A PROPOSAL FOR AN AUGMENTED DSM TO ASSESS PRODUCT SUSTAINABILITY

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ABSTRACT
The paper proposes an extension of the Design Structure Matrix to support designers in a rough sustainability evaluation of an industrial device in the early stage of its development.
The methodology of assessment is based on an Augmented DSM (A-DSM), where the original DSM layout has been modified to allow developers to record information about product lifecycle and to manage the interactions of product components among them, towards other systems and with the environment outside. After a description of the novel matrix layout, a method is formalized. The proposed methodology will show that product evaluation is achieved by means of a combination of partial results that can be calculated already in conceptual phase: a set of environmental indicators and a couple of sustainability performance values. In accordance with this approach, the method is conceived as sustainability control panel useful to evaluate early environmental performance.

Keywords: A-DSM, early assessment, conceptual design, functional analysis, simplified LCA

1 INTRODUCTION

Many researches have discussed Design Structure Matrix in problem decomposition, product design and process management for several years.
Although DSM and related visual tools present in literature have being applied to several scientific areas such as Risk and Decision, Project Planning, Requirement Management and Products Design (i.e. Proc. DSM 2010 Conference), this method could be suitable also in a great group of design issues strictly connected to the concept of sustainability, e.g. Life Cycle Assessment (LCA), Design for Environment (DfE), Recyclability and Functional Analysis. This fact suggests to analyze the problem of the environmental impact of industrial devices employing the matrix formulation, developing a DSM-based framework to be used as assessment tool.
To investigate about the use of DSM for sustainable product design is interesting, because sustainability is a very critical aspect, due to the impacts that products can have on the environment and society. In fact, environmental impact is an important issue that industrial companies must take into consideration, as it is, e.g., the basis of the European dispositions for Wastes of Electric and Electronic Equipment and the Restrictions on Hazardous Substances (Directive 2002/95/EC, 2003). These rules introduce new responsibilities for good producers and service providers and represent an hard challenge for producers, customers and designers.
As it is necessary, during the design phase, to think in terms of lifecycle of a device (from cradle to grave), technologists should anticipate the problem of product evaluation in the early stages of design.
A preliminary environmental appraisal of a first product layout could allow technicians to determine sustainable solutions as soon as possible. Unfortunately, it is impossible to achieve these results directly by a standard DSM, so a new formulation of the matrix is required.
In this paper, the authors investigate on further aspects of DSM in industrial context, with the aim to support designers in a rough product evaluation, already in the conceptual design phase. The approach is based on a extended DSM that represents not only connections among product parts, but also interconnections with environment and makes designers able to assess a device in a quantitative manner.

2 BACKGROUND

The generation of modified DSMs have been employed already in the past. Pimmler and Eppinger (1994) presented a modified DSM for product decomposition. In their research, a qualitative scale was

introduced in the off-diagonal terms to measure the degree of different interactions among components in the product structure. Another research team (Ma et al, 2008) developed a method to map the hierarchical workflow in order to obtain a more efficient planning in new product development, using a fuzzy DSM (FDSM) and a directed graph in the representation phase of design activity. The use of DSM is often associated to graph theory, as in Luh et al. (2011), where researchers proposed a method to plan better design strategies for product variety, exploiting a modified DSM that maps a product decomposition by a directed graph.
Also the topic of impact assessment has been discussed in different ways in engineering design, especially in terms of quantitative and qualitative environmental indicators. Dewulf and Duflou (2003) proposed to reduce the too extensive data efforts connected to a detailed assessment by using average values and a minimal life cycle information by means of a simplified Life cycle Assessment based on indicators. Kaebernick et al. (2003), in their research, showed to obtain a simplified assessment by a regression analysis based on energy and material impact drivers, whereas Bohm et al. (2010) discussed how to achieve data for the concepts using a repository of components with similar characteristic of design solutions, demonstrating that the information obtained is sufficient to make correct considerations on the concepts in terms of product life cycle.
The different studies above allow us to exploit these concepts in an approach where Sustainability, Product Development and DSM can be merged together in a new methodology.

