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A Procedure for Early Environmental Assessment of Industrial Products

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Abstract

The paper presents a procedure that a designer can use in the early phase of product development in order to assess the environmental impact of the solution on which he/she is working on.

Several methodologies are employed for this purpose, but basically we focus the attention on the functional analysis by means of its graph structure and the DSM, Design Structure Matrix. Both methods share the matrix format to manage functionalities and the relations among them or components and the connections among them.

The original DSM format has been modified, introducing new records where the interaction with the environment outside is recorded. A set of rules have been defined by which it is possible to reach a rough assessment of the environmental impact.
The paper discusses the employment of the methodology with a test case.

1 Introduction

The issue of sustainability of industrial products is a subject of scientific research and debate since several years. This topic is very important for the implications that design decisions have on the environment and society when products are sold in the markets.

Although today products can be assessed by methodologies such as Life Cycle Assessment (LCA) and related software, a vivid interest in their environmental evaluation, already in conceptual design phase, is developing in recent times.

The problem of assessment in early design has been discussed in two papers in recent literature, e.g. Devanthan et al. [1] and Bohm et al [2]. This fact gives us the opportunity to investigate on further aspects of this topic, especially on how designers can be supported in an early product evaluation.

In conceptual phase, where ideas and solutions can begin to be analyzed, designers can focus their attention on some parameters related to sustainability. Therefore, appropriate tools and methods to support concept selection on the basis of an environmental assessment are required.

Considering that to select an absolute index for environmental impact is not easy to reach in this stage and that a single quantitative method is not consolidated, in this paper, a proposal of methodology to assist designers is presented.

The present method exploits the well-established visual tool as the Design Structure Matrix (DSM), which is considered by several researches very suitable in product decomposition and, in this case, it is used also to verify the correctness of a product conceptual schema.

In the next sections, after a brief review on the latest researches on environmental assessments in early design process, the methodology is described in detail, defining data structures, presenting a formalization of rules that could guide it and providing an application to a case study.

2 Background

Several authors have discussed about environmental issues connected to product design and someone of these proposed to anticipate environmental considerations in the early design stage.

The methodology described by Devanathan [1] e.g. combines life cycle assessment with tools like quality function deployment, functional-component matrix and a new visual tool, called function Impact matrix, that is used to match environmental impacts with product functions. This approach can be considered very interesting, because it can be applied in early design stage and offers a semi-quantitative method of analysis.

The theme of environmental impact in early design is discussed also in terms of automated concept generation and product design knowledge [2], using a design repository. LCA is used to determine the environmental impacts of the concepts, trying to analyse identified real-life products that have functional similarities with the conceptual elements under evaluation. Then, the assessment is predicted on the basis of the information contained in the repository.

Yang and Song [3] also propose an approach to assess product sustainability in conceptual design stage. They discuss about an evaluation model developed to represent different environmental considerations through product lifecycle. Each design option is assessed respecting some hierarchical evaluation criteria and applying lifecycle engineering methods, such as LCA and Life Cycle Costing analysis. This methodology is proposed in a decision-support software prototype.

It is interesting to note the use of matrices already in the early design. Among the methods that employ this kind of representation we will focus on the Design Structure Matrix, used for static and dynamic applications. Browning [4] discusses about two types of DSM, static and time-based, showing several applications like: system component modelling facilitated by architectural decomposition strategies; the usage in organizational work; information flow management among process activities; integration of low-level design processes based on liaisons of physical design parameters.

Hong and Park [5] also deal with the subject of DSM, treating the decomposition of system into modules. They present a rational method linking DSM to Axiomatic Design and showing relationships between functional requirements and design parameters.

On this theme Pimmler and Eppinger [6] offer a great hint to our work. They suggest to use a DSM matrix to describe the interactions among product elements, quantified through a five-point scale (-2, -1, 0, 1, 2) and based on four types of interaction: Spatial, Energy, Information and Material .

DSM is discussed jointly to product Functional Analysis. The net, which is often managed as a graph, can be supported by a matrix formulation [7] (associated to a clustered graph model) to aid designers during the conceptual phase of product development.

These previous researches allow us to make some further considerations and to develop our proposal of assessment tool.

3 Methodology

The present methodology proposes to evaluate the impact of different product architectures during conceptual phase. During product conception, designers can model a functional net by means of a graph structure [8] and produce a set of solutions, each one characterized by a proper own architecture or peculiarity. Each functional net version can be translated into a Design Structure Matrix (see figure 1) with the aim to manage its complexity and, afterwards, to aid a reasoning towards the most sustainable solution.

