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Engineering design in food-packaging industry: the case study of a tuna canning machine

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Abstract

Food packaging industry requires machines able to perform different tasks and carry out several functions. Machine modularization allows to feed customer's needs creating a set of equipment with different features and technology. Module derivation is particularly important at the conceptual phase where main decisions are taken and where the degree of freedom are higher, avoiding subsequent costly modification. This study aims at investigating the adoption of engineering design process for the development of a tuna canning machine, deriving main modules for a definition of a product platform. The possibility to have a modular framework in this type of products allows to satisfy constraints coming from different markets and applications (i.e., product quality, adaptability, upgradability, assemblability, compliance with standards where the machine is installed, etc.). Modules were derived based on state-of-art approaches used for product development (i.e., functional analysis, module derivation and morphological matrix) and two examples (i.e., Cutter and Compactor & Shaper modules) were detailed to explain the developed design solutions. Results highlight how different design options can be adopted to overcome several issues (i.e., assemblability, upgradability) and fulfill requirements of different markets (i.e., product quality and aesthetic).

Keywords: Food packaging machine; tuna canning machine; conceptual design; functional analysis; modularity; morphological matrix; Industry 4.0

1. Introduction

The process of packing foods requires machines adaptable to perform different tasks according to the food that is handled. Food Packaging (FP) machines need to follow market trends, customer needs, technological improvements, standards, and regulations that are different from other types of packaging machines [1][2][3]. The design process of a new product, called product development process (PDP), is a set of subsequent tasks that can be divided into three main phases: (i) conceptual phase, (ii) embodiment phase and, (iii) detail phase [4] [5]. Conceptual design is the most challenging phase, where ideas are developed and where the engineers have the higher degrees of freedom in terms of solution spaces to investigate [6]. During the conceptual design phase, different methods and tools are available to help designers through the definition of a proper product architecture. The product architecture is a scheme describing how product functions are collected to create modules and how modules interact with each other [7]. The development of a product architecture requires the identification of highly interactive groups of elements and the collection into modules. Different tools are available in literature to perform the functional derivation such as function means tree [8], functional evolution process (FEP) [9], and functional analysis [4] which is considered the starting point for the development of a product architecture. Modules and modular products can be obtained starting from the functional derivation through an interactive manual process where the designer is not bounded to a particular scheme. Several methods are available in literature to perform product modularization (i.e., obtain a modular product) with respect to a specific aim and considering many criteria (e.g., reduce the

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number of product elements, improve product customization, improve product maintenance, etc.). Some of these methods use the design structure matrix (DSM) to visualize the product architecture and to develop basic building blocks required for the identification of product modules, achieved using an objective function (algorithm) to minimize [10][11]. Other methods use heuristics to cluster functions in a set of modules to develop alternative layouts and component selection for subsequent design tasks [12]. Regarding food packaging industry (i.e., the canning industry), different studies have been carried out to improve modularity of machine used for food processing and packaging. It is well-known that modularity is a key aspect in the development of such product (both machines and equipment) which allows to better understand a complex product architecture and it facilitates innovation through within-module autonomous improvements and mix-and-match of new module combinations [13]. Among these studies, few of them focused on the optimization of some aspects of canning machines such as the filling sauce system of fish products (by design a vacuum sauce filling machine to minimize the quantity of sauce loss in the process) [14], and the application of robotic systems for handling operations of food [15]. More recently, some studies focused on the development of food processing machines and equipment oriented to environmental sustainability [16][17]. Open innovation methods were also investigated with the aim to discover new technical solution in the food packaging sector [18][19][20]. However, from the design point of view, although these works provide interesting insights in the development of specific aspects of canning machines and equipment, an overall design approach which encompasses all the phases of the product development process from conceptualization to design solutions is still an open issue.