3 ROUGH SUSTAINABILITY ASSESSMENT BASED ON A-DSM

The Augmented DSM (A-DSM) has been conceived as a data structure on which several procedures can operate in order to aid designer in a rough sustainability assessment. It is used during conceptual design, where different solutions are subjected to early evaluation processes (e.g. by means of screening and scoring activities (Ulrich and Eppinger, 2008)), and it is also suitable to represent a functional network in order to manage connections among the product parts. It is used mainly for the following purposes:

- to assess a product in its proper characteristics;
- to assess product during its use stage;
- to verify the coherence of the several link combinations. Energy and material links, in fact, have to be inserted jointly to a force contact, otherwise cases with missing force connections may need more attention.

These objectives can be achieved processing the data that designers have collected in the A-DSM, respectively by means of:

- a vector composed of Environmental Performance Indicators (EPI) (Dewulf and Duflou, 2003) for each single component;
- the off-diagonal terms, where data about relations among components are recorded;
- the functional checks to be executed before the procedures that assess material and energy flows.

We have to consider that the A-DSM method should be applied when first product layouts are embodied, after their formalization from the clustered functional net that describes all functional relations. Furthermore, its use it is suggested only if all functional nodes can be managed as product components (or concept archetypes) with the related data.

3.1 The A-DSM layout

The A-DSM is a matrix composed of two main parts (as in Figure 1), where designer has to manage different data types before product assessment:

- one DSM, where n components are put in relation. In the diagonal terms, EPI are stored, whereas flows and mutual interactions are recorded in off-diagonal terms;
- two columns Ω1, called “External Relations”, and Ω2, called “Sustainability Issues”, where designer collects interactions with the environment in input and output related to the device. Quantities exchanged have to be inserted in the first one, the second, instead, contains energy losses and material wastes; both are added on the right side.

This new augmented matrix has dimensions *n x(n+2)*. Except for the diagonal terms and the column Ω2, each cell is divided in four parts, where values related to the functional links of Force (F), Signal (S), Material (M) and Energy (E) are stored. Moreover, a value is positive, if the link is outwards the component, whereas it is negative if the link is inwards; this property is not valid for Force connection, as it is considered a not directed link due to the mutual interaction of mechanical contacts (Rizzuti et al., 2006). In the column Ω2, each element is divided in two sub-cells to collect only material and energy quantities (M, E).

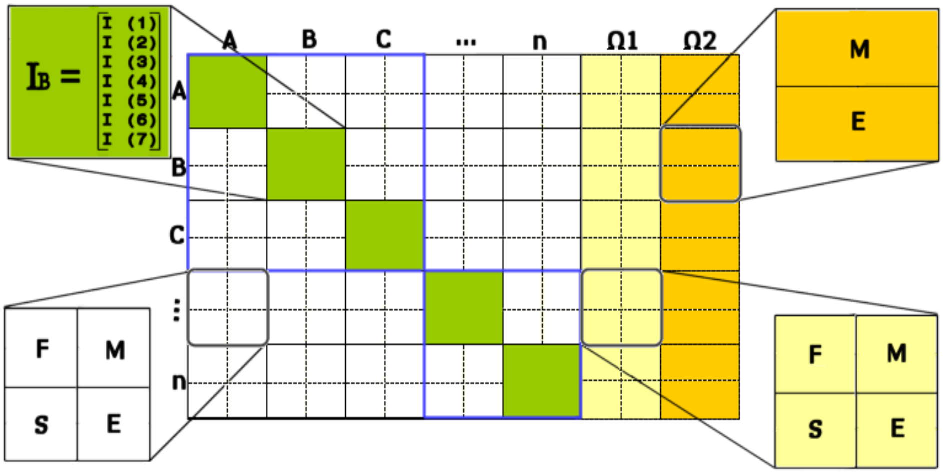

Figure 1. An example of Augmented-DSM layout

3.2 EPI-based assessment

Generally, in conceptual phase, assembled parts and single components (selected to be solutions for the nodes of a functional net) are unsupplied of detailed data and, therefore, information can be extracted from technical sheets of similar components (Bohm et al., 2010) present on the market with the same characteristics of the concept solutions and editing a simplified LCA for each element. In accordance with this approach, it is possible to evaluate a device by means of some Environmental Performance Indicators at the beginning, in the first stages of development. These indices allow designer to have a sufficient quantity of information, especially if a complete data inventory is not provided for the parts to be assessed. Each vector composed of the sustainability indicators has to be recorded in each DSM diagonal cell and presents values concerning the stages of Product Lifecycle (Zhang and Li, 2010) such as Raw Material, Production and Disposal (see Figure 2).