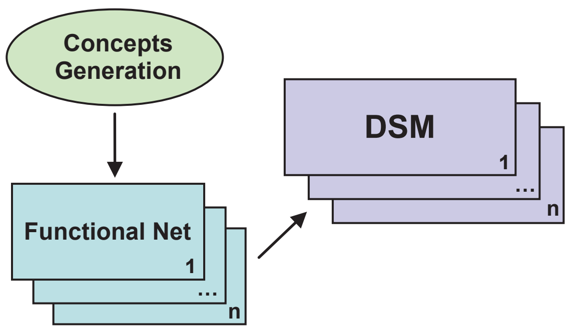


Fig. 1 Method paradigm

After the designer have drawn a functional net with its different versions, he/she can edit the related DSMs and compare them analyzing values in the matrices and component environmental indices.

The links involved in this DSM-based tool are:

1. Force. The Force link contains information related to mechanical relations between couples of components (e.g. contacts) to indicate mutual interactions;
2. Signal. Essentially, it represents an asynchronous notification sent to a process in order to notify it, to regulate interactions among sub-process and components or to indicate events that are occurred;
3. Material. This kind of functional link defines flows of substances that are involved mainly during device use;
4. Energy. This functional link is related to the energy interchanged among nodes and can have various meanings in different contexts (electric, mechanical, thermal, etc.).

The proposed procedure exploits a more complex DSM, that allows developers to collect data from links present in functional network and to show interactions exchanged in whole product and between it and environment. Moreover, matrix structure contains a set of indices that characterizes each component, with the aim to provide information about its life cycle.

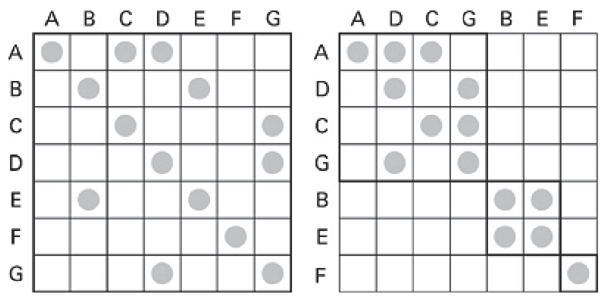
Furthermore, the DSM checks the consistency of a functional network, which is very articulated sometimes. It is modeled as a superposition of four layers related to the functional links, three of which defined as directed sub-graphs and one as an undirected sub-graph [8] (Force contact).

In order to describe the methodology in detail, it is necessary to discuss about data structures used and rules employed in the assessment.

3.1 Definitions: DSM

The Design Structure Matrix (DSM) is a particular N-square [9] matrix used in several contexts, especially in product/project decomposition, and it is considered a consolidated approach to manage complexity.

In literature, diagonal cells represent system elements and off-diagonal cells are used to record relationships among them. Here, the employed DSM is static, because it represents the entire system and all elements are present simultaneously. In figure 2, two examples of DSM are reported.



a) b)

Fig.2 a) An example of DSM; b) A clustered DSM (Courtesy of Tomiyama et al. [9])

As in the example above, both matrices are associated to the same product, but the second one has been subjected to a clustering activity, that can be applied to a not clustered matrix or not be necessary, as grouped elements could derive naturally by a clustered graph.

In the present context DSM is drawn on the basis of information provided by functional net, but only when a middle/high degree of detail is defined, the analysis is performed in a fixed instant of time and when functional nodes have reached the state of components. This fact suggests that it is possible to generate n different DSMs, one for each product configuration obtained.

3.2 Data Structures: Augmented DSM

The early environmental evaluation of a functional net requires a more complex matrix, structured in sections and presenting particular contents in diagonal and off-diagonal terms.

On the base this new DSM, called “Augmented DSM”, it is possible to have a functional check on the clustered net, to manage real values exchanged among system elements and to aid designer in an evaluation as quantitative as possible (figure 3).

