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DESIGN STRUCTURE MATRIX USED AS KNOWLEDGE CAPTURE METHOD FOR PRODUCT CONFIGURATION

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1. Introduction

Product platform and modularity are two concepts largely diffuse in recent years to approach the competitive and globalised market. A rapid New Product Configuration (NPC) activity based on the market requirements is a complex process, it constitutes a major contribution to the business excellence of many industries. The NPC has to be based on robust rules for structuring and managing company knowledge and product knowledge that we can resume in *design knowledge*. The rules identification and their organisation is a difficult task that requires much effort and experience. An examination of current product development processes in many companies reveals the weakness of the organization structures in various areas, such as managing, monitoring and controlling the NPC process.
According to Stone and others [Strawbridge, 2002] the *design knowledge* can be defined as the body of facts, principles or techniques accumulated by designers in their past experiences. Design knowledge refers to ideas inferred from information and represents an understanding of what is known about design. To store design knowledge, modules are mapped to the functions they solve in the product. To reuse design knowledge, a functional description of a product is useful to quickly generate the new design. But when a new product is conceived a relation between the market requirements and the product functional description is also necessary to configure the solution.
The present work focuses on the study of a method to acquire and formalise the design knowledge in a way usable for implementing a knowledge-based software system to support the NPC. The approach is based on the representation of corporate knowledge within a structured framework where market requirements, product specifications and functional aspects are interrelated. A multi-level DSM (Design Structure Matrix) [Steward 1981] structure allows representing such knowledge in a rationale manner. The result of the reordered matrices is the base to define the hierarchical stages to configure the new product. This paper presents the methodology to formalize the product knowledge, the used structure to define the specifications for implementing the knowledge-based product configuration system and, finally, a practical example to illustrate our proposed framework.

2. Background and research scope

A product configuration system is generally based on a product portfolio. There are an increasing number of examples of product configuration systems, which, for instance, are used to support sales, choice of product variants and production preparation [Leckner 2003]. But they determine the new product solution analysing a set of well-known preconfigured configurations explicitly collected in a product model. A product model can be defined as a model that describes a product's structure, function and other properties as well as a product's life cycle properties e.g. manufacturing, assembly, transportation and service [Mortensen, 2000]. A product model used as basis for a product configuration system also includes a definition of the rules for generating variants in the product assortment [Hvam 1999].

An effective knowledge-based system for product configuration has to represent an *intelligent* product model, which means that the model contains the tacit design knowledge useful for deriving new specifications for product instances. According to Nonaka [Nonaka 1994], knowledge is considered to exist in two forms: explicit and tacit. Explicit knowledge is recorded in formal syntax. Once codified, it can be readily stored and communicated, such as the designs stored in CAD files. Tacit knowledge, however, exists as the result of personal experience and memory that allow the engineer to judge the best design solution among other alternative ones. It requires context in order to be explained and communicated. No single communication process or tool accommodates all forms of knowledge transfer. Different strategies and information technology tools are required to achieve different modes of communication necessary for knowledge creation. The key is to understand how IT tools help implement tacit knowledge creation and sharing [Yassine 2004].

The attempt of structuring product configuration systems to support the elicitation of tacit design knowledge has been reported in previous research works. A preliminary approach has been described in [Germani, 2002] where functions and modules were properly connected and represented in a KBE system. Intelligent self-configuring components have been defined to collect the knowledge useful to instantiate automatically new design solutions [Germani 2004]. These approaches have been focused on the detailed product representation but they neglected the preliminary design process phases when the market requirements drive the product line definition. The first conceptual design phases are strongly influenced by tacit design knowledge

Experiences from a considerable number of industrial companies have shown that often the management of this phase is realised without the use of a strict procedure of the tacit *design knowledge* modelling techniques. As a result, many of the choices are unstructured and undocumented and they are therefore difficult or impossible to be stored and reused. Thus there is a need to develop a procedure and associated modelling techniques, which can ensure that the design decisions are properly structured and documented, so that high-level configuration systems can be developed and maintained continually.

