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Modular redesign methodology for improving plant layout

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This research aims to show how redesigning a product, specifically modular redesign, may lead to changes in factory internal plant distribution, increasing the production levels of a company. This increase was achieved by implementing a methodology that will be discussed in this article and that includes the whole redesigning process of products, from disassembly to plant layout. For this research, tools used include functional analysis, design structure matrix, Theory of Technical Systems, design for assembly, diagram of operations and some management concepts of the platform of a modular product. To illustrate the implementation of the proposed methodology, a blender was chosen as a study case, in which, after applying the methodology, an increase in modularity, in the efficiency of design and in the efficiency of assembly, as well as a reduction in assembly times were obtained. Finally, with the new proposed plant layout, a significant increase in the production of blenders was successfully obtained.

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Design for assembly; modularity and standardisation; design-for-X; product redesign; design for modularity

1. Introduction

It is evident that contemporary technology changes rapidly (Pedroza and Ortiz 2008). As more products come to the market, they easily lose validity, change market value and may decrease their profit margins, even turning them into obsolete and useless products (Nonaka 2000). The introduction of new products to the market is becoming increasingly difficult due to the competition, fashion trends, the implementation shortage of appropriate technologies and the complexity of the legislation. Historically, most industries have offered products with shorter life cycles, while consumers demand higher quality products with more guarantees.

To meet customers' needs, it is necessary that companies have production plants that are organised and flexible (Vokurka and O'Leary-Kelly 2000). Meaning that, according to the products that the company wants to launch in the market, it should have the possibility to make changes in their manufacturing and assembly processes, and even in the plant distribution.

In most of the engineering industry, the processes of designing and of preparation for manufacture take place in different departments, with non-overlapping personnel. In fact, in many cases the manufacture preparation department undertakes modification (redesign) of constructional parts to ease manufacture (and control costs), often without

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consulting the design department about these changes. This is obviously detrimental to the quality of the product, because unintended changes to functions are introduced.

To facilitate flexibility of organisation and business, modular design of a product is essential, since from the conception of the product, the layout of the production plant needs to be considered. In the case of products redesign, which as its name suggests starts from existing products, modular redesign allows improvements in the layout of a plant that is already operating, reducing assembly and manufacturing times, and making it more flexible in order to develop a great variety of products at lower costs and with shorter delivery times (Gupta 2013).

Ulrich and Eppinger (2012, 185) define modularity as the most important feature of the product architecture – understanding architecture as 'the scheme by which the functional elements of the product are accommodated in physical parts, and through which the parts interact'. Therefore, for Ulrich, modularity is a way of organising the architecture of a product through interacting parts. The term modularity has also been used to describe the use of common units and the ability to create, in a simpler way, variants of a product by changing only some of its modules on a basic platform (Huang and Kusiak 1998). Likewise, for Ulrich modular products are integral substructures of a physical product that have one-to-one correspondence with a subset of the functional model of a product (Otto and Wood 2001, 361), or like Pahl et al. (2007, 495) would say: 'a modular product can be defined by machines, assemblies, and components that fulfil diversified general functions through the combination of different building blocks or modules'.

Since global markets are increasingly segmented, the modular architecture of products is being implemented for new product designs in a growing number of companies (Daniilidis et al. 2011). This leads to common modules which promote the purchase of high volumes of the same material, and brings benefits of economies of scale. Furthermore, the modular architecture provides the ability to adapt products to different markets, having some modules as variant modules on a basic platform, and it is worth highlighting that when working in a modular fashion, modules are easily disassembled, recycled and reused (Erixon 1996, 358).

This research aims to show how, when a product is transformed into a more modular product, the layout of a plant and its productivity can be improved, reducing assembly times and optimising the arrangement of the workstations within the plant to manufacture the final product more efficiently.

The proposed procedure is based in part on a theoretical development. Any theory even, non-mathematical theories such as the Theory of Technical Systems (Hubka and Eder 1988; Hubka and Eder 1996; Eder and Hosnedl 2008, 2010) should be as complete and well founded as possible. A method, including one based on and derived from such a theory, is either compulsory (pilot checklists for pre-take-off routine) or voluntary – voluntary methods can and must be adapted by the user for the specific problem faced by that user, including the choice of not using that method –.

The redesign process (Eder and Hosnedl 2008, 2010) as adapted (probably about 95% of all design engineering tasks) formally proceeds through stages (P1) and (P2) of the methodology for novel products:

Task defining:

- (P1) establish a design specification for the required system – TrfS(s), TrfP(s) and/or TS(s) – a list of requirements;
- (P2) establish a plan and timeline for design engineering.