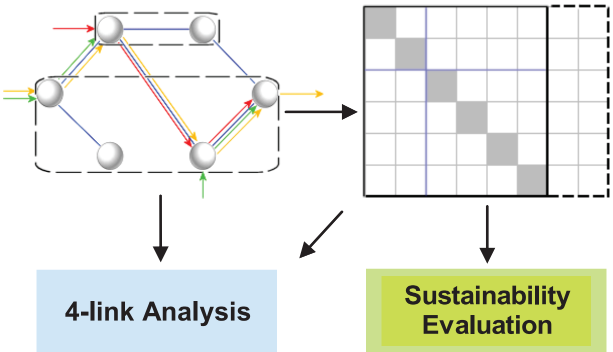


Fig 3 A-DSM method workflow

Augmented DSM (A-DSM) is composed of three sections:

- a DSM, where data about the four functional links are contained;
- two columns Ω1 (“External Relations”) and Ω2 (“Sustainability Issues”), where designer can collect links in input and output with outside. Both are edited collecting values that have negative and positive sign and are inserted as additional columns.

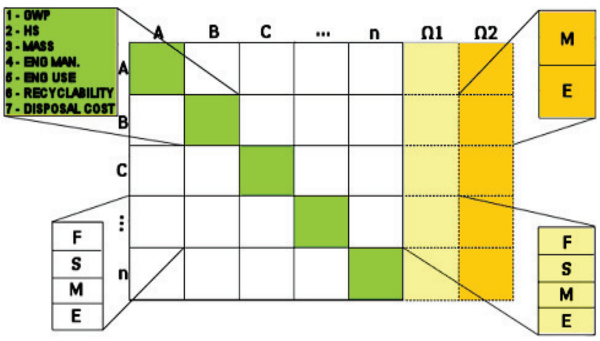


Fig. 4 Augmented- DSM

The first section of A-DSM is a special N-square matrix, in which n components are matched. A set of environmental indicators is stored in each diagonal element. They are related to the “Product Life Cycle” of specific component, in particular, to three of the typical stages of lifecycle: Raw Material, Manufacturing and Disposal. These indicators, described in next paragraph, can be calculated by formulas present in literature and by means of LCA software. However, indices in diagonal terms are discussed in theoretical way here and are not employed in the case study.

Off-diagonal elements, instead, are related to the Use phase, when product is performing. An example of A-DSM is presented in figure 4, whereas the content of the cells and the entire matrix drawing procedure are described below.

3.2.1 A-DSM editing: diagonal terms

Sustainability indicators describe each component individually. The set of parameters, that is represented by an array of 7 elements, is proposed in the methodology and includes:

1. Global Warming Potential GWP of the component. It indicates how much a GHG (Green House Gas) contributes to global warming. It can be calculated on the basis of formulations provided by the Intergovernmental Panel on Climate Change, or tabulated values [10] selecting a time horizon (25, 100, 500 years). In practice, it is measured in kilograms of CO2eq, converting each GHG with some conversion factors;
2. Presence of hazardous substances in raw material. It is a boolean value (1 if yes, 0 else);
3. Mass. It is a measure present in every LCA analysis and software tools. It is expressed i.e. in Kg, Kg/sec (in case of flows), etc;
4. Energy index in manufacturing phase. It measures the energy employed in component construction; it can be expressed in J, Wh, kWh, etc;
5. Energy index in use phase. This value is provided by constructor. It is present in every device (i.e. output power) and it is calculated in J/s, kW, etc.;
6. Recyclability. It is calculated as a ratio between the weight of recyclable materials divided by the total weight of product [11]. It is dimensionless;
7. Disposal Cost. They are expressed in €.

3.2.2 A-DSM editing: off-diagonal terms

In the off-diagonal terms, numerical values have to be recorded. They correspond to the four links of Force, Signal, Material, and Energy, as represented in functional network, and are collected in an array composed of four positions edited as follows:

- in Force sub-cell, the value is binary (in absolute value), 1 if there is a physical connection, 0 else;
- in Signal sub-cell, the value is -1 if a signal is in, 1 if it is out, 0 else;
- in Material sub-cell, the value is a decimal type and can be positive, if the link is in output, or negative if the link is in input;
- in Energy sub-cell, the value is a decimal type and can be positive, if the link is in output, or negative in case of link in input.

Interactions between device and environment have to be edited in the two columns Ω1 and Ω2 placed on the right side. The first one shows useful input/output or links by which product is connected to other devices; the second one displays links representing undesirable input/output, like energy losses and waste materials.

Discussing about A-DSM properties, it is necessary to make three considerations: the values of material and energy are provided with a negative or a positive sign according with flows in or out, respectively; the N-square matrix is symmetric in absolute value respect to the diagonal; column Ω2 is composed of cells divided in two parts in order to map only two type of functional links: Material and Energy.