In this context the DSM (Design Structure Matrix) technique has been used to represent the tacit and explicit design knowledge together. It can be used to define a new product line at different levels of detail. A design structure matrix (DSM), in fact, provides a simple, compact, and visual representation of a complex decisional system that supports innovative solutions to decomposition, integration and configuration problems [Browning 2001]. Such method allows to structure dependency between the company knowledge information and the product knowledge information. The matrix definition (product features and dependencies) has to be realised using the consolidated company know-how formalising the tacit rules that expert designers (thanks to their direct participation to matrix fulfilling) implicitly use during the early product design phase to preserve the product coherence. In these terms the DSM methodology can be considered as a solution to represent the tacit knowledge. The inheritance of information between the different levels of detail allowed defining a software system useful to manage the design knowledge for configuring new solutions. The test and validation of methodology has been carried out using domestic boilers.

3. Multi-level DSM methodology for design knowledge formalisation

The research goal is the study and definition of a method to classify and reuse the consolidated design knowledge during the early conceptual design phases in order to coherently develop the new specific solutions without incurring into previous design errors.

When a new product line has to be planned and realised, within a product platform structure, is useful to make choices coherently with the context (product platform itself). Especially during the first phases, when the NPC strategic decisions have to be established, is necessary to exploit the multidisciplinary companies competencies. The design knowledge (tacit and explicit), matured in the past experiences, has to be formalised to relate the market requirements with the functional

specifications. Such knowledge can be shared and consolidated within a software tool that can objectively support the right design decisions.
The analysis of product development processes, in several companies, showed that the strategic choices related to new product lines are characterised, in the first phases, by the definition of Market Requirements (MRs) and Product Requirements (PRs). MRs are determined by the marketing experts on the basis of customers analysis, PRs are the technical perspective of the product concept. Their elaboration leads to the realisation of the specific new solution. They have to be interrelated and structured through priority and dependence relations. Generally, otherwise, the design knowledge useful in the first product development phases, especially the tacit knowledge, is rarely formalised. When it is schematically represented is classified by "flat" methods, without structured hierarchical relations (an example is reported in figure 3 and figure 4) and using only a level of representation. Our idea (figure 1) is to organise information at two levels: the first one correlates the market requirements and product requirements, the second one translates them into the functional features.