It then analyses from stages (P6) or (P5b).

- (P5b) establish what constructional parts are needed, in dimensional-definitive layout, with alternatives;
- (P6) establish what constructional parts are needed, in detail and assembly drawings, with alternatives.

Reverse-engineer these structures:

The aim is to reach stage (P4), and/or (P3b), to reverse-engineer these structures.

- (P4) establish what technical system (TS)-organs (function-carriers in principle and their structure, with alternatives) can perform these functions;
- (P3b) establish what the TS needs to be able to do – its TS-internal and cross-boundary functions, with alternatives.

The resulting TS-functions can be (a) retained to ensure that the redesign does not alter them (as assumed in this paper) or (b) suitably modified to create a new, preferably improved system. The engineering designer can then use the stages and steps from (P3b) onwards in the usual order to complete the redesign.

- (P4) establish what TS-organs (function-carriers in principle and their structure, with alternatives) can perform these functions.

Embodying/laying out and detailing:

- (P5a) establish what TS-constructional parts and their arrangement are needed, in sketch_outline, in rough layout, with alternatives;
- (P5b) establish what constructional parts are needed, in dimensional_definitive layout, with alternatives;
- (P6) establish what constructional parts are needed, in detail and assembly drawings, with alternatives.

Examples of this redesign method are presented in Eder and Hosnedl (2008, 100–113, 2010, 299–307). All other quoted methods (e.g. design for manufacturing and assembly) are adjunct, and replaceable by other suitable methodical tools.

The novelty in this proposed methodology lies in extending the scope of redesign into the assembly process. The case study assumes that no changes will be made to either the principles of operation of the system or to the organs (parts interactions) that are chosen for redesign.

The important parts of the described methodology are (a) the design structure matrix to investigate the possible modules and constructional parts, and their interactions independent of function and (b) the redesign method based on the Theory of Technical Systems to ensure that the chosen interactions maintain their assumed functions regardless of any detailed design changes.

In essence, the proposed procedure is a synthesis of known steps and stages using known methods as adjuncts.

In order to demonstrate the proposed methods, an already existing product was taken as an illustrative example, a SAMURAI blender model FACICLIC black (Figure 1). The basic operation of the blender was assumed to remain unchanged. Only those component parts (and their interactions – organs) that could increase modularity and/or facilitate assembly or reduce the assembly time were subject to redesign. First, a starting study of the product is performed with the following steps: complete disassembly of the product; functional analysis (Otto and Wood 2001) of the existing blender operation processes; structure of the design structure matrix (Steward 1993), which identifies the interactions among the component parts, that is, the organs; measurement of the assembly times and completion of the operations diagram (García 2006). Following this study, changes that achieve a more modular product are implemented, always taking into account the assembly (often not a reversal of the disassembly process) and TS-internal functionality of the product, through a specific manipulation of the design structure matrix used by the methodology design for assembly (DFA) (Boothroyd, Dewhurst, and Knight 2002; Lucas 1989) to validate the changes made to the matrix. This functionality includes flow and non-flow functions internal and across the boundaries of a TS (Andreasen et al. 1988; Hubka and Eder

Figure 1. Blender SAMURAI (model FACICLIC); see also Figure 2.

1988; Otto and Wood 2001; Eder and Hosnedl 2008, 2010).[1] Finally, a modular layout of the plant was built, creating 'small factories within factories' (Ericsson and Erixon 1999, 102), where the modules were independently sub-assembled to later assemble them into the complete product, which will allow the company to 'reduce internal complexity, increase flexibility and create a proactive organization' (Ericsson and Erixon 1999, 93) in order to increase its profitability and reduce assembly times.

2. Methodological resources

For this research, a set of known tools and methods were used, which are frequently employed in product design. However, this project is focused on the redesign of products rather than on its novel design; these tools were used with a new approach adapted to our perspective. In order to understand the product objectively, functional analysis was used as presented by Otto and Wood (2001, 162–177), Hubka and Eder (1996) and Eder and Hosnedl (2010). The interaction matrix of Huang and Kusiak (1998), based on Steward (1993), was an essential tool to demonstrate the interactions between the parts and between the modules. To validate the changes made to the product, DFA of Boothroyd, Dewhurst, and Knight (2002) was used. While the first recognition of modules was based on disassembly, the assembly sequence may need to be different from a simple reversal of disassembly. The operations diagram as presented by García (2006) facilitated the understanding of the order in which the assembly should be performed. Finally, the changes in the layout of the production plant for the blender, specifically the distribution of the assembly points, were based on the platform management proposed by Ericsson and Erixon (1999).