4 Assessment procedure

After having described how the A-DSM is composed, it is necessary to formalize an assessment procedure for the conceived product, analyzing the entire functional network.

The analysis assists designer for two purposes:

- to discuss issues related to used components and their nature;
- to check the quality of energy and material flows exchanged among components and between the device and the environment.

4.1 Component Sustainability Indices

First of all, designers can evaluate product on the basis of data represented in diagonal terms in a generic instance of A-DSM *A*, which will have dimension [n, n+2] in the procedure. I_i is the set of *h* environmental performance indicators present in each diagonal cell and acting on each component represented by diagonal element *A(i,i),* in fact $I_i = \{I_i(h) \mid h = 1 \ldots 7\}$. For each indicator *h* is possible to calculate:

$$D(h) = \sum_{i=1}^{n} I_i(h) \tag{1}$$

where *D(h)* is the overall index that takes into account all components represented by A(i,i) terms; $I_i(h)$ is the h-th indicator of A(i,i) element.

Then, for a generic conceptual solution found *S*, the vector *D(S)*, presenting all seven sustainability indices, can be calculated. If a designer generates a set *r* of solutions, each one modeled by a functional net and the related vector D(S), he/she can make the necessary considerations about which is the best compromise of values and select the best product configuration.

4.2 Material flow evaluation

Designers collect values related to material flow exchanged among parts in the cells of A where i ≠ j.

The material link is represented by a digraph and it is subjected to flow conservation constraints [12]. Flow is not dispersed, although the state of material can change during product performance.

In every row, It is possible to control material quantities in input and output, reasoning on component properties, indeed, it can be a source, a transit node or a storage.

Below a procedure to control functional net, analyzing A-DSM, is presented. Index *i* represents row counter; index *j* represents column counter and *k* indicates the sub-cell of element A(i,j), k = 1,...,4

Initialization. Consider only Material links; i = 1; fix k = 3 (material sub-cell).

1. Analyze the component for each row and calculate Node Balance, called NB, until i = n:

$$NB(i,3) = \sum_{j=1}^{n+2} A(i,j,3) \tag{2}$$

   where *A(i,j,3)* is the sub-cell 3 of the element A(i,j); *NB(i,3)* is the node balance of the i-th row, related to i-th component respectively, calculated on the third link. Then, analyze these cases:
   - If NB(i,3) > 0 → component i is a source;
   - If NB(i,3) = 0 → component i is a transit node;
   - If NB(i,3) < 0 → component i is a storage unit.
2. Verify the presence of Force link, if element A(i,j,3) is enhanced, in order to support a deeper reasoning on a consistent functional net:
   - If A(i,j,3) = value AND A(i,j,1) = 1 → ok, else check functional net.
3. Analyze Ω2 (j=n+2) and calculate the sum of terms with positive sign (+) related to material link (k=1):

$$\alpha = \sum_{i=1}^{n} A(i, j, 3) \tag{3}$$

4. Repeat step 1, 2, and 3 for each solution found.
5. Select α(S)* as best solution:

$$\alpha(S)^* = \min \alpha(S) \tag{4}$$

   where *α(S)* is the total value of waste materials connected to the generic configuration *S*; *α(S)** is the minimum of the value α(S) calculated among the all configurations found.

4.3 Energy flow evaluation

In the cells of A where i ≠ j, designer collects values of energy exchanged among components in functional network on the basis of editing criteria described in sub-section 3.2.2.

It is necessary to consider that in functional schema energy layer is represented by a digraph and the property of energy flow conservation [12] is valid.

In every row it is possible to check energy quantities in input and output, verifying if components are i.e. transit nodes, generators or passive elements.

Below, a procedure to check functional net is presented. Here, index *i* represents row counter; index *j* represents column counter; *k* indicates the element A(i,j) sub-cell, representing link types (k = 1,...,4).

Initialization. Consider only Energy links (energy layer); i = 1; fix k = 4 (energy sub-cell).