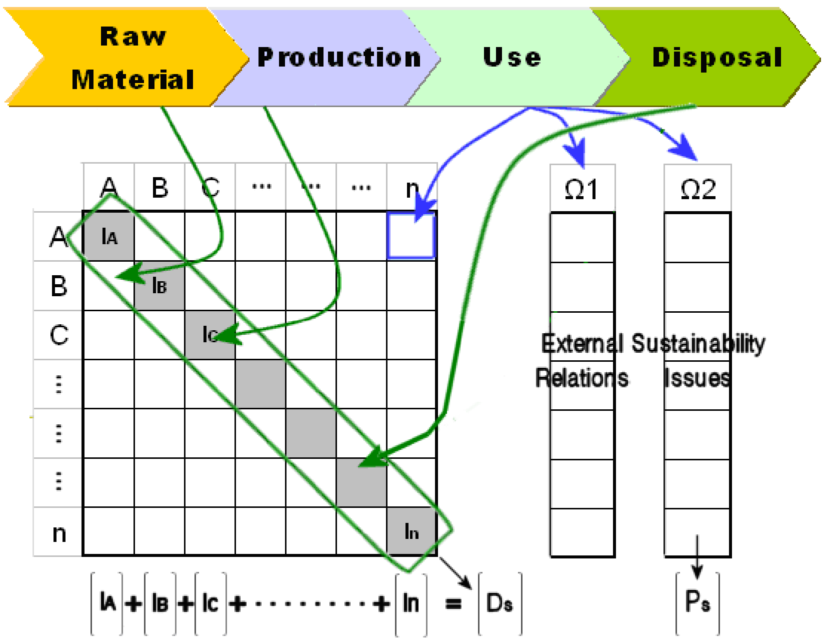

Figure 2. A-DSM Method framework

Each vector of EPIs includes:

1. Life time Global Warming Potential (GWP) of the component, expressed in Kg CO_{2eq};

2. Presence of hazardous substances in raw material by which a component is made (Boolean value 1/0);
3. Component total mass, expressed, i.e., in Kg, Kg/sec in case of flows, etc.;
4. Energy consumption in manufacturing phase, expressed in J, kJ or kWh;
5. Energy consumption in use, i.e., the output power in W, kW, etc.;
6. Recyclability (e.g. as percentage of recyclable mass on the total weight of the device);
7. Disposal Cost (€ or $).

Hence, the first stage of the sustainability assessment is executed calculating a vector of EPIs of the whole product by means of:

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

where $I_i = \{I_i(h) \mid h=1,\ldots,7\}$ is the set of h EPIs present in each diagonal DSM element A(i,i); n is the number of components; $I_i(h)$ is the h-th EPI contained in each A(i,i) element (related to component i); D(h) is the h-th EPI that takes into account all components represented by all diagonal terms; A is a generic instance of an A-DSM.

If a designer generates a set of r solutions (S_p, p = 1,…, r), each one modelled by a functional net, then the vector Ds can be calculated for a generic conceptual solution S. The designer can now compare, each other, all solutions and can select the best product configuration D*.

3.2.1 Clustering

The analysis by means of EPIs can be more detailed and more focused to sub-systems whether A-DSM is subjected to clustering activities, which are very common during design process. If the A-DSM were created already clustered, by employing clustered functional net during conceptual design (Rizzuti, 2010), could simplify the manipulation of matrix elements.

A clustered A-DSM could present a great number of sub-systems or clusters. For each one, the related sub matrix A' might have q components and, then, q vectors of EPIs. Hence, the vector D'(h) associated to the c-th cluster, can be calculated by means of Equation (2):

$$D'(h) = \sum_{i=1}^{q} I'_i(h) \quad (2)$$

where I_i' is the set of h EPIs related to the cluster A'; q are the components represented in A'; D'(h) is the h-th EPI that takes into account all components represented by A'(i,i) terms; I'_i (h) is the h-th EPI contained in each A'(i,i) element (component i). The aggregated indicator D(h) of section 3.2 can now be determined by:

$$D(h) = \sum_{c=1}^{m} D'c(h) \quad (3)$$

where m is the number of the clusters.