3. Developed methodology

3.1. Disassemble

The first step that was carried out to modularise the product was to disassemble it and choose the initial modules, which were chosen prioritising an easy disassembly – looking for the grouping of parts that facilitate disassembly. These selected groups were named with the letter 'm'. This selection of the product modules can be made intuitively as was done in this investigation, or it can be performed using the previously named methodologies such as (a) the ones exposed by Ulrich and Eppinger (2012, 194–195); (b) the heuristic model of Otto and Wood (2001, 379–390), which consist respectively of identifying and outlining the architecture of the product, and selecting some flows to name them as modules through the functional diagram; or (c) the Theory of Technical Systems (Hubka and Eder 1988, 1996) using the redesign approach demonstrated in case examples to deduce the organ structure and TS-internal and cross-boundary functions (Eder and Hosnedl 2008, 2010).

For the correct understanding of this research and to facilitate the explanation of its procedure, a name and a number were assigned to each part of the product and the parts were grouped in the initial modules (Figure 2). It should be clarified that the number of units of each part is not explicit because it does not bring anything new to the purpose of this research. Therefore, whenever identical parts were presented, such as the blade gasket, they were taken as a single part. The parts that connect the modules and that can be part of the interface, such as in this case the screws, are included in one of the modules that are connected. However, it should be highlighted that the parts

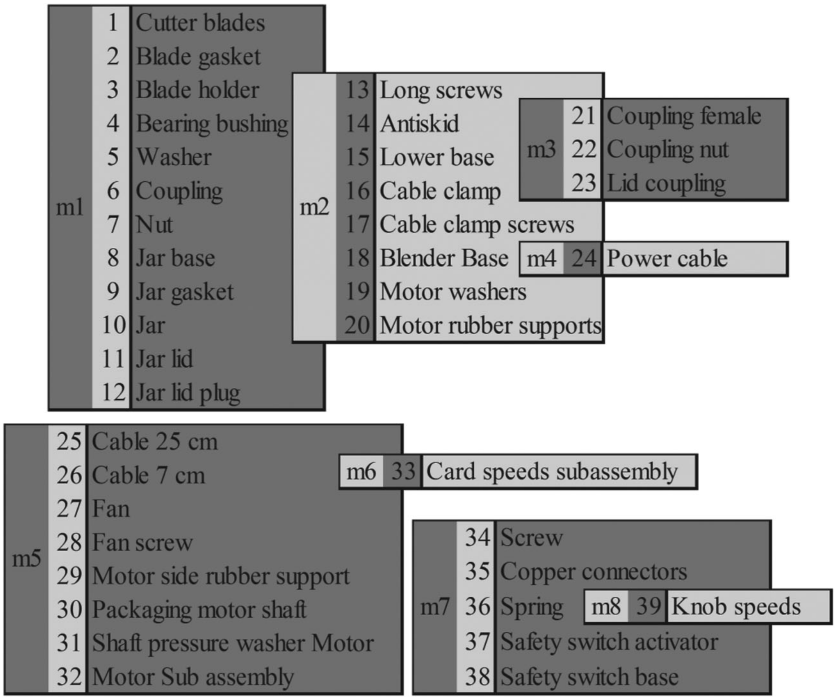


Figure 2. Blender disassemble. Note: First column, module number; second column, part number; third column, name of the part.

that connect the modules could not be considered belonging to the number of parts of any module, causing a decrease in the interactions between these two modules and affording the availability of these parts in the interface for further analysis.

3.2. Functional analysis

To understand the operation of the product, its transformation process, TrfP, a functional diagram of flow functions was prepared using the denominations recommended by Otto and Wood (2001, 172). This is a starting point for the blender to remain a blender and that the proposed modular redesign does not affect the blender (see Figure 3). For this redesign, each change was preceded by a careful analysis of the specific function of each module.

The different flows that comprise the correct operation of the blender: (a) inflows are electricity, manpower (and commands, signals) and air coming into the blender and (b) outflows are the decreased internal heat, hot air, noise and rotational energy to move the blades of the blender. Figure 3 does not include non-flow functions and does not follow the conventions of Theory of Technical Systems that functions and operations should be described by a verb (phrase) plus a noun (phrase).