1. Analyze each row corresponding to its component and calculate Node Balance (NB) until i = n. For each component we have that:

$$NB(i,4) = \sum_{j=1}^{n+2} A(i,j,4) \tag{2}$$

   where *A(i,j,4)* is the sub-cell 4 of the element A(i,j); *NB(i,4)* is the node balance of the i-th row, related to i-th component respectively, calculated on the fourth link. Then, analyze these cases:
   - If NB(i,4) > 0 → component i is a generator;
   - If NB(i,4) = 0 → component i is a transit node;
   - If NB(i,4) < 0 → component is a dissipator / heat sink / other passive element.
2. Verify the presence of Force link if element A(i,j,4) is enhanced, in order to support a deeper reasoning about a consistent functional net:
   - If A(i,j,4) = value AND A(i,j,1) = 1 → ok, else check functional net.

3. Analyze Ω2 (j=n+2) and calculate the sum of terms with positive sign (+) related to energy link (k=2):

$$\beta = \sum_{i=1}^{n} A(i, j, 4) \quad (3)$$

4. Repeat step 1, 2 and 3 for a number *r* of solutions found.
5. Select β(S)* as best solution:

$$\beta(S)^* = \min \beta(S) \quad (4)$$

where *β(S)* is the total value of energy losses connected to the generic product configuration S and *β(S)** is the minimum value of β(S), calculated among the all configurations found.

5 Case study

The methodology has been applied to a micro-gas turbine. The device is used mainly for electric power generation in several contexts, moreover it is widely used also for cogeneration purposes. In the present case study, assessment is conducted on two micro-turbines having the same power class, but some differences in terms of components.

Device architecture is represented in a functional network and processed with an A-DSM. The case study is focused on the evaluation of energy and material flows, furthermore, the presence of force contacts is checked. In the A-DSM of the present case study, energy is expressed in kJ/kg and kilowatts (thermal, electrical, mechanical); material flow is expressed in kg/sec; force link is indicated with a binary value, whereas signal links are not provided in this specific representation.

5.1 Application and results

The analysis evaluates energy and material output for two configurations of the same device. A low level of detail it is assumed, but it is enough to enhance the flows of interest. The links represented are the follows:

- air, water, fuel, combustion gases (material);
- specific heat; thermal power, electrical power, mechanical power (energy);
- force contacts.

It is possible to evaluate first turbo-gas schema. The device, in this case, includes five components:

- one air compressor (A). It pressurizes the air supply to the pressure required by the turbine;
- one air heater (B). It recovers part of the heat energy contained in the flue gas in order to heat the air to be sent in a combustor unit;
- one combustor (C). It makes the combustion of gas supply according to reports of excess air;
- one turbine (D). It expands the gases produced by combustion and generates mechanical energy by the rotation of its axis;
- one electrical generator (E). It generates electricity at low frequency by means of a static converter and an inverter.

Component A compresses the air flow in input, which is heated by component B. The air from B and pressurized fuel (in input by outside) arrive in C for combustion that produces gases to be sent in turbine D. Here, the turbine produces mechanical power for electrical generator E that converts it in electrical energy (155,8 kWe). Some Combustion gases exit from D with a lower specific heat and return in heater B, which release 0,821 kg/sec of gases, which corresponds to 190 kWth of thermal power not employed.

The representation below shows energy, material and force connections among components. Functional net can be modeled as represented in figure 5.

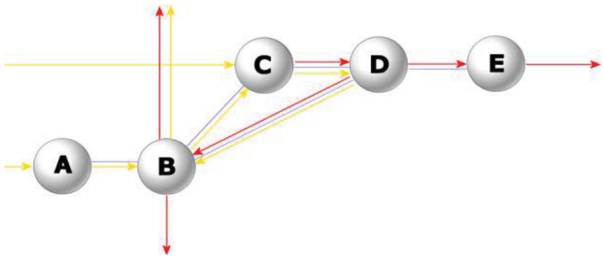


Fig.5 Functional net of the first micro-gas turbine (S1)

Then, the product schema is subjected to system decomposition by the Augmented DSM in figure 7 (DSM 1).

Analyzing column Ω2 in figure 7, we can estimate 211 kW of thermal energy losses, related to the air heater B (in fact thermal power of gases can not be used directly without a recovery system), and 8,2 kW derived by the inefficiency of the electric generator (only 5%). Material (α) and energy (β) outputs are calculated as follows:

- α = 0,821 kJ/kg;
- β = (190 + 21) kWth + 8,2 kWe = 211 kWth + 8,2 kWe.

The result of solution 1 (S1) shows that β is not a single value, because it is composed of two different energy type, then quantities remain not summed. Index α reveals only one flow of gas emission that can not be re-used.

