Design Matrix as starting point to assess product sustainability

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Abstract. Product development is a time-consuming activity trying to answer, at best, the demanding customer needs. In general, the design of an industrial product needs several competencies that work conjointly, in the respect of many constraints that urge from the firm' departments. Last but not least sustainability is gaining a relevant role, since the recent past, and absolutely not deferred for the destiny of humankind on earth in the future. Design Matrix is the first array that designers should compose in order to verify the feasibility of product architecture since it put in relation functional requirements and design parameters. Clearly, designers are really far from the embodiment of valid proposals, at this moment. It is necessary to map this information to other data structures that allow them to follow the evolving architectural work, in which physical components or effective parts perform the actions that satisfy functional requirements. Design Structure Matrix (DSM) is a promising data structure that shows the relationship among all subsystems that compose the developing product. This structure can be arranged also to collect all the environmental parameters or indicators in order to have a rough sustainability assessment since the early design phases. The paper will discuss such kind of relation and apply it to a case study in order to clarify it.

1. Introduction
Over time, since the '80 years of last century, when the first systematic methods around product design and development appeared [1, 2], many approaches have been tried with the intent to support designers and stakeholders in this task. Many are the points of view that can enhance peculiar characteristics of the product in the phase of development and the competition between designers and project management may influence significantly the final structure of the product.

Many emphases may be put on designing, considering the more relevant aspects that a product must embed and that characterize it. The strategic essence of today and next future products must be sustainability [3, 4], considered as the basic characteristic that all engineering solutions to problems must have.

Axiomatic Design is a powerful method to recognize the consistency of a design solution, verifying the nature of the Design Matrix [5] after the identification of the relation between functional requirements and the associated design parameters. This should be strengthened in order to check and stress the sustainability characteristics of the product in the phase of development. Considering that Axiomatic Design was born with the intent to pose a more scientific basis to design it was not equipped to assess all possible scenarios in which a device should have worked. About 10 years ago two interesting applications of it to eco-design were published. Shin et al. [6] incorporated ecological
issues into Axiomatic Design, including eco-factors as functional requirements and design parameters. Giorgetti et al. [7] proposed a smart eco-design platform able to support designers to develop products with a higher level of sustainability along all the product's life cycle.

The nature of the Design Matrix is extremely versatile, in that it can be integrated with other design methods in order to expand the concepts in many different directions. One step further designer must do is the choice of the components/subsystems that better will perform those functionalities. This step is strictly related to the building of architectural solutions, and several solutions may be invented. For this reason, new databases must be organized in order to collect information able to differentiate among design alternatives.

Design Structure Matrix (DSM) is one such database [8, 9]. DSM was born in a product management context and is employed for a variety of scopes. It collects the relationships among all components involved in a device. Knowing system interactions during the product development process is important for project management. Capturing system interactions between affiliated system elements is necessary for managing all phases of product development that must be performed efficiently and effectively. Although DSM is powerful in the analysis of design interactions, it is less effective in innovative design, where it is almost impossible to obtain a DSM for a new product that has never been designed before.

The integration of DM and DSM has been investigated recognizing a certain affinity between them, for the finality to support designers in product design and development [10-11]. The two theories have been integrated to augment the conceptual design process as a recursive interaction of AD’s design matrix and the corresponding DSM [12, 13].

In any case, the original DSM does not contain all the information able to identify the sustainability level of the product under development. To this task, an augmented version of the original DSM (A-DSM) has been conceived [14], able to gather all such kinds of information and interrelation.

DM and A-DSM may be linked together and conjointly may guide designers to develop products able to solve problems for human beings today, avoiding that the next generations may not be able to solve theirs in future.

The paper discusses such kind of relation and briefly explains how to combine DM and DSM in a case of study.

2. Relation between Design Matrix and Design Structure Matrix

The form of both matrices DM and DSM coincides (see Figure 1). Their contents differ, even if the context in which they have been conceived remains almost the same: to describe reasoning throughout product design and development.

Figure 1a represents a diagonal Design Matrix in which the relation between seven FR, Functional Requirements and the corresponding DP, Design Parameters is defined. The necessary condition to continue to develop a valid engineering solution is made checking the squared form of the matrix, assuring since the first study that it is not invalidated by a lack or an over-dimension of parameters [5]. Also, a triangular form of the matrix may describe a valid solution, a structure that is frequent in product development. During this stage, the DP,s are identified as a set of quantifiable elements of which the values or the range must be accordingly chosen in order to satisfy the best behaviour of the device. The X present in the cells reports that a relation exists. The robust design method may be applied to search for the best performances [15]. In any case, every DP, characterizes an actual component or a particular element of it.

