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Determination of the biomass content of waste: the software OBAMA

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Target of the project

The software OBAMA (Optimized Balance Method Applications) has been developed with the aim of realizing a flexible and fast tool in order to investigate dependencies of the amount of renewable energy from the waste for different plant and waste typologies, also connecting it with innovative measurement instrumentation developed in RSE.

It is based on the Optimized Balance Methodology, developed in the frame of the Electric System Research (RdS) activities on the base of the balance method described in the paper *"J. Fellner et alii - A new method to determine the ratio of energy production from fossil and biogenic sources in WTE plants – Env.Sci.Tech.,2007,41"*.

The software is used mainly to analyze real or hypothetic scenarios (e.g. changing parameters or analysis conditions) and their effect on the amount of renewable energy. It is also used for educational purposes

Basic items

1. Why using the indirect calculation methods
- Relevance of the determination of the correct biomass content of waste
- The optimized mass balance method as a low cost and easy-to-use methodology

2. The operating context of the optimized mass balance method
- The measured variables and the unknown variables
- The composition of the organic matter with special attention to different types of waste

3. Outlines of the model based on the mass and energy balances
- The balance equation system
- The measure uncertainties through the data reconciliation algorithm
- The evaluation of the biomass content and of the renewable energy

4. The OBAMA (Optimized BAlance Methodology Application) software
- Functional scheme and GUI
- Examples of analysis

Relevance of the determination of the correct biomass content of waste

Biomass → **Biomass definition includes the biodegradable fraction of products, waste and residual having biological, agricoltural, woodland and related activities origin and the biodegradable fraction of industrial and urban waste (2009/28/EC Directive)**

3D view of the designed WTE plant at Ferrara site

<u>It needs</u> to have some <u>criteria and methodologies</u> able to set the correct biomass content of "hybrid" waste , i.e. made up of a biogenic fraction (paper, wood, vegetables,..) and of a fossil fraction (plastic,..)

Sampling methods

classic
(based on laboratory analyses)

^{14}C
(based on ^{14}C isotope concentration in the CO_2 emissions)

optimized mass balance
(based on the numerical solution of a system of mass and energy balance equations)

Advantages and drawbacks of modeling tools

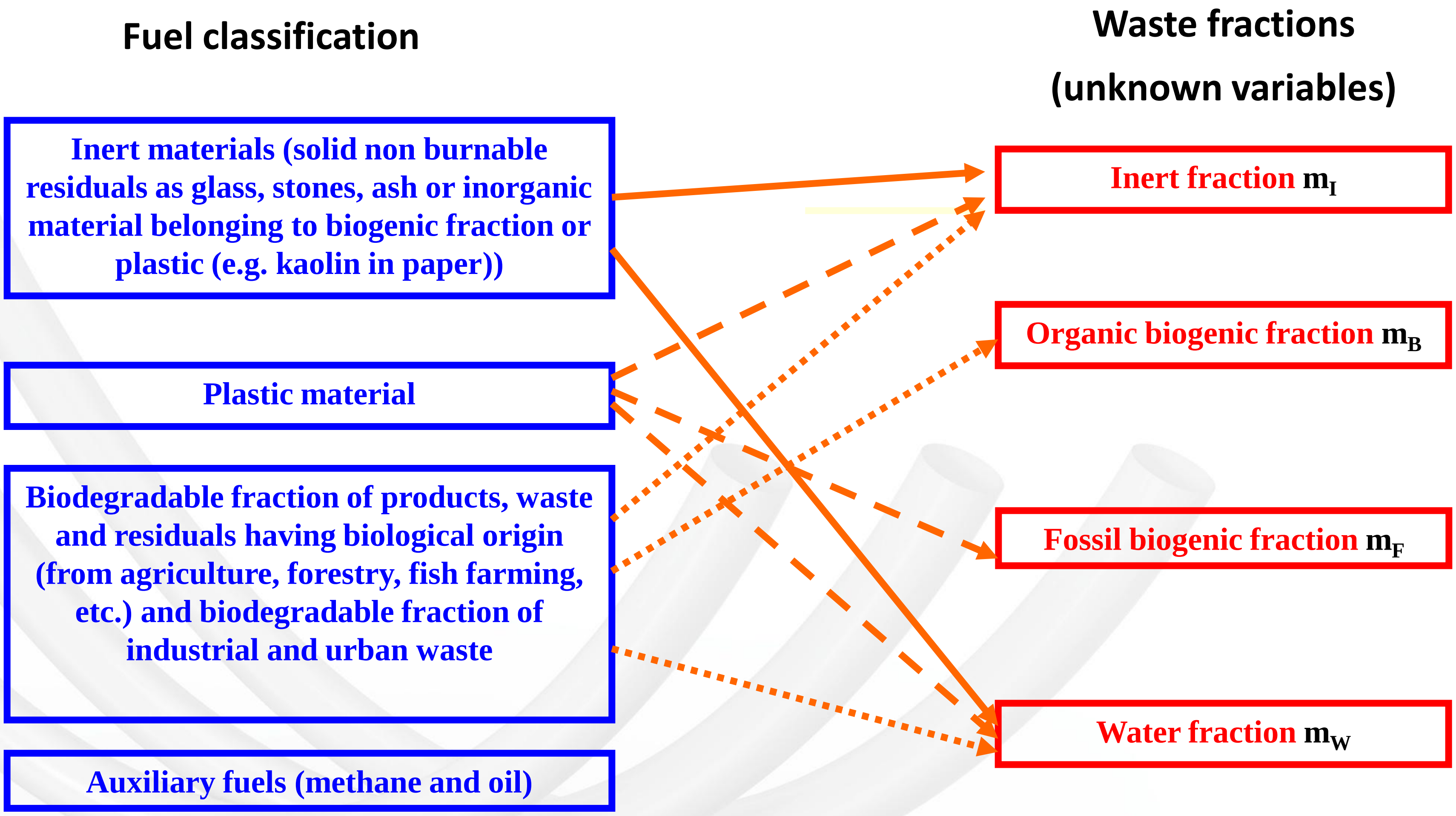
- **the use of classic sampling methods can be very expensive from the economic point of view and it can lead up to not very representative samples of the whole mass sent to the combustion process**

