventional energy supply system.

## 2. SIMPLE TRIGENERATION SYSTEM

The purpose of the trigeneration system (Figure 1) is to meet the demand of different energy services (electricity,  $E_d$ ; heating,  $Q_d$ ; and cooling,  $R_d$ ) of a consumer center.



The simple trigeneration system consists of the following productive units: a cogeneration module CM (providing heat,  $Q_c$ , and work,  $W_c$ ), an auxiliary boiler AB (providing heat,  $Q_a$ ), an absorption chiller AC (providing cooling,  $R_q$ , and driven by heat,  $Q_r$ ) and a mechanical chiller EC (providing cooling,  $R_e$ , and driven by electricity,  $E_r$ ).

Figure 1. Simple trigeneration system.

Demands will always be 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 ( $Q_l > 0$ ) of the cogenerated heat could be wasted, and the electricity could be sold to the market ( $E_s$ ).  $F_c$  and  $F_a$  refer to the fuel utilized by the cogeneration module and the auxiliary boiler, respectively. Environmental loads were generated in the cogeneration module and in the auxiliary boiler, which operate on natural gas. When electricity was purchased from the electric grid to help cover energy demands, environmental loads were also considered.

### 2.1 Operation of the system

The operation of the system was optimized using the LINGO [2007] modeling language and optimizer, and detailed explanation is given in Lozano *et al.* [2009]. The objective

<sup>1</sup> See <http://www.umberto.de/en>

function to be minimized was the operational variable cost (€/h), subject to physical and economic constraints that determined the operation of the system. Nine different operation modes were established (Table 1), considering the values of purchased electricity ( $E_p$ ), sold electricity ( $E_s$ ), auxiliary heat ( $Q_a$ ) and waste heat ( $Q_l$ ).

**Table 1.** Operation modes.

	$E_p > 0$ $E_s = 0$	$E_p = 0$ $E_s = 0$	$E_p = 0$ $E_s > 0$
$Q_a > 0$ $Q_l = 0$	<b>C<sub>1</sub></b>	<b>C<sub>4</sub></b>	<b>C<sub>7</sub></b>
$Q_a = 0$ $Q_l = 0$	<b>C<sub>2</sub></b>	<b>C<sub>5</sub></b>	<b>C<sub>8</sub></b>
$Q_a = 0$ $Q_l > 0$	<b>C<sub>3</sub></b>	<b>C<sub>6</sub></b>	<b>C<sub>9</sub></b>

Flows for different examples of optimal operation states corresponding to operation modes C1, C3, C7 and C9 are shown in Table 2.

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 appear in Figure 1 as blue arrows. Black arrows indicate the flows that were calculated by Umberto software.

**Table 2.** Energy flows (kWh) for different examples of optimal operation

	C1	C3	C7	C9
$E_d$	400	400	200	200
$Q_d$	400	100	600	100
$R_d$	400	100	100	100
$E_p$	100	50	0	0
$E_s$	0	0	130	150
$F_c$	1000	1000	1000	1000
$F_a$	300	0	250	0
$W_c$	350	350	350	350
$Q_c$	400	400	400	400
$W_{cc}$	350	350	220	200
$E_r$	50	0	20	0
$Q_l$	0	140	0	140
$Q_{cc}$	400	260	400	260
$Q_a$	240	0	200	0
$Q_r$	240	160	0	160
$R_q$	150	100	0	100
$R_e$	250	0	100	0

### 3. MODELING THE SIMPLE TRIGENERATION SYSTEM

Modeling is a powerful tool for investigating complex systems, such as information networks, material and energy streams. According to Wohlgemuth *et al.* [2006], all business activities create flows of energy and materials, and the management of these flows forms an integral part of how a company interacts with the environment. Environmental Management Information Systems (EMIS) are designed to detect, evaluate and prevent a wide range of environmental dangers and stresses.

MFA can be defined as an instrument for analyzing complex networks of materials and energy flows, stocks, as well as material and energy transformations. The most important concept in this field is LCA, which is considered to be a promising solution to address the problems of resource and energy efficiency as well as eco-efficiency [Moeller *et al.*, 2009]. In the Life Cycle Inventory Analysis (LCIA), anthropogenic material and energy flows are calculated. The modeling of such flows is accomplished through linear process specifications and links between them; the solutions yield the contributions of the processes [Heijungs and Suh, 2004].