3.3 Product performance assessment

In the second stage of the A-DSM method, a device (or a part of it) is evaluated by means of an analysis on force contacts and on the flows of signals, material and energy exchanged among the components during its performance. Functional links are enhanced as described below:

- Force value is binary, 1 if there is a physical connection, 0 else;
- Signal value is -1 or 1 if a signal is present (inwards or outwards respectively), 0 else;
- Material value is a decimal type;
- Energy value is a decimal type.

The assessment about energy and material links can be executed only after a functional check among the nodes, verifying missing force contacts and with the aim to make a reasoning on the nature of each single component. More in detail, these checks are described below:

a. the presence of Force link is checked if values related to energy or material links are present in the functional net and also in case a node is not connected to the product structure;
b. when row counter i and sub-cell counter k have been fixed, considering only material (or energy) links, the Node Balance (NB) is calculated on each component to detect if a node is a source, a transit point or storage in case of material flow, or a generator / passive element in case of energy flow.

In previous work by Rocco et al. (2011) two procedures have been described to manage the data collected in the off-diagonal terms of a generic A-DSM. Both algorithms can be structured in three steps as follows:

1. The sum of positive terms concerning material wastes or energy losses is calculated by values recorded in Ω2. Designer reaches the gross values α (for material wastes) and β (for energy losses), to be collected in a vector Ps, for each solution S;
2. The previous activity have to be repeated for the all solutions found;
3. Finally, the solution that shows the minimum values of α and β, called α* and β*, is selected.

At the end of product performance assessment α* and β* are stored in a vector called P*. The selection of the best Ps will depend on the constraints related to wastes or efficiency targets of the particular product development or re-design process.
It is useful to remember that connections of Force and Signal are collected to take better decisions in the design process, whereas Material and Energy connections are more strictly related to the concept of sustainability.

3.4 Comparison of results

At the end of the assessment processes, the results by EPI-based evaluation and Product Performance Assessment have to be merged in order to select the best product configuration.
The designer team can discover that the best solution found in the previous assessments relate to different product configurations, or D* and P* do not refer to the same solution. The designer, at this point, must compare, each other, all vectors Ds and Ps: a vector Ds with dimension *7x1* (composed of the EPIs); a vector Ps with dimension *2x1* (composed of α and β).
A comparison of solutions could generate problems due to possible contradictions between the contents of Ds and Ps, and the selection could require a deeper reasoning. In fact contradictions could have also been found in the previous steps, described in section 3.2 and 3.3. In any case a comparison term to term must be planned. A concept solution, e.g. S_j, could have good values in terms of sustainability during its phase of use, but may produce bad environmental performance indicators, whereas an another solution S_k may present the reverse situation. It is necessary then to highlight some cases of uncertainty:

- a discordance among values D_S related to different solutions, that the selection of a unique solution D* is difficult in the EPI-based assessment;
- a discordance between α and β values of vectors P_S among the different solutions, that the selection of a unique solution P* is difficult in the Product Performance Assessment;
- such a discordance between Ds and Ps, i.e. one solution S_j is better than S_k in terms of EPIs, whereas S_k is better than S_j in terms of Product Performance Assessment and vice-versa.

However, a set of criteria to support the selection of the best product configuration in a situation of uncertainty have to be decided and formalized in the future, in order to manage different results by EPI-based assessment and product performance assessment. In fact, a tool for the resolution of uncertainty will aids the designers in the interpretation of the data and in the selection of a solution (or a group of solutions) that will present the best compromise of results.

4 CONCLUSIONS

In conclusion, our work was aimed to give a quantitative approach for the issue of sustainability in early design phase employing the DSM paradigm, introducing an "augmented" DSM version.
The new A-DSM presents some innovations compared with the classic Design Structure Matrix, especially in terms of data amount to be managed. Different information can be obtained by mean of the present approach, such as early product life cycle impacts, resources employed during product performance and the improvement of a coherent functional schema. For these reasons it is possible to consider the proposed method as a "control panel" based on simple codified rules.

In the near future, more emphasis will be given to the best way to analyze and discuss the results and the methodology, employing it for the assessment of some test cases. These activities and the related collateral issues can be considered as cues for a deeper reasoning on sustainability.
Then, in future works, a visual tool will be implemented.