- **the ^{14}C sampling method can provide with continuity the mass ratio between the biogenic and fossil carbon content and the related ratio stated in terms of produced energy, but it is of instrumental type, i.e. it requires a special and complex measurement equipment**

- **the mass and energy balance method is based on the contrary on the numerical solution of an equation system and it provides with continuity the renewable amount of electric energy produced by WTE plants taking into account that:**

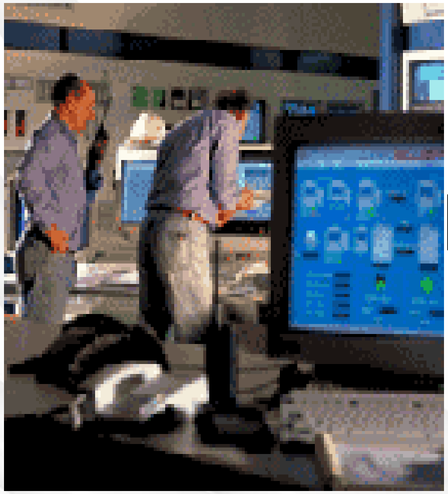
a. ***the required data comes from literature (e.g. the biomass chemical composition) and from operating data usually measured by plant instrumentation***
b. ***no additional sampling nor supplemental chemical analyses are required, resulting in a strong reduction of costs***
c. ***no special calculation resources are needed (a standard personal computer is enough)***

Outlines of the mass balance model: the unknown variables



Outlines of the mass balance model: the measured variables

The measured variables are the values of the plant data measured and recorded during time with an uncertainty depending on the accuracy of sensors and measurement methods. They are assigned as a mean value and an associated standard deviation, and usually they are registered with an assigned periodicity (e.g. any hour or half-hour)



Required value	Unit	Description	Uncertainty (typical values)
W_{tot}	kg/d	Mass of waste sent to WTE plant	5%
W_S	kg/d	Total solid dry and ash free mass	10%
V_{fumi}	Nm^3/d	Flue gas volume	5%
$x_{CO2,fumi}$	%vol	Percent of CO_2 in the flue gas	2%
$x_{O2,fumi}$	%vol	Percent of O_2 in the flue gas	2%
$x_{CO2,aria}$	%vol	Percent of CO_2 in the air	1%
$x_{O2,aria}$	%vol	Percent of O_2 in the air	1%
S_{vap}	kg/d	Steam production	5%
ΔH	MJ/kg	Net enthalpy	5%
H_u	%	Relative humidity in flue gas	5%
η	-	Boiler efficiency	10%
V_{CH4}	Nm^3/d	Auxiliary methane volume	5%
W_{Oil}	kg/d	Auxiliary oil mass	5%

Outlines of the mass balance model: the composition variables

The chemical composition of the fossil and biogenic material, dry and ash free, is required again as mean values and standard deviations; these composition variables are treated exactly as the measured variables