The aim of the paper is to describe the engineering design process for the development of technical solutions in the context of food packaging industry. The paper focuses on the case study of a tuna canning machine, starting from the analysis of requirements to the generation of design concepts for each identified module. Several design options were retrieved to fulfil specific aims (i.e., product quality, adaptability, upgradability, assemblability, compliance with standards where the machine is installed, etc.). The analysis is performed following available approaches, in particular the functional analysis theory [4] was used to derive the functional scheme of the product, module heuristics [12] were adopted to collect functions into modules and, finally, the morphological matrix was developed to identify and select the most suitable design option for each module [21]. The novel contribution of this work refers to the specific field of interest (food packaging industry) where modular and complex products need to be developed to fulfil different constraints and requirements. For the presented case study, the focus was set on two main modules: (i) the cutter module, and (ii) the compactor and shaper module.

The paper is structured as follow: after this Introduction (1), the application of design methods to create a modular tuna canning machine is described in detail (2). Then, Results (3) are presented and, finally, Discussions and Conclusions (4) are argued.

2. Materials and methods

The development of a modular concept for complex product such as a tuna canning machine was performed following steps presented in Fig.1. The modular concept is the base for the development of product architectures and design solutions.

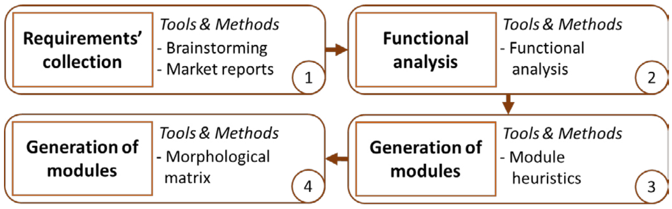

Fig. 1. Analysis workflow

The first step is the requirements' collection. The process was carried out using a concurrent approach where manufacturing, design and marketing departments were involved. The purpose of this task is to collect information about the requirements that must be fulfilled by the product (tuna canning machine), and about the existing constraints and their importance [22]. Three brainstorming sessions with engineers experienced in the field of tuna-canning machine (thanks to a cooperation with a manufacturing company operating in this field) were performed to identify the highest number of requirements. Moreover, market analysis reports provided by the marketing department of the company were used to spot additional requirements, not identified yet. The requirement list was developed including the following item: (i) requirement number (label), (ii) requirement type (demand or wish), (iii) responsible (person or department who identified the requirement), and (iv) date. It is worth to noting that the record about the source of demands and wishes is also very important for subsequent step where main functions and auxiliary functions are defined as well as to track changes over time (i.e., standards upgrade or market trends). For the sake of brevity, the entire list of requirements developed for the tuna canning machine (more than one hundred items) is not reported within the paper. Among the items of the entire list, few hotspots are reported here as interesting examples. The first one refers to the possibility to adapt the machine to several can sizes not only in terms of dimension (demand) but also in terms of shape (wish) as reported in Fig. 2.

Fig. 2. Can dimensions (A) and shapes (B) analysed for the definition of a requirement item (adaptability of the machine to several can sizes).

The second one refers to the modularization for assembly; indeed, this kind of machine need to be shipped all over the world and assembled in-place where the production is performed. Easiness in assembly and disassembly tasks is mandatory (demand) to reduce the overall cost of shipping and the time necessary to reassemble the overall equipment at the production site. Another interesting item of the requirement list recalls the possibility to have different standards in term of aesthetic features of the tuna chunk once it is inserted in the can (i.e., minimum piece size, and the possibility to clearly see the marks that are characterizing the tuna steak). This requirement is mandatory (demand) for specific markets (i.e., east EU country and far east countries) but less important (wish) for other markets (i.e., Latin America).

Once the task clarification phase was finalized, the functional analysis was performed based on the requirements' list and applying the method proposed by Pahl & Beitz [4]. Functions were defined as well as mass, signal, and energy fluxes according to the "black box" model, and the functional basis was obtained. The black box represents the main function (overall function) of the product, while the flows of material, energy and signal are transformed by the function itself passing through the black box [23]. In this specific case, the main function is defined as "*Transport, cut, form and package tuna into cans*" (Fig. 3). Input flows (material, energy, and signal) entering the black box are: (i) tuna chunks, (ii) electricity, and (iii) weight, density. Output flows (material, energy, and signal) going out from the black box are: (i) heat, friction, (ii) tuna cans, tuna waste, and (iii) weight control. The main function is then divided into sub-functions and a complex tree structure (function structure) is created. For the sake of brevity, the overall functional structure is provided in Fig. 3 together with the identified modules. It is worth noting that most of these functions are primary functions (box with black solid line) such as "*Guarantee operator safety and ergonomic*", "*Collect and shore tuna steaks up*" and "*Package tuna chunks*", while others are auxiliary functions (box with black dotted line) such as "*Control temperature*", "*Guarantee cleanability and sanitization*" and "*Minimize tuna waste*".