Figure 1b represents the DSM squared matrix that puts the relation among them the components in which the DP, have been embedded. The Design Structure Matrix has a squared form and it is formed as a non-diagonal matrix, in that it identifies the way in which the components interact with each other. The X present in the cells reports this interaction. The components are identified by a letter and moving along a line it may be discovered how/what a component gives to others, and moving along a column it may be discovered how/what a component receive from others. DSM is the first matrix that collects the components of a product and implicitly describes its architecture. During product
development, a set of other matrices may be joined to this one, as DMM-Domain Mapping Matrix [17] and MDM-Multi Domain Mapping [18], in order to have a clear picture of all interactions among processes, people, organization, scheduling, which give for complex systems synthetic schemas with which operate to identify bottlenecks along the time.

There is a strict relation between both matrices, because $DP_s$ and components are related and from one DM a set of DSM may be built, considering that several are the actual components that embed the parameter identified in the DM [16]. Several product architectures may be generated by a DM. This is obviously true if the decomposition of $FR$ is stopped to a certain level, and a certain freedom of choice is allowed to designers.

In order to enrich the content of the DSM, each cell may be subdivided into four sub-cells where a set of information may be stored [19].

![Figure 1](image)

**Figure 1.** Comparison between the matrices: a) Design Matrix; b) Design Structure Matrix.

### 3. Nature of the Augmented-DSM for sustainability assessment

The nature of the DSM has been further structured for its usage in eco-design [14, 18]. By reasoning around the product life cycle and considering “Raw Material”, “Manufacturing”, “Transportation”, “Use” and “End of Life" as the main phases that characterize a product, the original DSM has been redesigned, and its name is now preceded by “Augmented”.

The A-DSM is a matrix composed of two main parts (see Figure 2), where the designer has to manage different data types for the scope of product environmental assessment:

a) one DSM (the white square matrix), where $n$ components are put in relation. In the diagonal cells, a set of Environmental Indicators (EIs) are stored that characterize each component in terms of eco-design. In the off-diagonal terms the flows (Material, Energy, and Signal) and the mutual interactions (Force) between components are recorded;

b) two extra columns (in yellow tonalities):

c) Columns $\Omega_1$ (yellow), called “External Relations”, where the designer collects interactions with the environment in input and output of each component that has interaction with the outside, with the same organization of the internal cells.

d) Column $\Omega_2$ (amber), called “Sustainability Issues”, contains in each cell the energy dissipation and the material wastes directed towards the outside.

This augmented matrix has an $n \times (n+2)$ dimension. Except that for the diagonal terms and the column $\Omega_2$, each cell is divided into four parts. Moreover, the values inserted in each cell are numbers, where 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. In column $\Omega_2$, each element is divided into two sub-cells to collect only material and energy quantities (M, E).
The nature of each component may be characterized in terms of environmental indicators. The indicators give essential information that allows identification and quantifying of the environmental impact of each specific archetype related to the typical phases of the life cycle.

Figure 2. The structured form of the Augmented–DSM.

The indicators may be chosen in different ways. In a previous work [20] the authors have identified a set of 7 Environmental Indicators: Mass, Hazardous substances, Global Warming Potential, Impact in the manufacturing phase, Power in the use phase, Transport, Recyclability, even if many other parameters may be identified by designers and stakeholders in relation to the peculiarity of the product to be assessed.

4. Framework of a methodology for sustainability assessment
The strict relation between DM and A-DSM can be seen in Figure 3, where the main passages on product design are highlighted. The first step of the work is the functional analysis of the problem to be solved. The first data structures that must be organized are the graph of the interrelations of functions and the corresponding functional tree, in which the decomposition of functions is stored as dependence father-son (in upper-left of the figure). A functional tree in the axiomatic design approach is associated with the zig-zagging process in order to characterize the associability of a functional requirement to its design parameter.

The functional study is the basis for the concept generation step, where a lot of product architectures may be conceived, each one characterized by a proper set of design parameters. Each product architecture is represented by a proper Design Matrix, because different may be the design parameters associable with a functional requirement. Or, on the other side, the identification of a set of design parameters requires a different decomposition of functions and the building of Design Matrices of different dimensions. In the figure, three solutions were conceived with different structures.