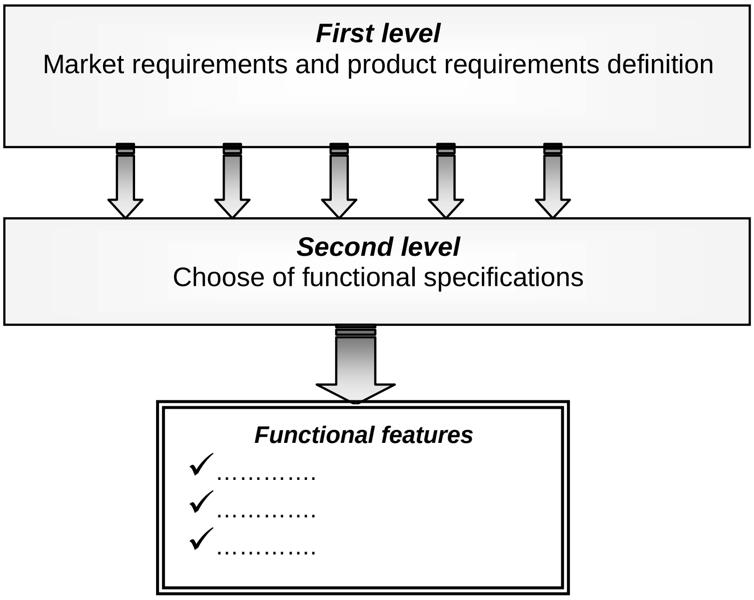

Figure 1. Methodology for knowledge management

The knowledge formalisation and elaboration tasks have been based on the DSM methodology that uses matrices to represent interdependency relations between market requirements and product requirements.
DSM models have been used in previous research work as knowledge capture method [Whitney, 1999]. In that approach the DSM is used as a roadmap of knowledge needed to populate a knowledge-based system as well as to link that system to other sources of knowledge outside its knowledge base.
The DSM formalism allows reordering the information managed by "flat" models in order to easily have an order of priorities and dependence relations within the same level and between different levels. These are fundamental specifications to develop a suitable product configuration system. It has been observed that if MRs and PRs can be managed at the same level (figure 2) adopting an elaboration based on partitioning, tearing and banding algorithms.
The functional specifications are reported in a lower level that is influenced/constrained by the choices established at higher level. Currently the connection between the two levels it is based on *a priori* rules dedicated to the specific applicative field. The information management within the second level can be pursued using the same algorithms. The process DSM can identify clusters of information or ways to rearrange a product development process so that people with relevant information are linked to each other in a formal structure.

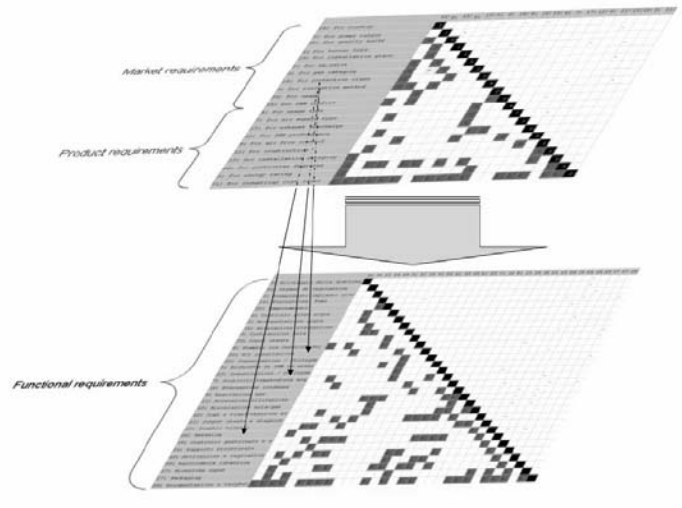

Figure 2. Multi-level DSM structure

4. Practical example: domestic boilers

The methodology experimentation has been deployed analyzing a real test case in collaboration with an Italian company (MerloniTermosanitari s.p.a.) that is world leader in the design and manufacturing of domestic boilers. Such products can be considered modular and configurable; the product platform has been defined in terms of functional structures. The challenge is the definition of a new product architecture, corresponding to a new range of products, within the same platform definition. The market requirements and the product requirements have to be combined to support the conceptual design phase using the design knowledge deriving from the different experts competencies.
The result is the development of a software tool able to represent the tacit and explicit knowledge related to the MRs and PRs. Such a tool has been conceived to manage the dependencies and the hierarchies between different design choices. A high-level choice influences the variables and the parameters for the correlated lower levels choices. For example, for the gas domestic boilers, if the designer adopts a *premix* burner it implies a sealed combustion chamber. The objective is that the software tool automatically manages this kind of relations restraining the possible options on the basis of previous decisions.

4.1 Product knowledge formalization

Currently, the marketing area, once collected the customers needs, identifies a set of specifications which describe *what* product should make reporting detailed features in terms of customers viewpoints. The features listed in figure 3 give a complete picture of the possible alternatives for market requirements (MRs). On the left are reported the parameters, on the right the values that they can assume. Generally, within a range of products a combination of different solutions can coexist. But many combinations are technologically inconsistent or economically disadvantageous.
In the illustrated features representation there is not an explicit connection between the different choices (“flat” description). Hence, the marketing area can option every path and set of solutions.
On the other end the technical department represents the product features by a similar structure where the product perspective is different. In fact the parameters are linked to design principles and technical performances (figure 4).
The marketing area, generally, launches the preliminary product development study defining the emerging MRs. Then such information is transferred to the technical department that tries to convert the MRs in PRs. Very often the marketing area requirements are impractical ideas by using the current technological state of art. This incongruence sparks off long iterations and misunderstandings. The main problem is that the two areas elaborate their decisions using different competencies and know-

how. The classification of information by “flat” methods does not support an effective shared knowledge base useful for both departments in coherently designing new product configurations.