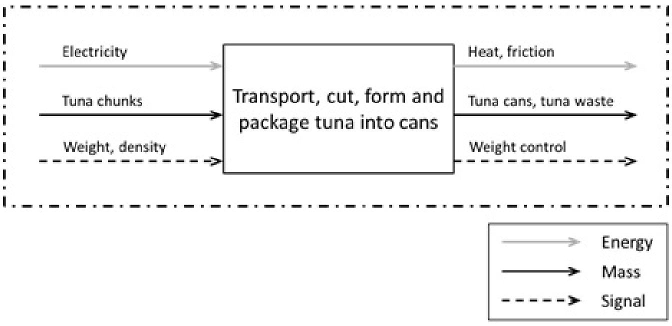

Fig. 3. Functional analyses (main level)

Once the functional analysis was obtained, it was possible to proceed with the generation of modules. The lowest level of the function structure was used to identify modules by adopting the module heuristics method for product modularization [12]. This step consists of grouping functions by using three separate strategies (heuristics) to identify modules: (i) dominant flow, (ii) branching flows, and (iii) conversion-transmission modules. Module heuristics allows to generate modules starting from general consideration, without the need of identifying a minimization function. The method of module heuristics keeps the solution space wide, allowing the design thinking process. The creation of a modular product leads to many advantages such as reduction of interface complexity between product parts, easier maintenance, customization, reduced development costs, possibility to easily upgrade the product, etc. [24][25]. Fig. 4 reports the exercise of module identification done following the dominant flow heuristic. It is worth noting that all retrieved modules were labelled from letter A to letter L. As reported in Table 1, by adopting the first heuristic (*dominant flow*) ten modules were obtained. On the other hand, by adopting the second (*branching flows*) and the third (*conversion-transmission modules*) heuristic nine modules and ten modules were obtained, respectively. With the aim to not double account modules identified by different heuristics that collect the same functions, most of them were discarded and only thirteen of them were selected as unique. The list of final modules selected for the development of product architectures is reported in Table 1. Last step of the presented workflow is the creation of the morphological matrix (also called morphological chart) [21].

The morphological matrix aimed at generating an exhaustive set of solutions for a given problem (in this case each product "module"), organizing them into a matrix where rows identify modules and columns identify possible solutions (i.e., design options). The morphological matrix enables to analyze all the engineering solutions that may occur during the development of new machines and equipment for the tuna canning process. The morphological matrix concerns the analysis and the permutations of any possible solutions generated to fulfill each module identified within the previous step [26][27]. To complete the matrix with design options for each identified module, research activities focused on both side: the overall product and each single module.

Table 1 - Identified modules.

ID	Module Name	Dominant Flow	Branching Flows	Conversion-Transmission
A	Loading	X	X	X
B	Conveyor	X		
C	Compactor	X		
D	Shaper	X	X	X
E	Optimizer	X	X	X
F	Waste collector	X	X	X
G	Safety	X	X	X
H	Weigher	X	X	X
I	Package	X	X	X
L	Controller	X	X	X
M	Cutter		X	X
P	Compactor			X
T	Compactor & Shaper		X	