- **the composition values can be taken from literature data with reference to the particular waste classification, and usually they have a small range of variability**
- **the composition values are required for elements C, H, O, N, S and for Cl if significative**
- **the composition values can also be provided by exhaustive laboratory analyses. Literature data can be substituted in the model by more specific measurement information, when available**

	biogenic		*fossil*	
	value	*σ*	*value*	*σ*
x_C	468	6.9	769	20.0
x_H	66	1.1	109	7.0
x_O	446	8.3	88	22.0
x_N	12	1.6	13	5.4
x_S	3.3	0.7	3	1.1

Example of table for urban waste [from Fellner et alii (2007)]

	biogenic		*fossil*	
	value	*σ*	*value*	*σ*
x_C	461.15	10	706	10.0
x_H	62.36	2	95.17	2
x_O	462.42	5	173.81	5
x_N	3.24	1	3.23	1
x_S	1.5	1	0.43	1
x_{Cl}	=	=	21.4	3

Example of table for HCW-HR [from DB-WASTE of RSE]

The mass balance model: the equations

The model is based on the numerical solution of a system of five mass balance equations and of an energy balance equation, in the unknown variables m_B, m_I, m_F and m_W:

a) total mass balance equation

$$m_B + m_I + m_F + m_W = 1$$

b) ash balance equation

$$m_I = \frac{\sum W_S}{W_{tot}}$$

c) carbon balance equation

$$m_B x_{C_B} + m_F x_{C_F} = \frac{\left\{ V_{fumi} \left[x_{CO_{2,fumi}} - x_{CO_{2,aria}} \frac{100 - x_{O_{2.fumi}} - x_{CO_{2,fumi}}}{100 - x_{O_{2.aria}} - x_{CO_{2,aria}}} \right] \frac{W_C}{100 V_m} \right\}}{W_{tot}} - \frac{x_{Cng} V_{ng} + x_{Coc}(W_{occ} + W_{ocp})}{W_{tot}}$$

d) oxigen and CO_2 balance equation

$$m_B \left(\frac{x_{H_B}}{4M_H} - \frac{x_{O_B}}{2M_O} + \frac{x_{N_B}}{M_N} + \frac{x_{S_B}}{M_S} \right) + m_F \left(\frac{x_{H_F}}{4M_H} - \frac{x_{O_F}}{2M_O} + \frac{x_{N_F}}{M_N} + \frac{x_{S_F}}{M_S} \right) =$$

$$\frac{\left\{ V_{fumi} \left[(x_{CO_{2,aria}} + x_{O_{2,aria}}) \frac{100 - x_{O_{2.fumi}} - x_{CO_{2,fumi}}}{100 - x_{O_{2.aria}} - x_{CO_{2,aria}}} - (x_{CO_{2,fumi}} + x_{O_{2,fumi}}) \right] \frac{1}{100 V_m} \right\}}{W_{tot}} - \frac{\frac{x_{Hng}}{4M_H} V_{ng} + \frac{x_{Hoc}}{4M_H}(W_{occ+} W_{ocp})}{W_{tot}}$$

e) water balance equation

$$m_B \frac{x_{H_B}}{4M_H} + m_F \frac{x_{H_F}}{4M_H} + m_W + \frac{\frac{x_{Hng}}{4M_H} V_{ng} + \frac{x_{Hoc}}{4M_H}(W_{occ+} W_{ocp})}{W_{tot}} = \frac{\left\{ V_{fumi} \frac{Hu}{100 V_m} \right\}}{W_{tot}}$$

f) energy balance equation

$$m_B \left(PCI_C x_{C_B} + PCI_H x_{H_B} - PCI_O x_{O_B} + PCI_N x_{N_B} + PCI_S x_{S_B} \right) +$$
$$m_F \left(PCI_C x_{C_F} + PCI_H x_{H_F} - PCI_O x_{O_F} + PCI_N x_{N_F} + PCI_S x_{S_F} \right) =$$
$$\frac{\left\{ S_{vap} \frac{\Delta H}{\eta} \right\}}{W_{tot}} - \frac{H_{ng} V_{ng} + H_{oc}(W_{occ} + W_{ocp})}{W_{tot}} + L_{vap} m_W$$

The numerical calculation scheme

- the **a-f equation system is mathematically overestimated** being the number of equations (six) greater than the number of unknown variables (four)
- the **equation coefficients are not exactly established since they depend on the measured and composition variables**, affected by uncertainty

⇩

- as the consequence, **the data reconciliation algorithm** is considered in order to improve the accuracy of the measured data

⇩

- the improved measured data are then used to estimate more accurate coefficient values and to **evaluate the correct values of unknown variables m_I, m_B, m_F, m_W** and their uncertainties

⇩

- since **the numerical system is not linear**, the data reconciliation algorithm is linearized and the system is solved iteratively; the linearization is based on the Crowe projection matrix technique

⇩

The model requires a multistep iterative solution

The data reconciliation algorithm: short outlines

The data reconciliation algorithm include a number of mathematical and statistical tools that allow to detect the errors in a set of measurements and which parameters are involved in a number of balance equation describing a physical process (e.g. chemical, mining or combustion processes).