Umberto software allows the visualization of processes, units and flows, carrying out mass and energy balances and analyzing from an environmental point of view the loads/emissions generated. Petri Nets and 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. As Material Flow Networks (MFN) are Petri-Nets, they consist of Transitions, Places and Arrows (directed graphs), which can be formalized as 3-tuples, with  $N = (T, S, F)$  and  $F \subseteq (S \times T \cup T \times S)$ ; where T is a set of Transition nodes, S are inventory nodes, called Places, and each element of F describes a flow between two subsets of Places triggered by a transition of T [Wohlgemuth *et al.*, 2006].

Using a diagram notation, Transitions are shown in Umberto software as squares, indicating the location of material or energy transformations. Places can be input or output

places connecting the material flow network with its environment, and are represented by circles. The "connection" place has two concentric circles, and is utilized to connect transitions (link from the output of one process to the input of the next process). Arrows link places and transitions, and thus create the actual network structure. The functional unit was the production of the demanded energy services during one hour of operation of the different alternatives.

### 3.1 Places

An important function of places is that they delimit the MFN from its environment; they are points of contact with the world. The inputs of the simple trigeneration system (Figure 1, green circles) were the consumption of fuel by the cogeneration module ( $F_c$ ) and auxiliary boiler ( $F_a$ ), and the electricity purchased from the grid ( $E_p$ ).

The outputs of the system (red circles in Figure 1) were the demands of electricity ( $E_d$ ), heat ( $Q_d$ ), and cooling ( $R_d$ ). Freedom was available to the consumer to decide how the system operated, to minimize costs or environmental impacts; wasted heat permitted the operation of the cogeneration module to match the demand of the consumer center and the sale of surplus autogenerated electricity permitted to realize profit. Therefore two more outputs of the system were waste heat ( $Q_h$ ) and the autogenerated electricity sold to the grid ( $E_s$ ).

The place "Emissions" accounted for the environmental loads originating from the consumption of natural gas (in CM and/or AB) and from the purchase of electricity from the grid. The two "emissions" outputs seen in Figure 1 are duplicate places. If an arrow leads to a place far away, the graphical display might become incomprehensible. Therefore the "emissions" 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.

### 3.2 Transitions

Each piece of equipment was modeled as a transition. A slightly more complex but more flexible method to specify transitions was applied, utilizing expressions to describe the relationships between input and output flows of a transition, making it possible to model non-linear transitions. To guarantee that the network could be calculated in both directions, the user-defined functions also considered the inverse form. Table 3 shows the technical parameters of the equipments, which establish the relationship between inputs and outputs of each transition.

**Table 3.** Technical parameters of the simple trigeneration system.

Transition/Equipment	Efficiency coefficient	Nominal capacity (kW)
CM	$\alpha_w \equiv W_c/F_c = 0.35$ $\alpha_q \equiv Q_c/F_c = 0.40$	$W_{c \text{ nom}} = 350$
AB	$\eta_q \equiv Q_a/F_a = 0.80$	$Q_{a \text{ nom}} = 400$
AC	$\text{COP}_q \equiv R_q/Q_r = 0.625$	$R_{q \text{ nom}} = 250$
EC	$\text{COP}_e \equiv R_c/E_r = 5.0$	$R_{e \text{ nom}} = 250$

Environmental loads were calculated with SimaPro [2008], utilizing environmental databases [IDEMAT, 2005; Ecoinvent, 2007] on the consumption of natural gas and electricity. A more detailed explanation is found in Carvalho *et al.* [2010a]. Umberto software could have been used to calculate the environmental loads, as it supports import and export of datasets from the Ecoinvent database, with all datasets ready-to-use as an Umberto Library. However, the working version installed was *educ*, especially designed for educational purposes and did not include the Ecoinvent database.