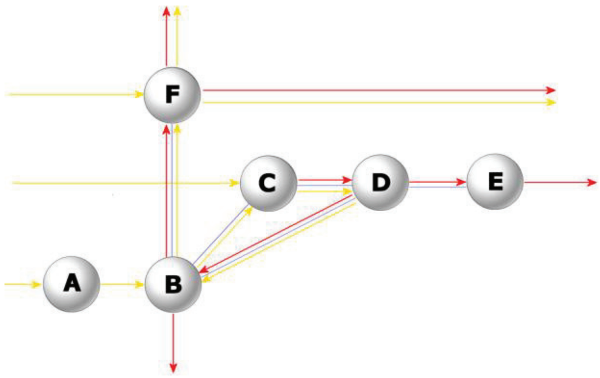


Fig.6 Functional net of the second micro-gas turbine (S2)

In second solution, a heat recovery system (F) is added to the turbo-gas schema, then the device will include six components. Component (F) is a recovery unit that produces hot water and steam at low pressure (see figure 6). Analyzing column Ω2 in figure 8, we can estimate 69 kW of thermal energy losses related to the recovery system, and 8,2 kW derived by the electric generator, then α and β are:

- α = 0,821 kJ/kg;
- β = 69 kWth + 8,2 kWe.

In this new solution S2, the gases expanded by the turbine D acquire more energy and, passing in the heater B, arrive in F, where energy and water flow became suitable for a civil or industrial use. The material quantity in output remains the same for both configurations of the gas-turbine.

Finally, it is possible to compare the solution S1 with the second S2:

- Min [α(S1) ; α(S2)] = α(S2) = α(S1)
- Min [β(S1) ; β(S2)] = β(S2)

The solution S2 is the most sustainable in terms of energy consumption.

6 Conclusions

The main attempt of the present paper has been to formalize early environmental assessment activity using a DSM. The whole methodology has, as result, a codified grammar that could aid designer in an early product evaluation.

More focus should be done in the environmental assessment of components that, at the early stage, are only rough defined and many variables should be considered.

The proposed procedures can be considered a first step towards a formal schema with which operate for this kind of problem.

The authors hope to have given a contribution in the vast field of design methods and sustainable product development.

Acknowledgement

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	A		B		C		D		E		Ω1		Ω2
A	I_A		1	0,808 (kg/s)								-808 (kg/s)	
				386 (KJ/kg)								-242,16 (KJ/kg)	
B	1	-0,808 (kg/s)	I_B		1	0,808 (kg/s)	1	-0,821 (kg/s)					0,821(kg/s)
		-386 (KJ/kg)				655,24 (KJ/kg)		-788,7 (KJ/kg)					190 KWth 21 (KWth)
C			1	-0,808 (kg/s)	I_C		1	0,821(kg/s)				-0,013 (kg/s)	
				-655,24 (KJ/kg)				1177,4 (KJ/kg)					
D			1	-0,821 (kg/s)	1	-0,821 (kg/s)	I_D		1				
				-788,7 (KJ/kg)		-1177,4 (KJ/kg)				164 (KWe)			
E							1		I_E				
								-164 (KWm)				155,8 (KWe)	8,2 (KWe)

Fig 7 Augmented DSM related to first functional net (S1)

	A		B		C		D		E		F		Ω1		Ω2
A	I_A		1	0,808 (kg/s)										-808 (kg/s)	
				386 (KJ/kg)										-242,16 (KJ/kg)	
B	1	-0,808 (kg/s)	I_B		1	0,808 (kg/s)	1	-0,821 (kg/s)			1	0,81 (kg/s)			
		-386 (KJ/kg)				655,24 (KJ/kg)		-788,7 (KJ/kg)				447 (KJ/kg)			21 (KWth)
C			1	-0,808 (kg/s)	I_C		1	0,821 (kg/s)						-0,013 (kg/s)	
				-655,24 (KJ/kg)				1177,4 (KJ/kg)							
D			1	-0,821 (kg/s)	1	-0,821 (kg/s)	I_D		1						
				-788,7 (KJ/kg)		-1177,4 (KJ/kg)				164 (KWm)					
E							1		I_E						
								-164 (KWm)						155,8 (Kwe)	8,2 (Kwe)
F			1	-0,81 (kg/s)							I_F			0,84 (kg/s) -0,84 (kg/s)	0,821 (kg/s)
				- 447 (KJ/kg)										142 (KWth)	29 (KWth) 19 (KWth)

Fig 8 Augmented DSM related to second functional net (S2)