The reconciliation algorithm, provided that the system that must be solved is overestimated, quantify these errors, both for systematic and random ones, and they return a set of measurement "cleaned" from the errors themselves.

The detection of errors in measurements is the base of a smart monitoring, since the presence of measurement errors can indicate material losses, sensor malfunctioning or instrument lack of calibration.

The improvements provided by the data reconciliation algorithmis more clear when the measurements are used as input values of mathematical models devoted to a process control: the input values to a model must be validated, otherwise also the better mathematical model, when considers incorrect data, will provide incorrect results

The data reconciliation algorithm: calculation scheme

- is typical of **numerical system including measured and unknown variables**
- is basically expressed as a problem of **weighted leasted squares optimization**

$$Min\left\{\frac{1}{2}(x_m - x)^T \Sigma^{-1}(x_m - x)\right\}$$

where:
x is the array of N measured variables
x_m is the array of the corresponding N measured values

Σ is the variace-covariance matrix of range N for the measured variables

- the optimization condition is then completed by **non-linear constraints**:

$$f(x, y, z)=0$$

where:
x is the array of the N measured variables
y is the array of the K unknown variables
z is the array of the M constant values
f is the unspecified system equation

The renewable amount of electric energy

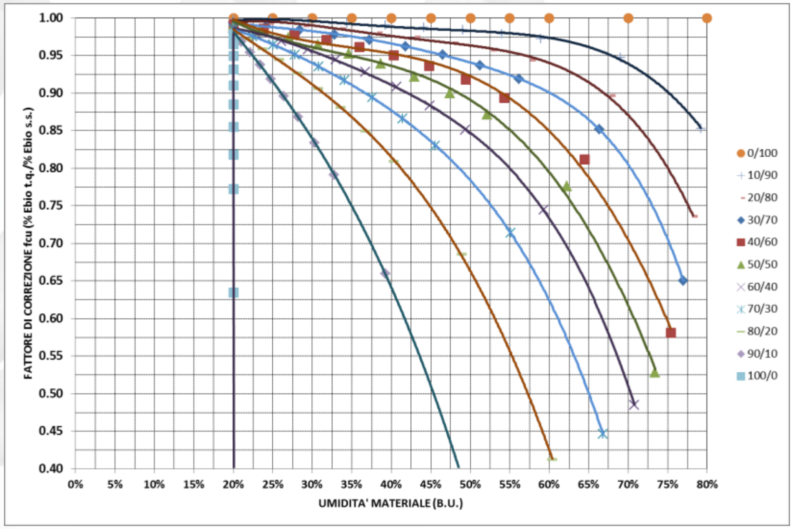
The final result provided by the optimized mass balance model is the calculation of the amount of renewable energy generated

On the base of the values resulting from calculation for the biogenic fraction m_B the amount of renewable energy is:

$$E_{bio} = \frac{m_B(PCI_C x_{CB} + PCI_H x_{HB} - PCI_O x_{OB} + PCI_N x_{NB} + PCI_S x_{SB})}{\dfrac{S_{vap}\Delta h}{W_{tot}\eta} + L_{vap} m_W - \dfrac{H_{ng}V_{ng} + H_{oc}(W_{occ} + W_{ocp})}{W_{tot}}}$$