3.3. Interaction matrix

For this research, the interaction matrix and the procedure used by Huang and Kusiak (1998, 67) were considered; 'the interaction matrix, $A = [a_{ij}]_{mxm}$ is an incidence matrix

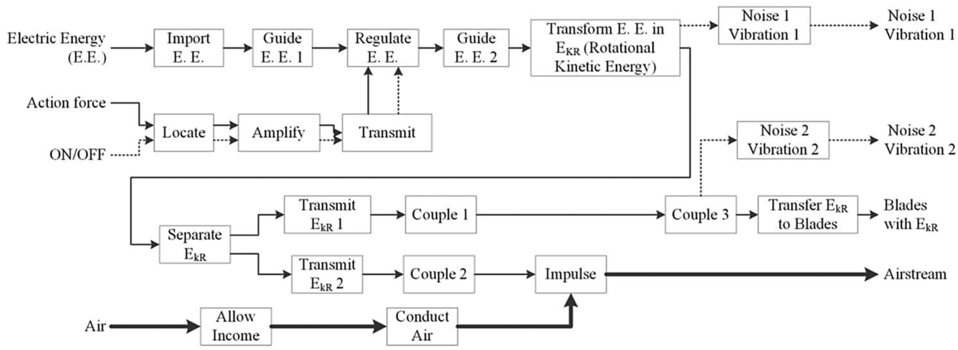


Figure 3. Functional diagram of the blender.

component by component, where a_{ij} represents the interaction between components j; i *and* $j \in C'$ and $C = \{1, 2, \ldots, m\}$ is the set of integers representing the number of rows and columns. This symmetrical matrix allows viewing the interactions between each of the parts in a complete manner (Figure 4).

To create the interaction matrix, the first column and the first row show the numbers assigned to the parts, in the order of disassembly, to then define how each of the parts interacts with each of the others. Contact between the parts i and j was denoted with a one (1) in the box that intersects them. The map of *ones* that is created in the matrix depends on the order in which the parts have been located in the columns (or in the rows); for this reason, when the blender was disassembled, the parts were grouped into subassemblies. This way of disassembly allows viewing in the matrix the groups of parts that interact more (Steward 1993).

The interaction matrix evidenced eight different main modules which have parts with a large number of interactions within each module, except for m4, m6 and m8 that are shown with a single part. It was assumed that these parts are assembled or manufactured somewhere else and enter as supplies into the production line. There are interactions of parts outside of these modules which correspond to the interactions that exist between the different modules (Figure 4).

Each interaction between parts shown in Figure 4 represents an 'elemental organ' according to the Hubka and Eder (1988, 20, 21, 22) approach. Each module represents an 'organ group'. Each such organ and/or organ group is capable of performing one or more actions, a 'TS-internal and/or cross-boundary function' of the TS – these are by definition either 'flow' or 'non-flow' functions according to Otto and Wood (2001).

Part 1 in Figure 4 is a fixed subassembly of the shaft and the cutter blades, as a module delivered from a separate supplier – a sub-module of module m1. The interaction organ between parts 1 and 4 has the TS-functions: 'guide part 1 rotationally' and 'provide life-long oil lubrication'. Part 4 is a sinter-bronze oil-retaining bearing. For more complex systems, the proposed procedure can be applied to show modules of higher complexity (e.g. for a car, the modules may be the engine, the transmission, the wheel suspension and so on), which can then each be treated by an identical procedure to review the internal details of that module – a recursive approach. Such an approach was also demonstrated in Eder and Hosnedl (2008, 100–113, 2010, 308–327).