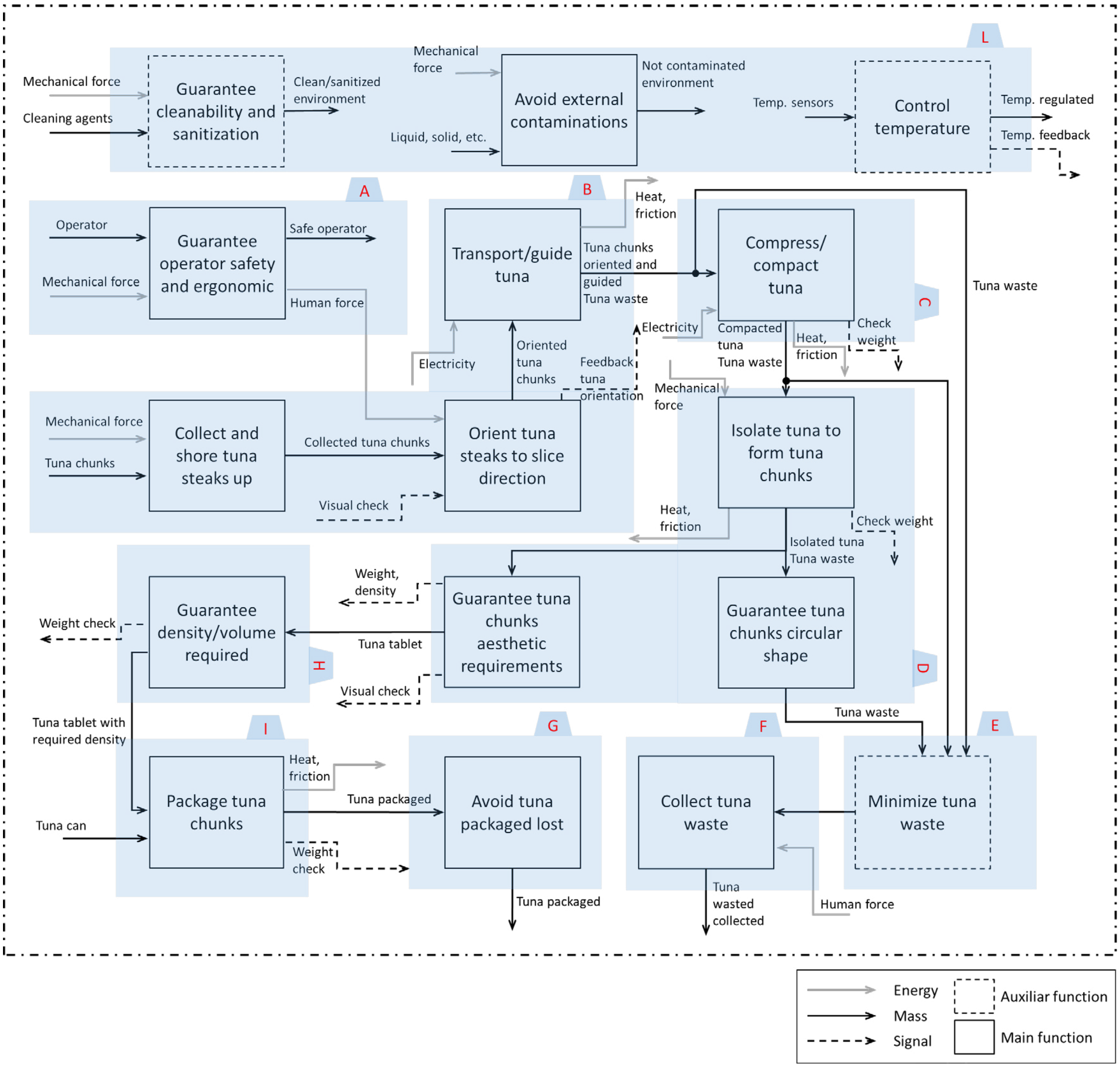

Fig. 4. Application of the “Dominant Flow” module heuristic to the functional analysis