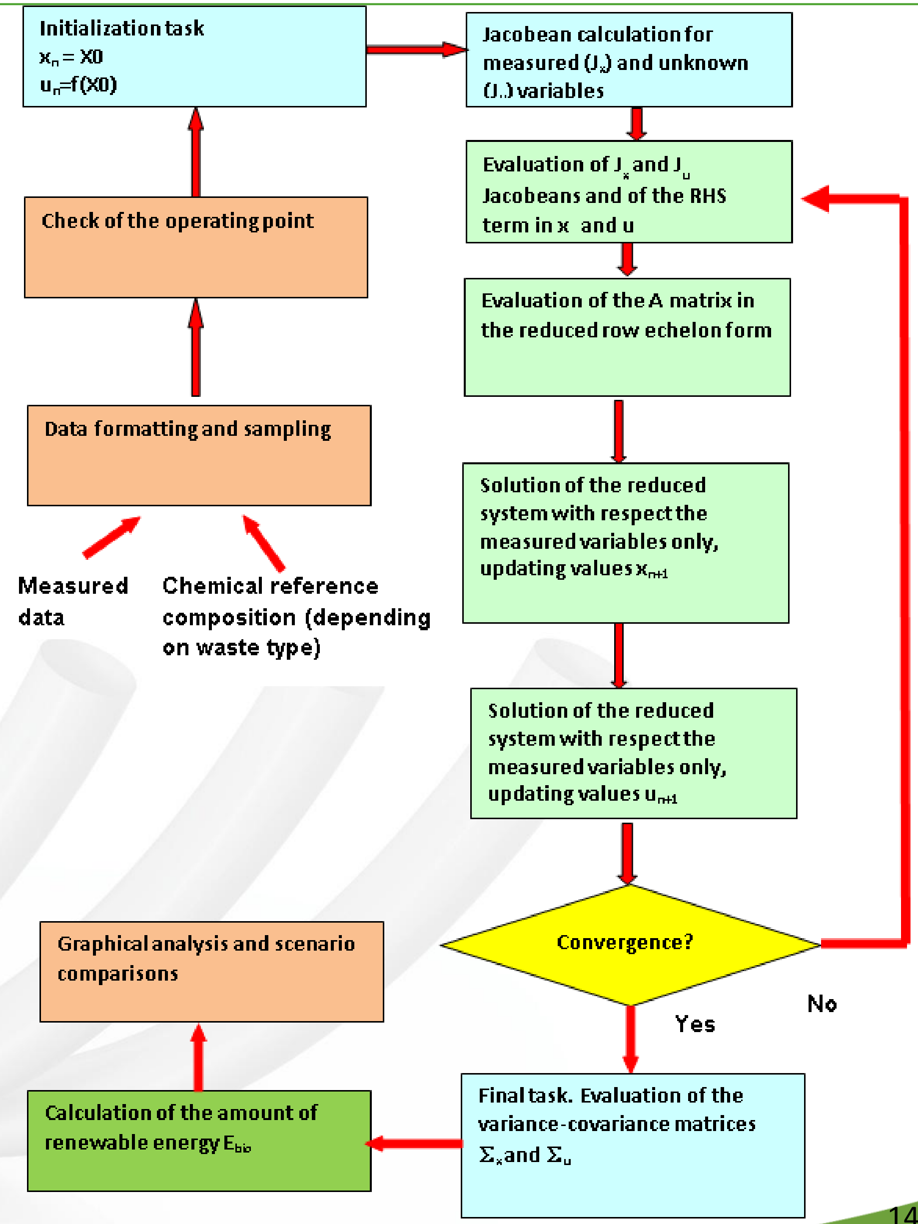
being L_{vap} the latent heat of vaporization of water (2.44 MJ/kg at 20.4 C and 1 atm)

The treatment of the different water content in the fossil and biogenic fractions is also considered using an approach dependent on waste characterization and ash contents
(Riva, 2011)



The OBAMA software functional scheme

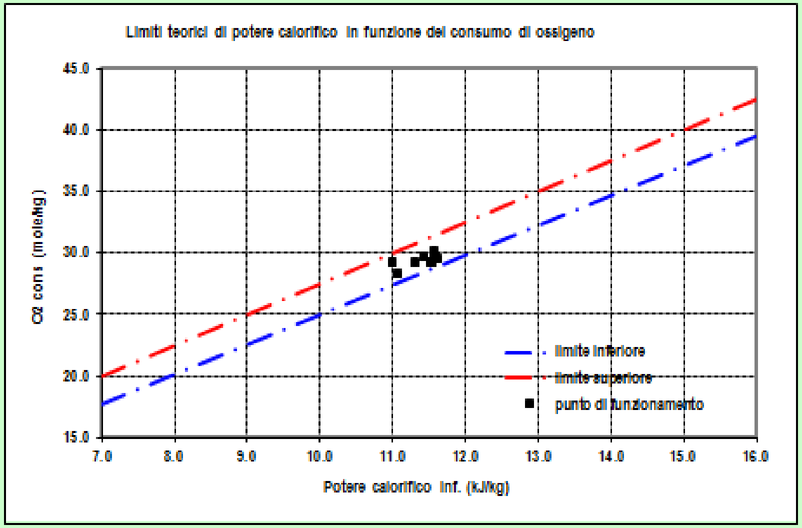
The model based on the optimized mass and energy balance method has been implemented in the OBAMA software