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Introduction

- Sustainability
  - The issue of sustainability is really important due to the impact that products have on environment and society
  - A particular interest in product environmental evaluation has been developing in recent times
  - Designers should focus their attention on some parameters related to sustainability
  - Environmental impact is not easy to reach in conceptual stage
  - Appropriate tools and methods to support concept selection are required
- How designers can be supported in an early product evaluation?
  - Design Structure Matrix (DSM) can be employed as suitable tool to assess product resources and impacts

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Background

- Modified DSMs have been employed already in the past
  - Qualitative scale to measure the degree of different interactions (Pimmler and Eppinger, 1994)
  - Fuzzy DSM (FDSM) to improve a more efficient planning in new product development (Ma et al., 2008)
- Quantitative and qualitative environmental indicators
  - Simplified Life Cycle Assessment based on indicators (Dewulf and Duflou, 2003)
  - Simplified assessment by a regression analysis based on energy and material impact drivers (Kaebernick et al., 2003)
- Graph representation and Functional Analysis of product architectures
- Need to analyze real-life products that have functional similarities with the conceptual elements under evaluation to measure the “environmental impacts of the concepts” (Bohm et al., 2010)

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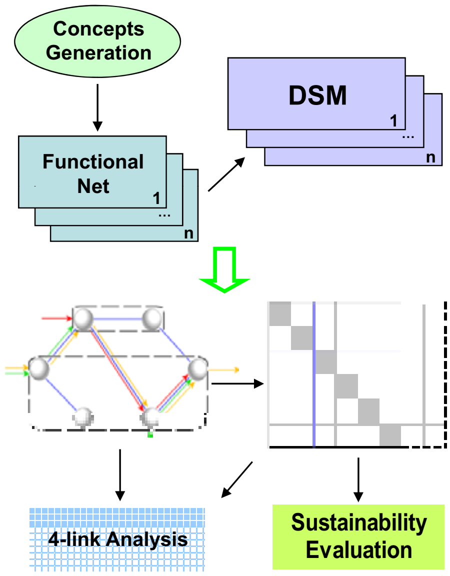
Methodology: Framework

- Extend the original DSM layout to evaluate the sustainability of different product architectures



- Functional net modeled by clustered graph structure
- Each functional net version can be translated into one Design Structure Matrix
- New approach:
  - Expand DSM in an Augmented Matrix
  - Collect data in A-DSM
  - Check functional coherence among the links
  - Apply procedures
  - Evaluate the most sustainable solution

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Methodology: Objectives

- Objectives
  - to verify the coherence of several links combinations
  - to assess a product in its own characteristics
  - to assess product during the use stage
- These objectives can be achieved processing the data that designers collect in the A-DSM by means of:
  - a functional check to verify the existence of force contacts in association with material and energy flows
  - a procedure based on a vector composed of Environmental Performance Indicators (EPI) for each single component, stored in the diagonal terms
  - a procedure based on off-diagonal terms, where data about relations among components are recorded

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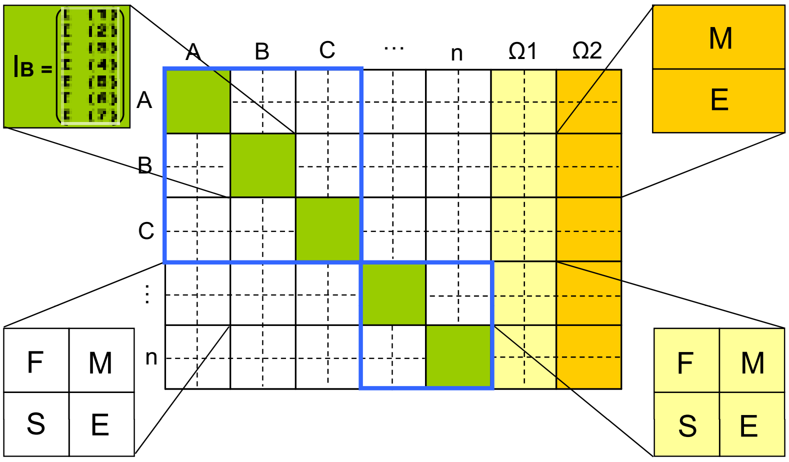
Methodology: A-DSM layout