The CO<sub>2</sub> emissions associated with the consumption of natural gas in Spain were calculated as 0.272 kg CO<sub>2</sub> per kWh of consumed natural gas (related emissions of burning natural gas and total aggregated system inventory for a user in Spain).

The CO<sub>2</sub> emissions associated with the Spanish electricity mix considered the proportions (25.8% Coal, 24.4% Natural gas in combined cycle, 19.7% Nuclear, 10.4% Others (biomass, cogeneration, minihydraulic), 9.4% Eolic, 9.4% Hydraulic, and 0.9% Fuelgas to produce the electricity [REE, 2007]. The average CO<sub>2</sub> emissions associated with electricity in Spain in 2007 were calculated as 0.385 kg CO<sub>2</sub> per kWh consumed.

These environmental load values were incorporated into Umberto as net parameters, which are parameters valid not only locally for a single transition but for an entire MFN or for subnets. Net parameters can be used in the functions of the transition specifications in the same way as transition parameters.

Branching points S (Sale), L (Waste heat), P (Purchase), Q (Heat node), and R (Refrigeration node) were also modeled as transitions. Branching points can be interpreted as decision points, in which possibilities are reflected. Point S refers to the possibility of selling autogenerated electricity to the grid; point L refers to the possibility of wasting part of the cogenerated heat; point P refers to the possibility of purchasing electricity from the grid; point Q refers to the possibility of operating the auxiliary boiler, and point R adds the contributions of the chillers to satisfy the refrigeration demand.

### 3.3 Allocation

Allocation is a very important issue when apportioning environmental loads to multiproduct systems, to ensure each party is credited with their appropriate share. When using the full capacity of Umberto's Life Cycle Inventory (LCI) calculation method, coupled processes can be modeled as multi-material processes. Research on allocation of emissions and environmental burdens will allow the environmental benefits of cogeneration technologies (adequately designed and operated) to be better understood and exploited [Abusoglu and Kanoglu, 2009; Rosen, 2008].

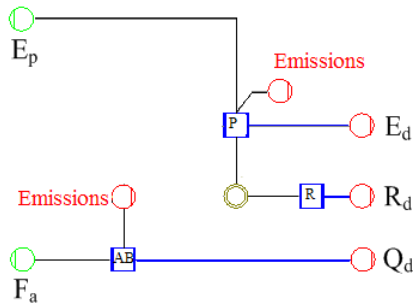
The issue of allocation was not addressed in this paper. An economic reference was considered to apportion the emissions between the products of the cogeneration module; the fractions allocated to electrical and heat productions, on the basis of their market value, was 75% to electricity and 25% to heat (market values: 0.100 €/kWh for electricity and 0.030 €/kWh for heat; [Lozano *et al.*, 2009a]).

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. The authors proposed a different allocation method in Carvalho *et al.* [2010b], which was implemented in Umberto software through an assistant, allocating emissions to the consumed products of the cogeneration module ( $W_{cc}$  and  $Q_{cc}$ ) in proportion to the emissions generated by their alternative production. The allocation of environmental loads to the internal flows and final products of the trigeneration system was accomplished by the application of algebra and rules similar to those used in thermoeconomic analysis for the evaluation of internal costs.

In modes C3 and C9 the environmental loads associated with waste heat were charged to the useful cogenerated heat,  $Q_{cc}$ .

## 4 RESULTS AND DISCUSSION

Based on the flow quantities entered in the input monitor, the system calculated the flows of the entire network using the transition specifications.



For comparison, a reference system (Figure 2) 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 examples C1 and C3 for the trigeneration and conventional systems.

**Figure 2.** Conventional system.

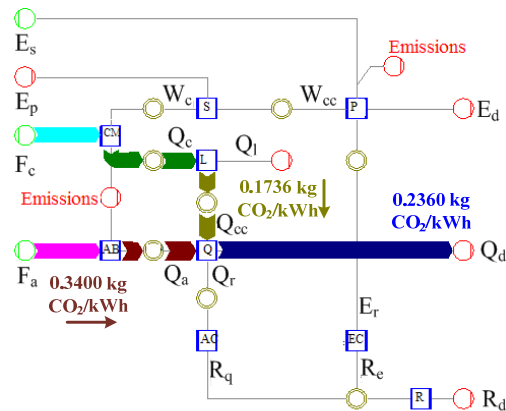
**Table 4.** Emissions (kg CO<sub>2</sub>/kWh) for example: Kingdom and Spain.