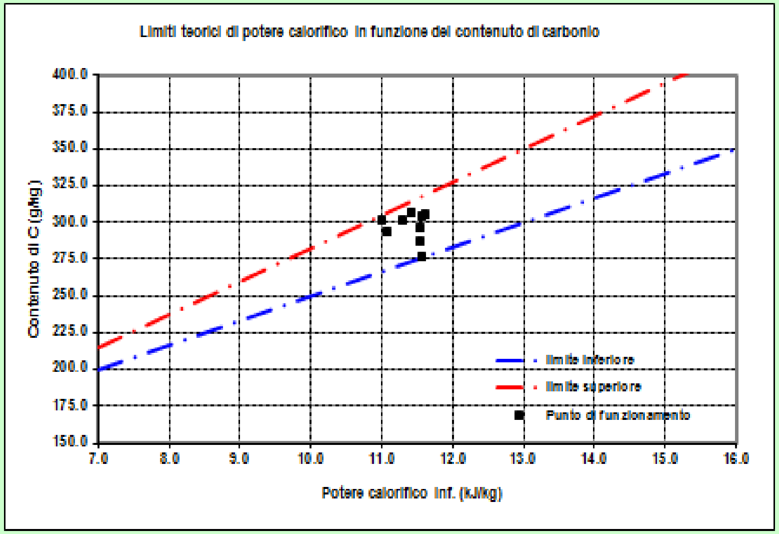


Congruence check at the operating point

- the values of measured variables often have a low accuracy
- instrumentation failures can occur including non physical values in the measured data set

therefore it is necessary to check the physical acceptability of each set of data; this is possible performing a data congruence check based on the fact that the flue gas and the steam production values at each operating point are connected between them, with a well defined PCI: the carbon content and the oxygen consumption must fall at the PCI value between two theoretical extreme values considering a100% fossil material and a 100% biogenic material respectively





The OBAMA GUI

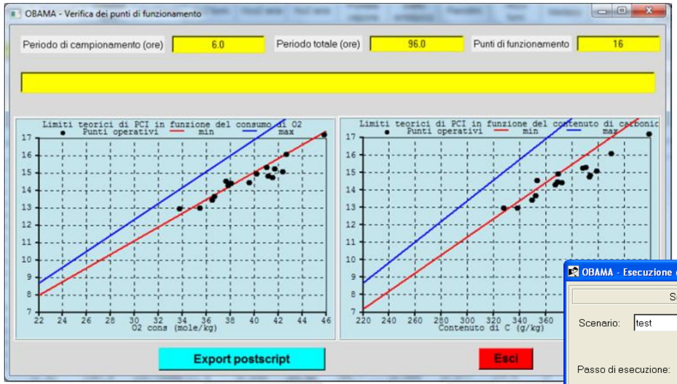
A proper GUI has been developed with the aim of:

a) easily define a scenario of analysis and automatically create the input data set

b) performing automatically the check of data congruence

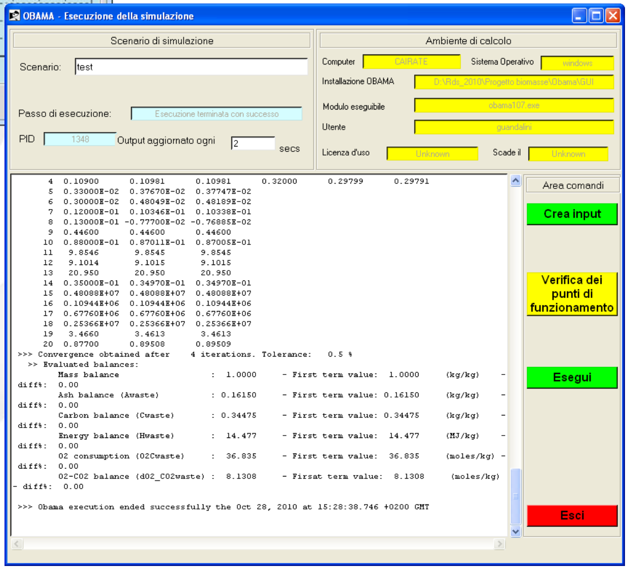
c) managing and solving the system independently on the running platform