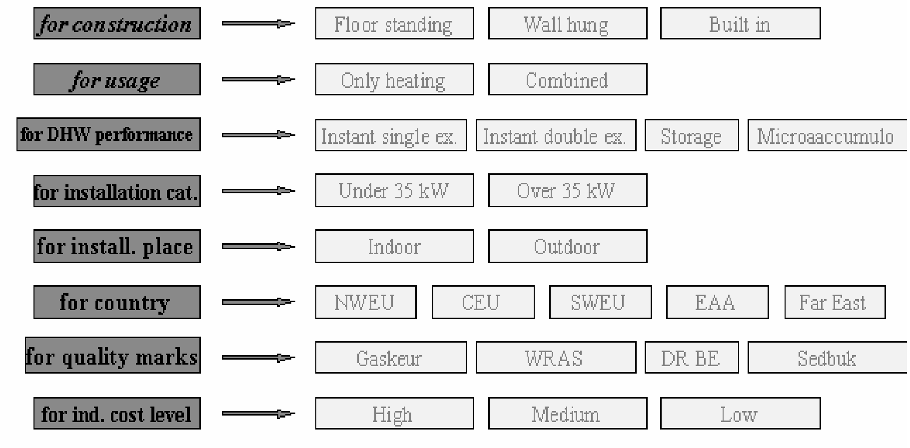

Figure 3. Classification of domestic boilers for Market Requirements (MRs)

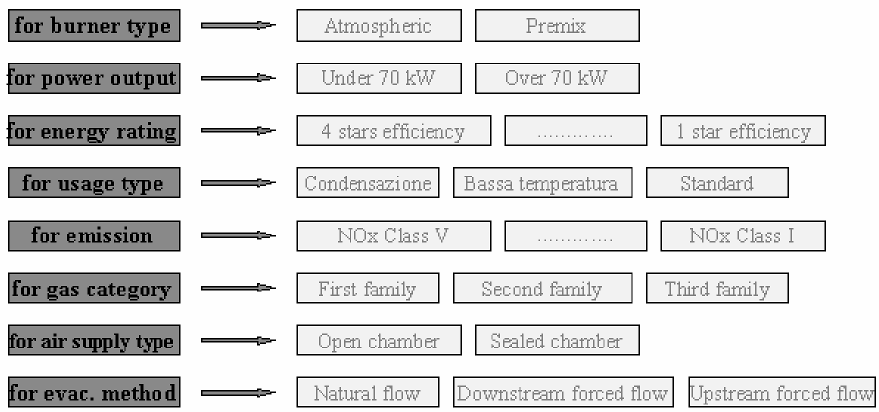

Figure 4. Classification of domestic boilers for Product Requirements (PRs)

The DSM approach allows collecting the marketing and technical information in an ordered structure that can be analyzed to reconfigure such information in a way suitable for developing a configuration software tool. The PSM32 (www.problematics.com) software tool has been used to manage and to process the matrices. Dedicated algorithms for *partitioning*, *tearing* and *banding* have been used.
At the first level the matrix reports in a single structure MRs and PRs. The company experts have fixed the dependency relations (blue boxes in figure 5) and the relations’ weight.
The simplicity and immediacy of DSM representation is important since it allows the experts to focus the attention on the dependency relations between two parameters, neglecting the priority rules that generally are expression of the tacit design knowledge. The parameters are reported in the matrix in a casual order, then, the following partitioning and tearing operations redeploy them according to an order coherent with the dependency relations (figure 5, right). The upper parameters (*for country*, *for power output* and *for image*) are completely independent from the others hence their values can be immediately chosen. The lower parameters values are strongly influenced from the previous choices, hence many options have to be disabled.