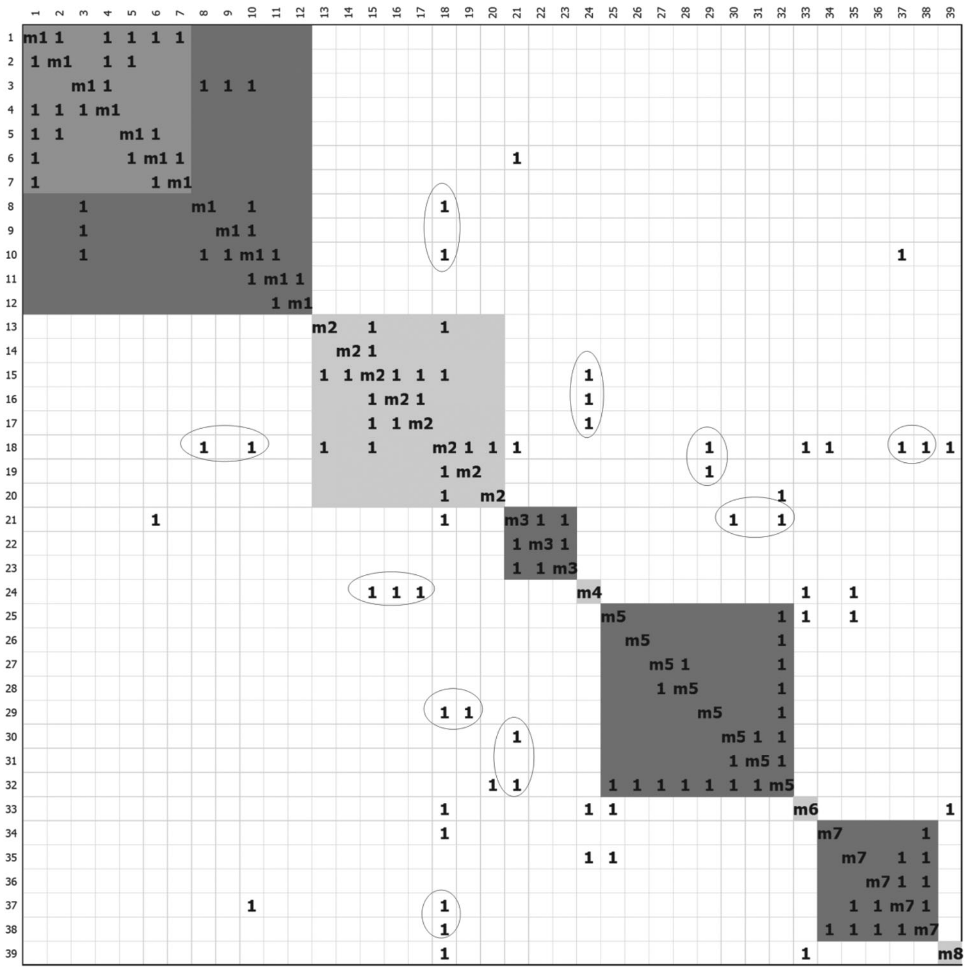


Figure 4. Interaction matrix. The numbers to the left and at the top of the matrix represent the numbering of parts, *ones* symbolise the interactions between the parts, the grey boxes demarcate the initial modules and the ovals show the interactions that are candidates to be modified.

The interactions between parts 1 and 2, parts 2 and 3 (two locations), parts 2 and 5 and parts 5 and 6 have the TS-function 'retain part 1 axially'. Parts 1–7 form a sub-module or organ group that has the overall TS-functions 'retain the cutter blade sub-assembly, part 1, axially fixed but rotationally free with life-long lubrication' and 'transmit rotation and energy to the cutter blades'. For the user of this blender, the strict instructions are that this organ group (module) shall not be disassembled by the user, and that it shall only be cleaned under running water, and not be immersed under water. All other parts of the blender jar assembly can and should be disassembled for cleaning and washing (Figure 5).

The interaction of parts 6 and 32 has the TS-function 'transmit motor rotation and energy to the cutter blades'.

Such a co-ordination among the individual parts, the interaction matrix, and recognising the functions of each interaction help the redesigner to understand the way of existence and operation of the product. It therefore helps in allowing recognition of and avoidance of errors, potential failures and manufacturing difficulties.

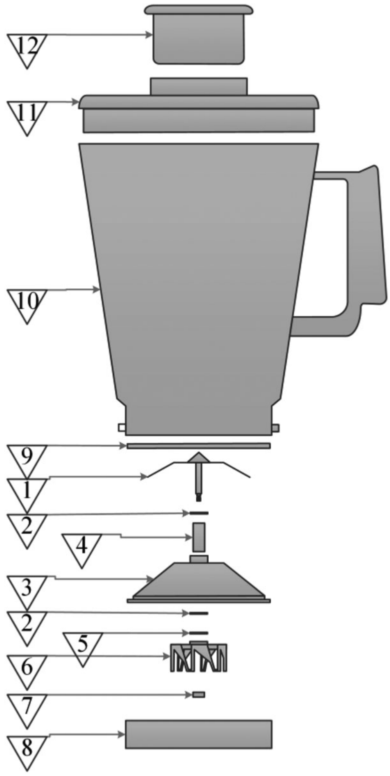


Figure 5. Exploded view of the blender jar.