In order to be able to analyze a product by the axiomatic design approach, it is necessary to describe it by a Design Matrix. After this first step, a set of DMs is available for further analyses.

For each DM, the corresponding A-DSM may be built, considering the strict relation by these. This may be done only considering how each Design Parameter may be instantiated in an actual component. Each A-DSM is a collection of fluxes and values associated with the environmental elements that have been chosen to perform sustainability assessment.

The correspondence from the problem to the solutions is one-to-many, but the correspondence from Design Matrix to A-DSM is one to one because each A-DSM describes precisely what will happen in the associated device. The consistency of each Design Matrix is guaranteed after the application of the first axiom and the verification that its structure is at least uncoupled. The nature and structure of each A-DSM are also guaranteed because it derives from a solution validated by the Axiomatic Design method.
5. Case of study
In order to explain how the methodology can be employed during product development, a case study focused on the design of an orange juicer is presented. There may be several different types of such a device and this concept derives from a grinder; in fact, it can be used for all kinds of vegetables. It is based on another point of view about the juicer, which considers grinding all the orange parts, and mainly the white zone (the pith) where many vitamins are concentrated.

The user puts one whole orange inside the device and uses a pusher to push it towards the grinding. Figure 4 presents the functional model of such a solution. The schema is shown with a certain degree of detail, in fact, the functional model was created starting from the macro functionality “to squeeze an orange” expressed in the classical verb plus noun form. The macro function is then broken down into more sub-functions. The sub-functions form a graph (see Figure 4a) where connections are represented by functional links: Force (blue), Signal (green), Material (yellow), Energy (red). The associated functional tree is reported in Figure 4b.
During concept generation a set of Design Matrices may be identified, differentiating for the DPs chosen for each FR. The zig-zagging method may require further subdivision of FRs and consequently, the dimension of the matrix grows. Initially, the DM may have a diagonal form, which associates each Design Parameter to each Functional Requirement. The matrix must be further investigated in order to discover the possible conjoint influence of many design parameters on the same functional requirement. This is due to the way in which the component, where DP explains its task, may interact with the other components and the other functionalities.

Behind such a matrix, there is the instantiation of product architecture. As can be seen, Figure 5 shows a lower triangular matrix, derived from the choices made for the component/archetypes reported in Table 1. Some functionalities that were originally subdivided (FR2, FR4, and FR6) are now grouped into single components that explain them and became more complex items, respectively the cover (B), the perforated blade (D), and the bowl/spout (F).

Figure 6a represents the graph of the components, that corresponds to those of the functionality of Figure 4a, where such kind of aggregation has been made. In Figure 6b the sketch of the device is represented with the indication of each component.

![Design Matrix](image)

**Figure 5.** Design Matrix built in relation the data of Figure 4.

| Function       | Archetype/Component                  | Design parameter |
|----------------|--------------------------------------|------------------|
| FR1 Press Orange | A (Plunger)                          | diameter         |
| FR21 Cover Container | B (Cover)                          | height           |
| FR22 Drive Orange | C (Nut)                              | diameter         |
| FR3 Transmit Motion | D (Perforated Blade)                | grid roughness   |
| FR41 Grind Orange | E (Container)                       | grid hole diameter |
| FR42 Filter Pulp | F (Bowl + Spout)                    | volume           |
| FR5 Hold Pulp   | G (Electric Motor)                  | power            |
| FR61 Contain Juice | H (Housing)                        | volume           |
| FR62 Pour Juice | I (Switch)                          | position         |
| FR7 Provide Mechanical Energy | L (Power Cable)                  | cable cross section |

**Table 1.** Relation between FRs and the DPs identified by a well specified component.
Figure 6. The instantiation of the device built, in strict relation with the Design Matrix of Figure 5: a) graph of the concept in terms of components and links; b) sketch of the concept with component’ label.

6. The associated A-DSM for sustainability assessment.

On the basis of the study performed so far, it is possible to build the A-DSM (see Figure 7). The content of such matrix is organized in strict relation to the graph of Figure 6a. It is in many parts symmetric and represents, for the interaction of Force, the adjacency matrix of the associated graph, in that it describes the relations that occur among the components. The diagonal terms, represented in the figure as grey-filled cells, contain the Environmental Indicators associated with each component, as designers and stakeholders decide to investigate the sustainability of their product. Each diagonal cell is structured as an array of seven positions. From these data, an environmental assessment may be done on each component or on the whole product.