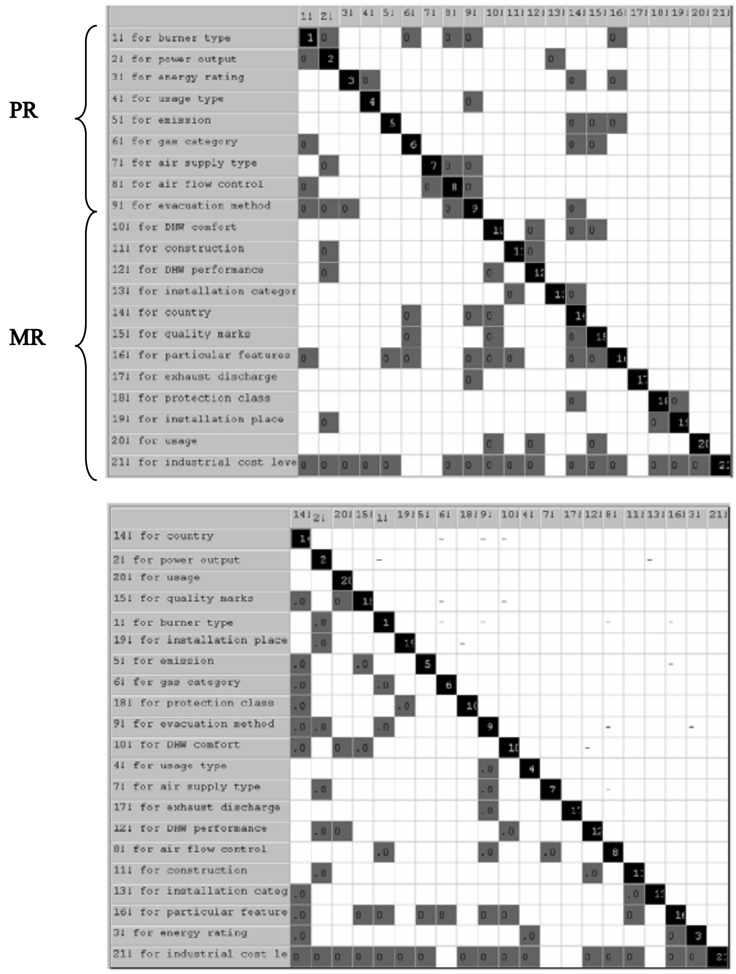

Figure 5. Matrix for the first level configuration (PRs and MRs)

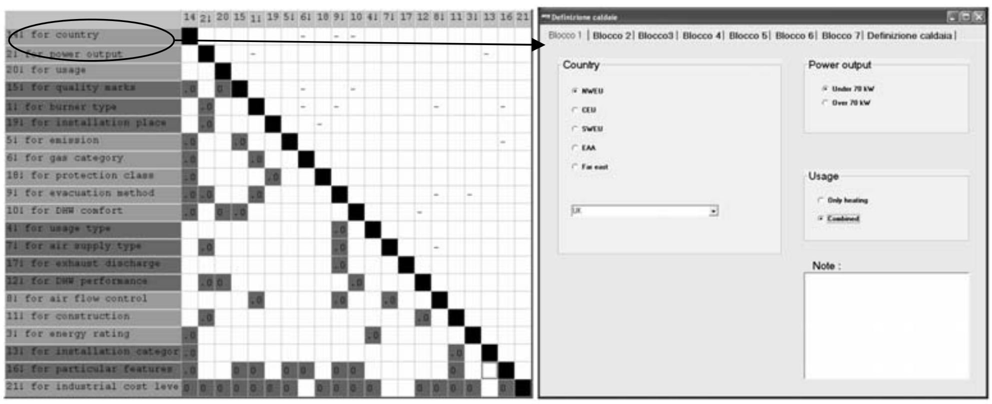

Figure 6. Groups of information based on the independence and priority rules and the related configuration software user interface

A further matrix processing operation is the *banding*, it allows to identify the groups of design decisions that can be simultaneously performed (figure 6, left), this implies the determination of the basic sequential steps for the configuration accomplishment. Once parameters have been completely reordered and grouped respecting the dependency relations and the priority between MRs and PRs, we have the right flow of information (design process specifications) for developing a suitable software configuration tool for the domestic boilers (figure 6, right), as described in detail in the next section.
An analogous procedure has been used to structure and analyse the functional requirements (FRs) (figure 7).