d) performing an immediate graphical analysis of the results

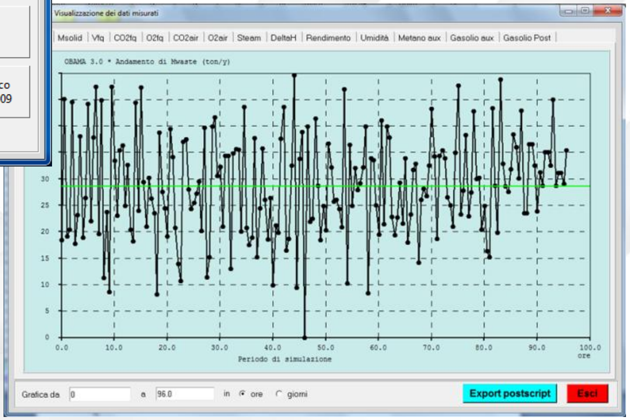


Operating point check

Execution manager



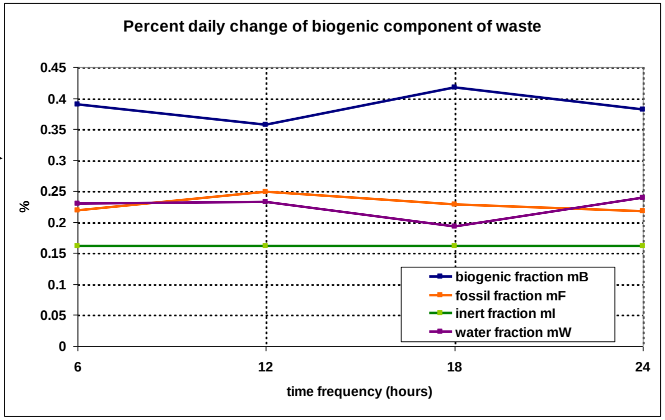
Session manager

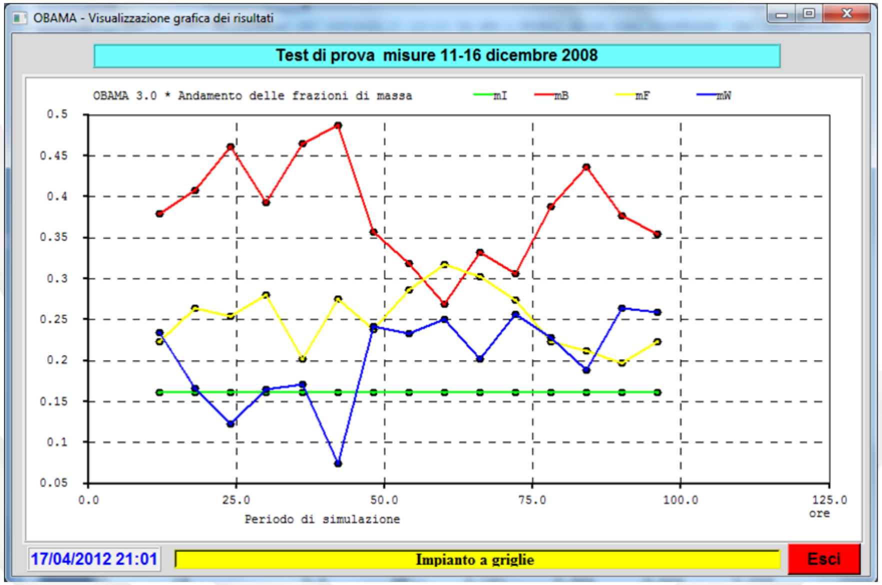


Graphic analysis of measured data

Examples of analysis

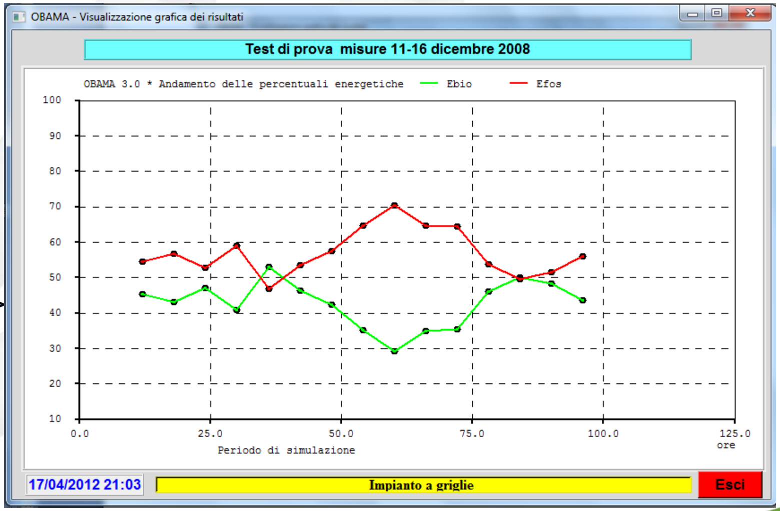
Use of the model for parametric analyses (e.g. evaluation any six hours against daily)