First, a research about patents was performed using dedicated repository (i.e., Espacenet patent search). Then, a research of the available solutions on the market was done through the analysis of the website of the main tuna canning machine manufacturers (i.e., JBT, Herfraga, Hermasa, Luthi, Marlen International). In this specific case study, two different morphological charts were developed: (i) deep chart, and (ii) light chart. The deep one refers to design concept which are consistently different in principle (i.e., a mechanical force versus a magnetic force), whereas the light one refers to alternative design options inside a given design concept coming from the deep chart (i.e., mechanical force can be obtained by rotational or linear movement). The idea to have two separate charts lies on the possibility to have disruptive ideas for the generation of new concepts (new modules for innovative machines), and optimized solution when a design concept is selected. Two examples of deep and light morphological chart for the *Cutter module* (Fig. 5) and for the *Compactor & Shaper module* (Fig. 6) are reported hereafter. In the case of the *Cutter module*, the deep morphological chart reports four different concepts which allow to cut the tuna chunk to reach the right height: (i) mechanical, (ii) laser, (iii) ultrasonic cut, and (iv) water jet. Among the concepts, the mechanical one was deeply analyzed to develop the light morphological chart with four design options, which includes different types of knife, metallic wire, and a sliding system.

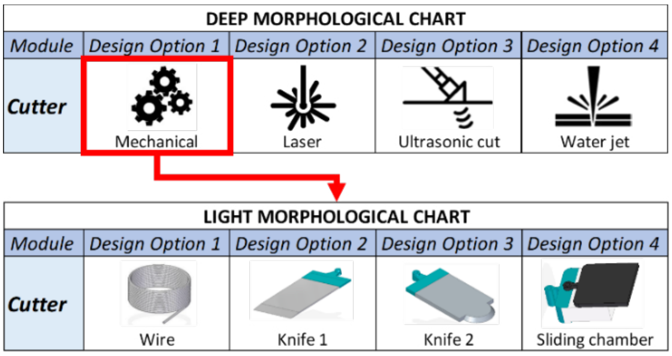

Fig. 5. Morphological charts (deep and light) for *Cutter module*

In the case of the *Compactor & Shaper module*, only mechanical concepts were developed because no further ideas were retrieved for the deep morphological chart. Among the different solutions identified within the light morphological chart, lateral shaper can be used to provide the right shape and tuna density, as well as cylinder with piston or an inflatable cylindrical chamber. It is worth noting that the *Compactor & Shaper module* is a merge of two modules: the *Compactor module* (P) and the *Shaper module* (D). In this case, the provided solutions integrate all the following functions: (i) *isolate tuna to form tuna chunk*, (ii) *guarantee tuna chunk circular shape*, (iii) *guarantee tuna chunk aesthetic requirements*, and (iv) *guarantee density/volume required*.

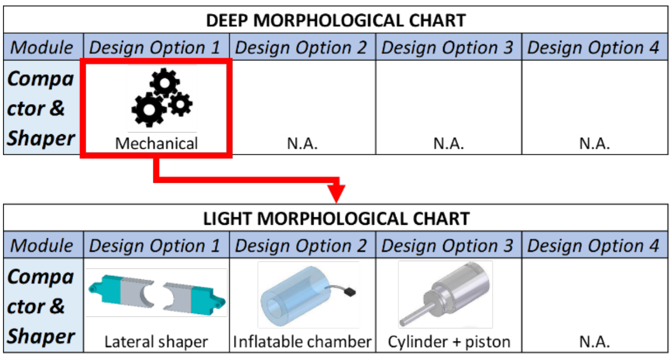

Fig. 6. Morphological charts (deep and light) for *Compactor & Shaper module*

3. Results

Modular analysis developed for the tuna canning machine allowed to drive the detail design process starting from the solutions identified within the morphological matrix to fulfill the initial requirements. In a such a complex product, modularity is a key factor in order to posterior re-designs, upgradability and maintenance. Product modules based on functions retrieved by the analysis of requirements, allows building several machines on a common product platform. By doing so, the product can be upgraded over its useful life without the need to ship a new machine but only changing the module referred to a specific function. For example, the *Cutter module* has been developed to be interchangeable among the different options, allowing to fulfil different requirements: (i) productivity and durability by using the knife design option, and (ii) product quality and aesthetic by using the wire design option (Fig. 7).