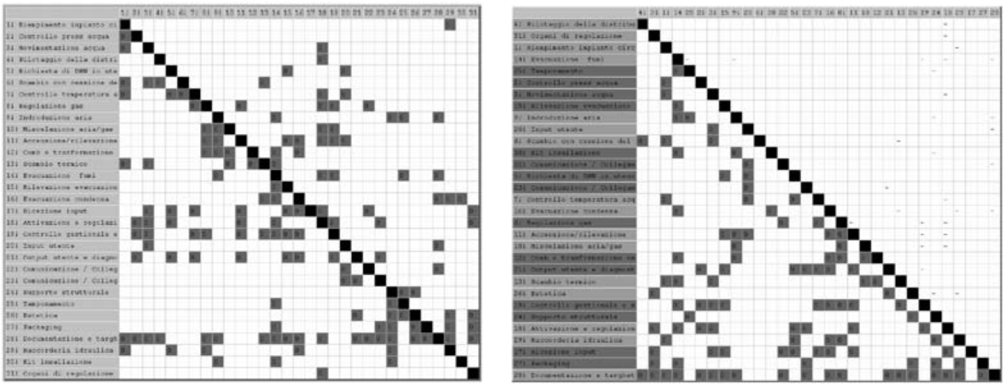

Figure 7. Matrix for the second level configuration (Functional Requirements)

4.2 The New Product Configuration software system

The software configuration tool for managing the new range of products reproduces the interdependencies established through the reorder and banding of matrices. The parameters values for the different alternative options are interrelated, hence, on the basis of the identified priorities; such parameters assume only consistent values and generate the new configuration.

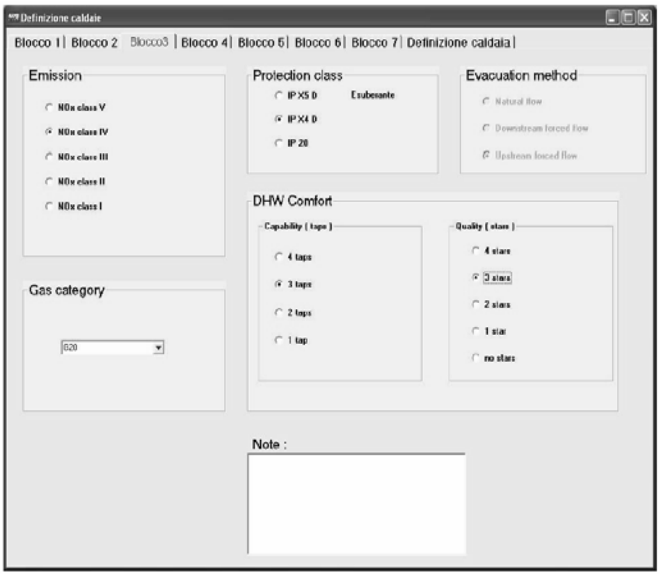

Figure 8. Phase 3 of the domestic boiler system configuration by the NPC software

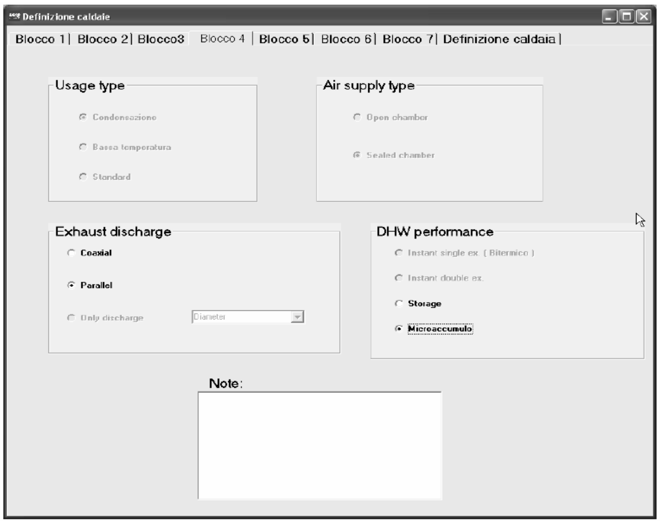

Figure 9. Phase 4 of the domestic boiler system configuration by the NPC software

The system has been implemented by Visual C++ programming language in a windows based environment. The user interface has been properly simplified to be easy-to-use. The blocks represented in the set of windows (figures 8 and 9) correspond to the grouped information in the DSM matrices; the order of blocks intrinsically represents the tacit design knowledge since it defines how the priority of choices have to be respected. Many parameters values are inhibited on the basis of bottom decisions.