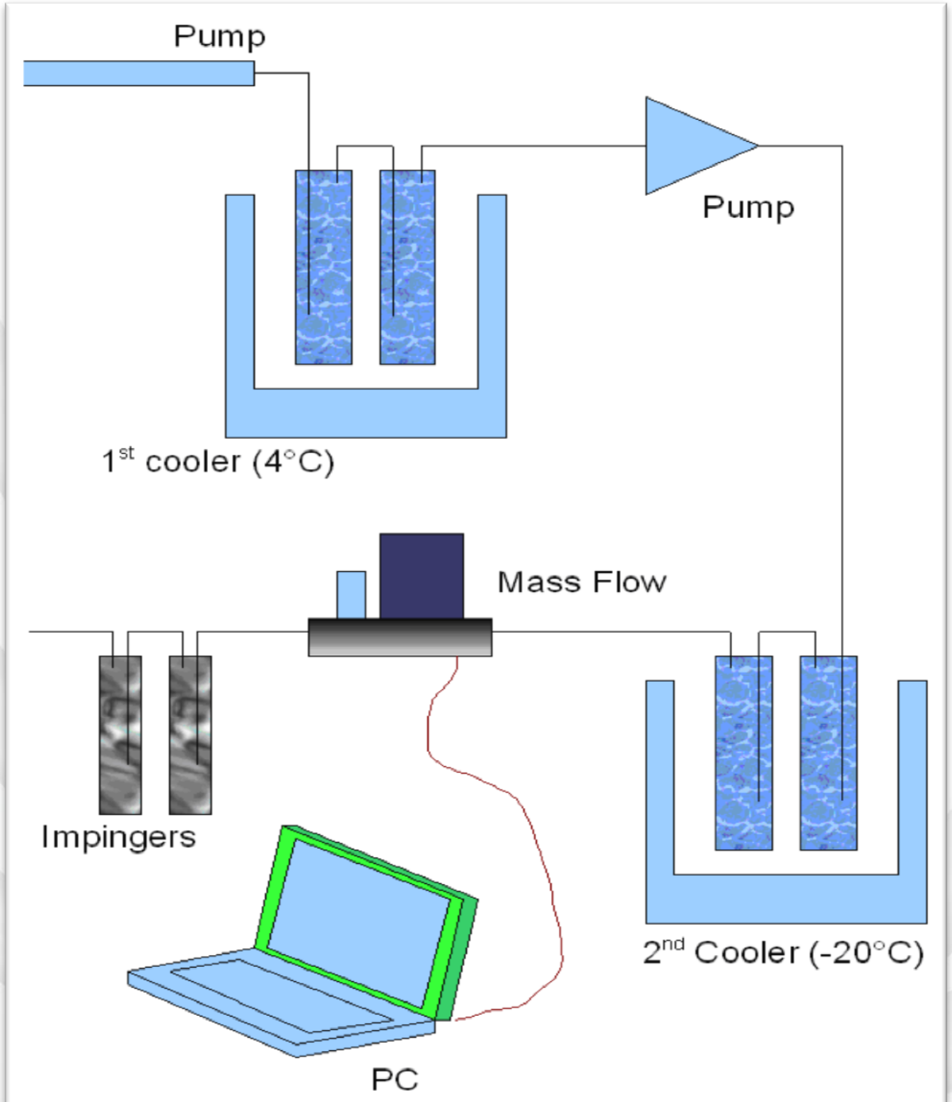


Evaluation of the material fractions during a test period

Evaluation of the energy produced from biogenic mass during a test period



The connection with experimental system



OBAMA results can be compared with the experimental system pointed out at RSE

Operating conditions:

- Adsorbing solutions: KOH at 4M concentration and Carbosorb (CH_3-O-C_3H_6-NH_2)
- Treated quantity: between 10 and 100 g
- Flow: from 30 to 500 ml/min
- Test duration: from 2 to 24 h
- Target efficiency: about 80% for KOH and from 40 to 70% for Carbosorb
- Test samples in a day: from 1 to 4

Final considerations

- **OBAMA has been developed with the aim of evaluating the biomass contents of waste and the production of renewable energy both in real and perturbed scenarios, also in connection with experimental instrumentation**

- **Different waste types or mixtures of them can be considered:**
  - **urban waste**
  - **HCW-HR**
  - **refuse derived fuels**

- **Different plants type are also considered including**
  - **fluised bed**
  - **biomass boiler with removable step-grate**
  - **rotary kiln**

Thanks for your attention!

How to contact us:

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