- Diagonal Terms
  - Sustainability indicators describe each component individually
  - The set of parameters is represented by an array of 7 elements
- Off-Diagonal Terms
  - Force link
  - Signal link
  - Material link
  - Energy link
- N-square Matrix
  - Components liaisons
- Additional columns
  - External Relations (Ω1)
  - Sustainability Issues (Ω2)



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Methodology: A-DSM Editing

- Editing of environmental parameters (EPI) in diagonal terms
  - Global Warming Potential (Kg CO_{2eq})
  - Presence of hazardous substances in raw material (Boolean 1/0)
  - Mass (Kg, Kg/s, etc)
  - Energy index in manufacturing phase (KJ, J, KWh)
  - Energy index in use phase (W, KW)
  - Recyclability (%)
  - Disposal Cost (€)
- Editing of functional links in off-diagonal terms and Ω1 column

  Each cell is composed of four elements edited as follows:
  - Force → binary, 1 if physical connection, 0 else;
  - Signal → -1 if inwards, 1 if outwards, 0 else;
  - Material → decimal type, positive if the link is in output or negative if the link is in input
  - Energy → decimal type, positive if the link is in output or negative in case of link in input
- Editing of sustainability issues in Ω2 column
  - All cells is divided in only two allocations (Material and Energy)

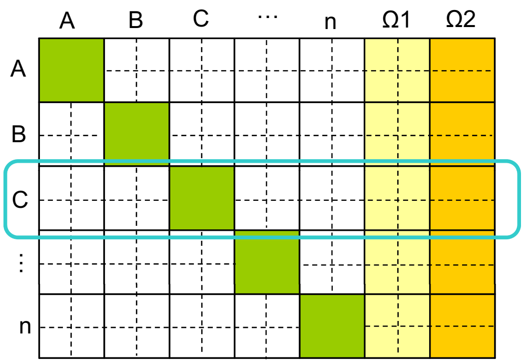
Functional Checks

- Calculate Node Balance (NB)
  - Fix row counter i and analyze links ingoing and outgoing to determine the nature of all components

$$NB(i,k) = \sum_{j=1}^{n+2} A\text{-}DSM(i,j,k)$$

$i = 1, \ldots, n;\ j = 1, \ldots, n+2;\ \ k = M, E$

- If NB > 0 → generator (source)
- If NB = 0 → transit node
- If NB < 0 → dissipator (storage)



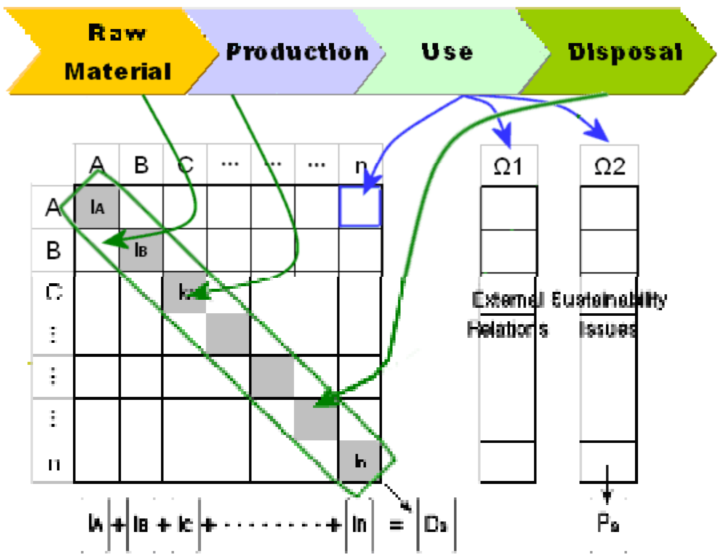
- Verify force contacts if:
  - One link of energy and/or material is present in the sub-cell
  - A component (or a functional archetype) is not connected to the product structure

Assessment Procedure (1)

Interaction between product life cycle and data structure stored in the A-DSM

Two sub-procedures

- First: EPI evaluation based on product characteristics stored in diagonal terms (green lines)
- Second: Product Performance Assessment based on product efficiency concerning Energy and Material flows (blue lines)



Assessment Procedure (2)