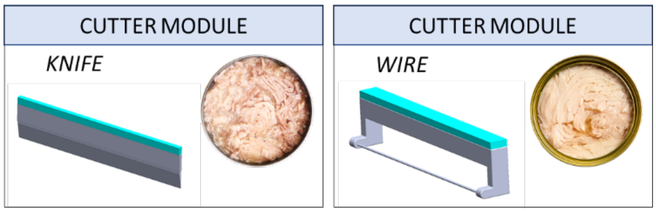

Fig. 7. Two design options for *Cutter module (knife and wire)*

It is worth noting that the knife solution does not allow to reach the aesthetic requirements of the high-end market of tuna cans due to the quality of the surface resulting from the cutting process. The possibility to switch from one design solution to another one allows to reduce the shipping cost, which is generally affected by item size and weight, thus by shipping separated modules and assemble them in place, both direct (e.g., shipping) and indirect (e.g., risks) costs are reduced. Once design solutions have been defined (both deep and light morphological matrices), the subsequent steps of the engineering design process are performed (embodiment and detail design) and technical solutions for module replacement can be adopted (e.g., positioning of bolted joints, size of bolts, etc.). These phases guarantee the feasibility of module change and product upgradability. With the aim to tackle the requirement of an improved assembly, a design for assembly analysis was performed considering module assemblability [28]. The necessary data to perform the DFA analysis were retrieved from a dated design of the same product, where design assembly optimizations were introduced (e.g., number and type of screws, size of modules, etc.). Results showed an improvement of 11% for both the assembly time and assembly costs.

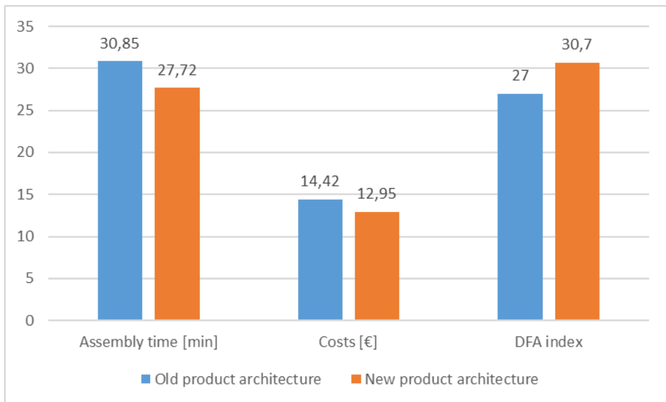

Fig. 8. Assembly improvements old/new product

Considering the other requirements, the possibility to fulfill different can sizes was accomplished working on two modules: *Cutter* and *Compact & Shaper*. Indeed, they need to work together to fulfill the final requirement. However, it was not possible to merge them together since aesthetic requirements are mainly driven by the module *Cutter*. The possibility to have product modules based on functions retrieved by the analysis of requirements, allows to build several machines on a common product platform. Small adjustments are mandatory, and they will be managed in the detail design phase, where specific manufacturing aspects will be considered, integrating the design concepts and how those concepts are inter-related.

4. Discussion and Conclusions

The paper described the engineering design process oriented to the conceptual design of a machine in the food packaging industry (tuna canning machine). The engineering design process was developed following available design methods and tools, such as the functional analysis [4], the module heuristics [12] and the morphological matrix [21]. The proposed approach has demonstrated to be a useful design tool for product modularization in this specific context (identify and characterize modules of a tuna canning machine) as well as for development of product architectures (module arrangement) based on specific aim. The possibility to change and replace modules within the product enhance the product maintainability, upgradability, and the possibility to adapt the tuna canning machine for different markets, both in terms of can size/shape and aesthetic quality of the product (tuna chunk). Moreover, the adoption of the proposed approach will be beneficial for engineers and designer to transform tacit implicit knowledge into explicit knowledge, collecting several design options for modules and product. Future works will focus this aspect defining a structured repository for the collection of ideas and design options based on requirements and related functions. The repository will be used with two aims: (i) to allow the collection of engineering and design knowledge that can be used in technical departments, (ii) to allow to develop a software tool (product configurator) that can be used by the consumers for a rapid customization of the machine. The defined methodology can be reused to develop product concepts (modular products and architectures) for other machines related to the food packaging industry.

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