	United Kingdom				Spain			
	C1		C3		C1		C3	
	Trig	Conv	Trig	Conv	Trig	Conv	Trig	Conv
$E_d$	0.4656	0.5610	0.4536	0.5610	0.5357	0.3850	0.5545	0.3850
$Q_d$	0.1787	0.2575	0.2023	0.2575	0.2360	0.3400	0.2671	0.3400
$R_d$	0.1654	0.1122	0.3237	0.1122	0.2086	0.0770	0.4274	0.0770
TOTAL kg CO <sub>2</sub>	323.9	372.3	234.1	261.4	392.1	320.8	291.3	195.7

Umberto software answered the question of what amount of emissions (kg CO<sub>2</sub>/kWh) was associated with the consumption of each energy service. The results for Spain shown in Table 4 were not totally unexpected, and corroborate with the results of Carvalho *et al.* [2010a], in which it is confirmed that trigeneration systems have a great potential to reduce emissions, but this reduction depends on the energy consumption profiles and the fuel mix of the electric grid region. Thus, in the case of United Kingdom, in which natural gas and electricity mix emissions are, respectively, 0.206 kg CO<sub>2</sub>/kWh and 0.561 kg CO<sub>2</sub>/kWh [U.K. DEFRA, 2008], it can be observed in Table 4 that trigeneration reduces emissions, contributing to carbon offsetting. Carbon offsetting is the process of reducing the carbon emissions of activities, and in the UK the estimates of carbon offset by energy substitution are greater than those by sequestration, when considering realistic and achievable offsets [Cannell, 2003].

It is worthwhile to comment that the operation modes have been optimized from an economic viewpoint. The concept of wasting heat is not environmentally friendly as shown in example C3 for Spain; it could even be considered a potential threat to the climate [Nordell and Gervet, 2009]. Waste heat plays an important role in affecting the urban thermal environment, ambient air quality, and other attributes of the urban climate system, resulting in the Urban Heat Island (UHI) phenomenon [Fan and Sailor, 2005].

Umberto software uses diagrams to display materials, energy and cost flows. Figure 3 shows how the emissions associated with the consumption of heat ( $Q_d$ ) were formed in case C1 for Spain. A scaling variant (Maximum flow) was utilized for visualization purposes, so the maximum width in the network was limited to  $Q_d$ . All other values were calculated proportionally.



**Figure 3.** Emissions associated with the consumption of  $Q_d$  in example C1 for Spain.

## 5 CLOSURE

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.

A trigeneration system was modeled in Umberto software, with the flexibility to purchase/sell electricity from/to the 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  $\text{CO}_2$ .

By incorporating environmental information on the usage and consumption of resources into Umberto software, the approach of MFN gave insight on the environmental loads associated with each flow of the system. The use of Umberto software with LCA databases provided a relevant climate-related aspect. Flow analysis of individual production steps specific to operation made it possible to study the operational activities more precisely. Thus, the consumers of the trigeneration system knew the environmental loads associated with the consumption of each energy service (electricity, heat, and cooling).

Different allocation methods bring very different results, confirming the controversy as to what was the most appropriate allocation method and what was most logic in different situations. A rational distribution of costs or environmental loads toward the products in the cogeneration module must consider the nature of the operation mode [Lozano *et al.*, 2009a, 2009b]. Therefore, the issue of environmental allocation rules requires detailed analysis that will be presented in future work by the authors.

Strategies aiming at the mitigation of climate change link the reduction of emissions to the consumption of resources by a system. Changes in lifestyles and consumption patterns that emphasize resource conservation can contribute to developing an economy that is both equitable and sustainable [IPCC, 2007].

The application of EMIS and LCA tools could be promoted to i) analyze the distribution of material and energy resources throughout a productive system, ii) allow an emission-efficient economy to develop; iii) identify the most beneficial among competing technologies, and iv) serve the numerical registration and interpretation of environmental effects.



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