3.4. DFA in function of the interaction matrix

Product evaluation of the interaction matrix with DFA (Boothroyd, Dewhurst, and Knight 2002) as a function of the interaction matrix was focused on removing and realigning the *ones* that were outside the modules. According to Hölttä-Otto Suh, and De Weck (2005), a completely modular product is one in which each of its modules interacts once with the rest. Therefore, the first aim was to decrease the interactions that are integral within the different modules, and then to decrease the interactions between a single part and the different modules without taking into account the module to which it belongs. Since the elimination of a *one* in the matrix has strong implications in the product, it is important that each improvement proposal is validated by DFA, a theory that requires to assess the scope of each possible change in the final product, keeping intact its functionality and performance. One goal of this process is to make the interaction matrix as modular as possible and in order to implement it four steps were applied: identify the parts that have interactions outside its module, row swap, parts removal and removal of interactions (Steward 1993).

3.4.1. Parts identification

As a first step, the parts that had more than one interaction with the same module were evaluated, without taking into account the module to which the parts belong. After that,

Table 1. Parts that interact outside its module more than once.

Part number	Part name	Interacts outside its module with
18	Blender base	8 and 11, 37 and 38
21	Coupling female	30 and 32
24	Power cable	15, 16 and 17
29	Motor side rubber support	18 and 19

the *ones* that meet the premise above in the interaction matrix were identified (Figure 4). This scheme evidenced which parts should be redesigned to try that each part has at most one interaction with the other modules. In the blender such parts are the base (18), female attachment (21), power cord (24) and motor side rubber support (29) (Table 1).

3.4.2. Rows swap

The second step is where these parts interact more outside its module than within its own module, to make appropriate exchanges between the matrix rows (and the columns to keep symmetry) and reorganise it so that interactions between modules are reduced (Figure 8). The motor side rubber support belongs to m5, allowing two interactions with m2 while interacting once within it own module (29); this scenario meets with the conditions described above for the blender. The first operation that was performed was to remove the motor side rubber support (29) with TS-functions (Hubka and Eder 1988, 1996; Eder and Hosnedl 2008, 2010), 'isolate motor vibrations' and 'react motor torque to base' from module m5 and put it in the module m2. To put the rubber supports first onto the base would not allow their assembly. So a change was made in the way of assembling the motor subassembly (32) to the blender base (18), altering a simple reversal of the disassembly process, and a change in the physical form of the motor side rubber support (29) (Figure 6). To recall, the modules were chosen to simplify the process of taking the pieces apart; therefore, the pieces belong to a module in the same order in which they should be disassembled. A change in the order may imply disassembly, and therefore assembly in a different way, as occurs in the illustrated case.

3.4.3. Parts removal

As a third step, the parts that interact more than once out of their module were identified; they can be eliminated or integrated into other parts. Studying the parts of the blender and evaluating them according to their functions and assembly, it was seen that two parts can be eliminated with little effect on the functionality of the product. The cable clamps (16) and cable gland screws (17) have the TS-functions of 'holding the power cable (24) to the

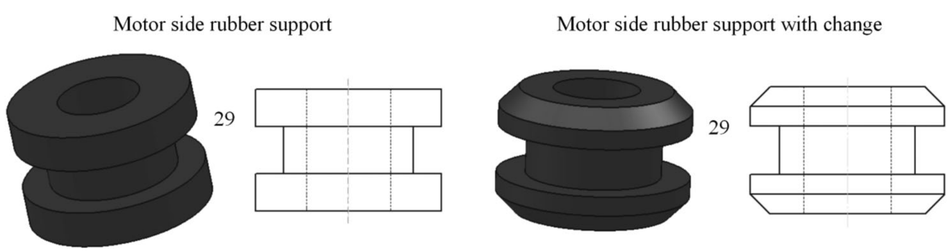


Figure 6. Change made to the motor side rubber support (29).