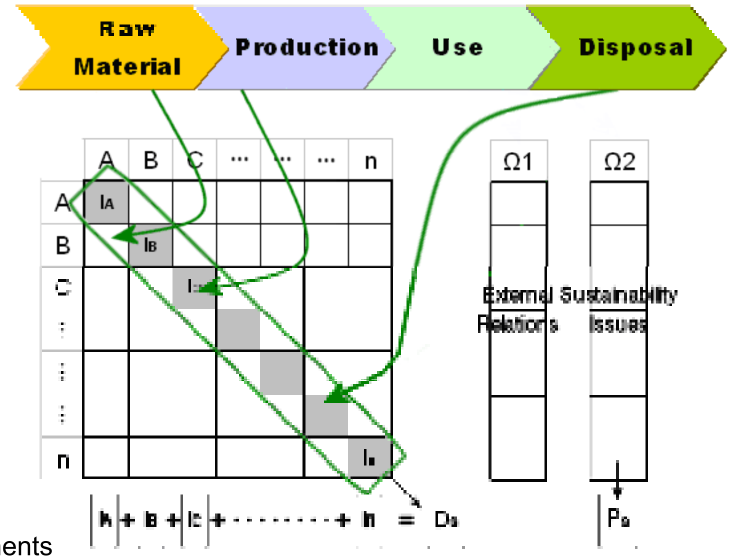
Product life cycle assessment based on Raw Material, Production, Disposal stages

Calculate the sum of each environmetal parameter on all product components (vector Ds)

$D_s = [D(1)\ldots D(h)\ldots D(7)]$

where

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

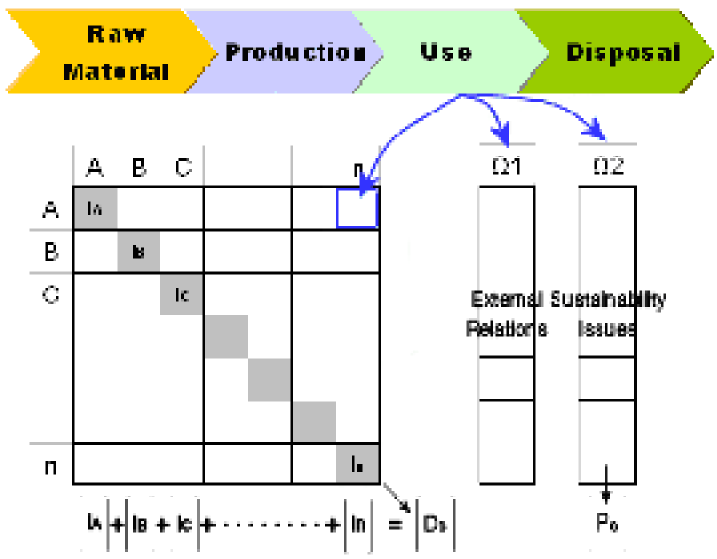


- n is the number of components
- $I_i(h)$ is the h-th EPI contained in each diagonal cell
- D(h) is the h-th EPI that takes in to account all components

Assessment Procedure (3)

Product life cycle assessment based on the Use stage using a 3-step algorithm

1. Compute material wastes (α) and energy losses (β) by Ω2 for a solution S (Ps)
2. Repeate step 1 for the all design solutions
3. Select the solution that minimizes α and β



Discussion of Results and Uncertainty

- The results by EPI-based evaluation and Product Performance Assessment have to be merged
- Each solution S is characterized by vectors D_s and P_s
- The best performance represented by vectors D* and P* must be identified

Problem: D* and P* could not refer to the same solution

It is necessary, then, to highlight some cases of uncertainty:

- A discordance among values of D_s related to different solutions, that the selection of a unique solution D* is difficult in the EPI-based Assessment
- A discordance between α and β values of vectors P_s among the different solutions, such that the selection of a unique solution P* is difficult in the Product Performance Assessment
- A discordance between D_s and P_s of different configurations. Solution S_j, e.g., is better than S_k in terms of EPIs, whereas S_k is better than S_j in terms of Product Performance Assessment and vice-versa

Conclusions

- A procedure has been proposed to:
  - Formalize early environmental assessment activity using a DSM
  - Create a codified grammar to designer in an early product evaluation

The procedure can be considered a first step towards a formal schema

- Issues
  - Difficulties for the environmental assessment of rough defined components in early design stages
  - Low quantities of data available
  - Solve conflicts related to the uncertainty
  - Define methods to select better solutions