In the off-diagonal terms and the column of the “External Relations” (Ω₁), each cell is divided into four sub-cells (as an array of four positions) where data are stored. Data have different nature and refer to the links of Force, Signal, Material, and Energy that the archetypes/components exchange among each other in the concept architecture. These data are derived from the links of the graph which represent the interaction among components (see Figure 6a). For example, node I interacts with the outside Ω₁ and with G, H ad L nodes. It gets from L energy that transmits to G. It is in contact with G, H, and L, and receives a signal from the outside that transfers to G.

Data related to functional links have to be stored following these rules:
- in the Force sub-cell, in blue, the value is Boolean, with the meaning: 1 if there is a physical connection, 0 (or “empty”) else;
- in the Signal sub-cell, in green, the value is a number type: -1 if a signal or information is in input, 1 if it is in output, 0 (or “empty”) else;
- in the Material sub-cell, in yellow, the value is a number type: it represents a quantity with a proper unit (e.g. g, kg, etc.); it is positive if the link is in output from the node/archetype, or negative if the link is in input; 0 (or “empty”) if the link is not present;
- in the Energy sub-cell, in red, the value is a number type: it represents a quantity with a proper unit (e.g. kJ, J, etc.) and it is positive if the link is in output from the node/archetype, or negative in case of link in input; 0 (or “empty”) if the link is not present.

The last column of “Sustainability Issues” (Ω₂) contains cells with only two slots in order to store links and quantities referred to material and energy and data follow the rules for these. It reports the quantity of energy that is lost and materials that are wasted.
Figure 7. A-DSM built as collection of all the information associated to the device.

With the help of the arcs, it is possible to follow the flux of energy and material, how each of these comes from (or goes towards) the outside and is elaborated into the device. Further, it may be checked in correspondence of the elements where may be identified some problem, for the functionality in itself or for the influence on the environmental performance.

7. Extension of the Axiomatic approach.
A sustainability assessment may be done by Axiomatic Design characterizing the Functional Requirements with an environmental emphasis, codifying e-FRs [6]. As a matter of fact, it is important to start the design process by adopting a point of view oriented to sustainability, to be guided better along the process. Nevertheless, starting the design process with environmental Functional Requirements may not guarantee that products are built with the right degree of eco-design.

Fundamental is the necessity to assess, at the end of the process, the design solutions. For this, it is important to collect and use data in a structured way.

The association of DM and A-DSM allows designers to identify where problems are concentrated and where to intervene for improving the environment critical aspect hidden in a product. Working backward from A-DSM, identifying environmental problems, designers may find which DPs and components are responsible for them, modifying or changing them, and then the whole architecture of the product. Further, this may require a redefinition of the FRs from which the design process started.

Figure 8. The backward process from A-DSM to DM.
Figure 8 reproduces such kind of situation, where changes may be guided in DM on the basis of the suggestions gathered by A-DSM. This process can be activated on a single product, or as present authors made in [20], on a set of A-DSMs that had been employed in order to compare several devices conceived for the same task. Attaining information from the enriched content of the A-DSM the comparison involved the Environment Indicators collected in the diagonal cells and the level of interaction with the outside, in terms of material wastes and energy losses.

8. Consideration and conclusion.

The A-DSM may be used in several ways. First of all, as a set of data that describe synthetically the nature of the interrelations present in the device.

Considering the possibility to implement a software check, immediately a set of contradiction could be highlighted on the device, i.e.: have a link of energy or material between two components, without a physical connection between them; at each node checks the balance of the global energy/material flux, and every time an unbalance happens in recognizing that something has been missed; jumping from a node to the other follows the direction of energy and material, also signal may indicate where to actuate some control.

Indubitably the link between DM and DSM during product design may open new ways that allow designers to take under control their work. Obviously, this can be done during the initial phases of designing, those where higher are the possibility to introduce mistakes or subtle inconclusiveness that may be unveiled with difficulty.

The authors would like to wish that other researchers may be encouraged to investigate such a kind of relation between DM and A-DSM and that this will open new possibilities to investigate product sustainability since the early phase of design.

9. References

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