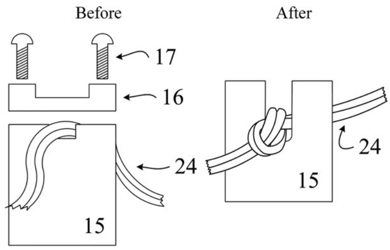


Figure 7. Parts removal. Power cable (24) and a small portion of the lower base (15). Left side: candidate parts to be eliminated, cable clamp (16) and cable gland screws (17). Right side: redesign proposal in the small part of the lower base (15).

blender base' and 'transferring any pull force on the power cable (24) to the base'. To remove these two parts, it is necessary to modify the lower base (15), while the power cable (24) is maintained in position (Figure 7), now with a knot. The elimination of these two components produces a reorganisation in the matrix of interactions (Figure 8), showing a lower amount of *ones* outside modules, which implies an approach to a more modular product.

3.4.4. Interactions between modules are eliminated

Finally, based on the modules that interact more than once evidenced in the matrix (Figure 8), we proceeded to eliminate the interactions between modules. It is worth remembering that the analysis of the interactions of individual parts was performed previously; hence, in this section account will only be taken of the interactions between the different modules (Table 2). After completing this process, a new matrix was built that includes all the modifications performed and that shows an increase in the modularity of the product (Figure 10). Each of the modifications made in the parts of the blender to decrease the interactions between modules is described below:

- To generate a single interaction between m1 and m2, the jar base (8) was modified, making it 20 mm higher to eliminate interaction between the jar (10) and the blender base (18). By making this change, the activator for safety of the jar (10) became part of the fastener of the jar base (8). This, in addition to eliminating the interactions between m1 and m2, facilitated uncovering the jar (10) at the bottom, providing two points to support this action. It must be considered that the jar needs to be 20 mm shorter in order to maintain the overall dimensions of the product (Figure 9). Another variation that can be seen after this modification is that the safety switch activator (37) stops interacting with the jar (10) and passes to interact with the holder of the jar base (8), which means that the interface between modules m1 and m2 is simpler. The simplicity of the interactions and the precise definition of these are an essential part to modularise a product. This can be seen in the module definition of Hölttä-Otto (2005, 27): 'A module is an independent building block of a larger system with a (one or more) specific function and well-defined interfaces.' Is important to clarify that this change does not affect the TS-function of the jar (10).
- It was evidenced that modules m2 and m5 have two interactions: one through the motor rubber supports (20) and another by the motor side rubber support (29). The modification made to achieve a single interaction was to unify these supports. Now

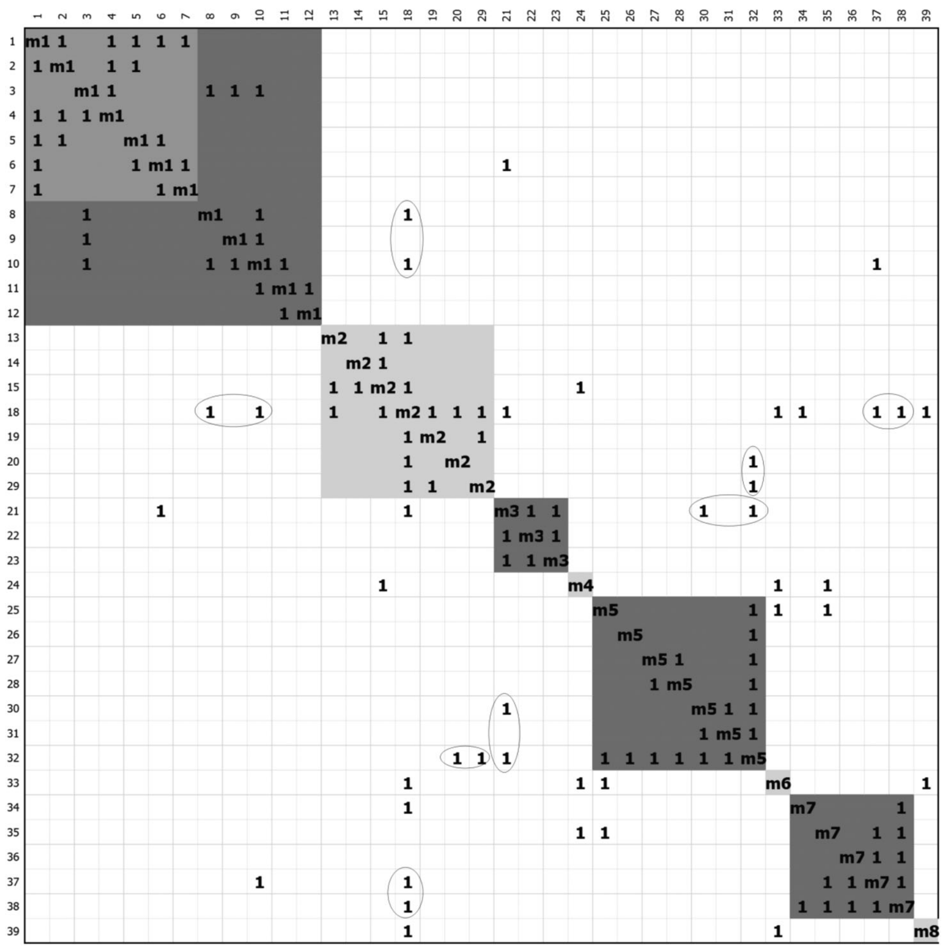


Figure 8. Interactions matrix with changes implemented.