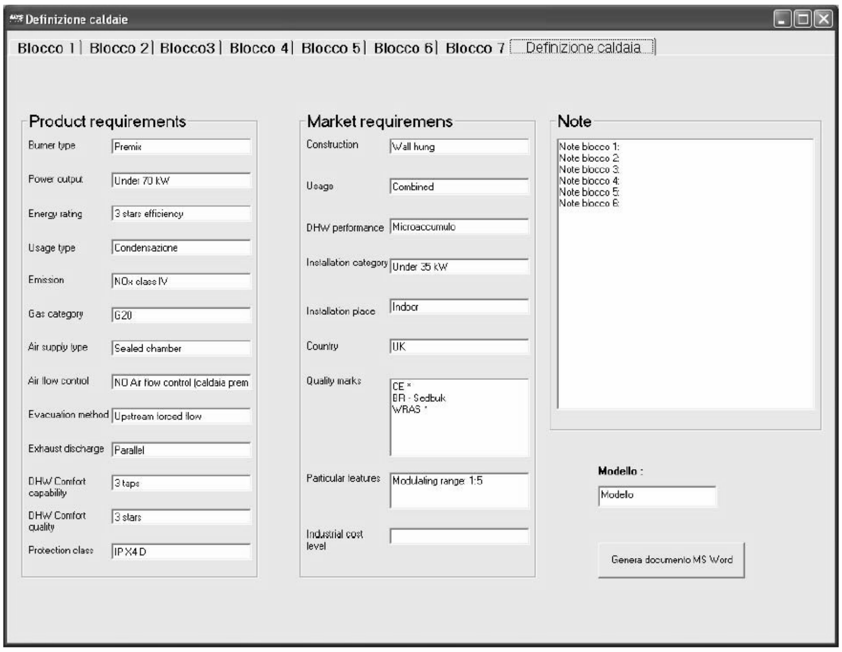

Figure 10. NPC software system output for the first level of the domestic boiler

The software system automatically presents different options (different user interfaces configurations) coherently with the product typology that is in course of definition. In this way the not expert designer (marketing, novice designer, etc) can employ the tool without risks of errors and incongruence during

the configuration phase. On the other hand, such approach supports also the standardization of design choices.
The system once identified the first level choices in order to fulfill the product requirements and the market requirements, export this information to the second level allowing managing the related functional groups. A limited number of functional options are offered to the user due to the constraints defined at the bottom level; the designer can generate a customized functional solution that is coherent with the new product range and with the product platform architecture. The software tool produces a report where are listed all information related to the new range of products, considering and grouping the different rough configurations/instances (figure 10). On the other hand it generates a report of a set of functional solutions that can be used as input for the automatic configuration of 3D CAD geometric models representing the products. This functional product representation is currently under study to define the information level of detail necessary to make a solution cost estimation and to analyze solution productive feasibility.

5. Conclusions

The potential extensive use of knowledge based product configurators useful for new products conceptual design phase will only be completely exploited if the interdisciplinary company competencies can be collected in a single structure. The improvement of product development processes requires an optimal formal rearrangement of the corporate and product information. This requires methodologies that are simple and robust to represent the product structure and the rules to elaborate the information. Our research focuses on the definition and implementation of a multi level DSM structure to formalise and represent the explicit and tacit design knowledge for New Product Configuration. The Design Structure matrices analysis allows reordering the interrelations and the interdependencies to support the implementation of a KB product configurator. A specific test case, domestic boilers, allowed a preliminary validation of the approach. This case indicates that a more subtle multi-level approach based on the DSM is useful and can lead to greater design process improvements than traditional "flat" methods. On the other hand, the application on a more vast number of cases will be useful to refine the methodology and to objectively validate the robustness, comparing the experimental results in terms of product quality and minimisation of errors and process iterations.

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