Table 2. Interactions between modules specifying the parts involved.

Module	Interact more than once	Parts involved
m1	m2	8 and 10 interact with 18
m2	m5	20 and 29 interact with 32
	m7	18 interacts with 37 and 38
m3	m5	21 interacts with 30 and 32

being identical parts, it performs two functions and can be ordered as equal pairs of supports, instead of pairs of different supports. To achieve that the supports fit into the cavity of the blender base (18), the size of the supports is adjusted to make them fit on it. Taking into account that equal parts are taken as if they were a single one, a single interaction between these two modules is obtained, even though there are four contact points between the blender base (18) and the motor subassembly (32) through the supports.

- Since modules m2 and m7 also interacted more than once, it was possible to reduce the interactions between these two modules, making the blender base (18) not to be the

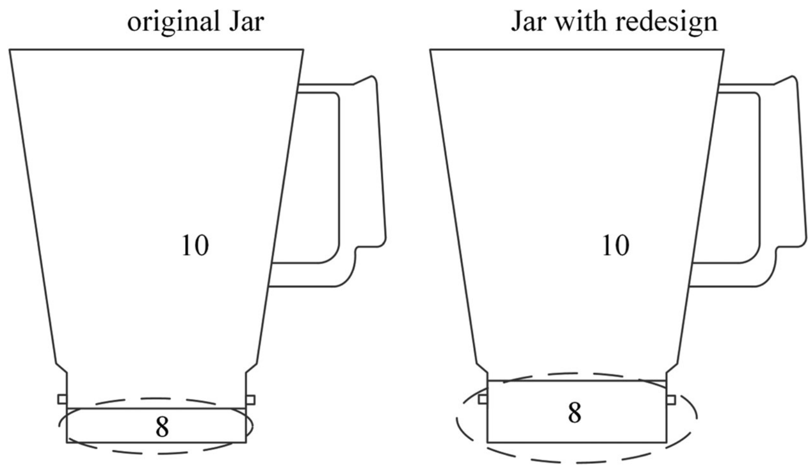


Figure 9. Change made to decrease the interactions between modules. The jar base (8) was made higher to eliminate interactions between the jar (10) and the blender base (18).

guide of the safety switch activator (37); instead, this function will be done by the safety switch base (38), which is its own base.

- Interactions between modules m3 and m5 involve essential relationships for the operation of the blender, such as coupling female (21) with the packaging motor shaft (30) and the axis of the motor subassembly (32); therefore, it is not possible in this case to change the product.

After the mentioned four steps were implemented, an analysis of the blender assembly was made, and modules m4, m5, m6 and m7 were combined, as this facilitates the assembly, and a single module was generated comprising all the electrical parts of the blender. To understand the new matrix of interactions, the resulting modules after implementing all changes are denoted with the letter 'M'. The new modules were composed from the previous ones as follows: m1 became M1; m2 into M2; m3 into M3; m4, m5, m6 and m7 into M4 and m8 into M5 (Figure 10). As the objective was to make the product as modular as possible, in this case it is evident that the base module cannot have a single interaction due to its functionality. This is not the only feature that makes modularity difficult, also is important to keep in mind that a large size module and/or a module with many parts is more difficult to modularise (Figure 11).

After the identification of the parts, the exchanging of rows and removing of parts depended on the interaction matrix, and it can be concluded that the implementation of the changes described increased the modularity of the blender by 27.78%. This percentage was calculated by enumerating the eliminated interactions and comparing the number of initial interactions, obtaining a simpler product in which the interactions between modules have decreased (Figure 12). Likewise, the modularity index of singular value applied to the interaction matrix before applying modularity (Figure 4) and after (Figure 8) shows that the resulting matrix is more modular as it has an index value 0.167 closer to 1 than the index of the initial matrix (0.154).[2]

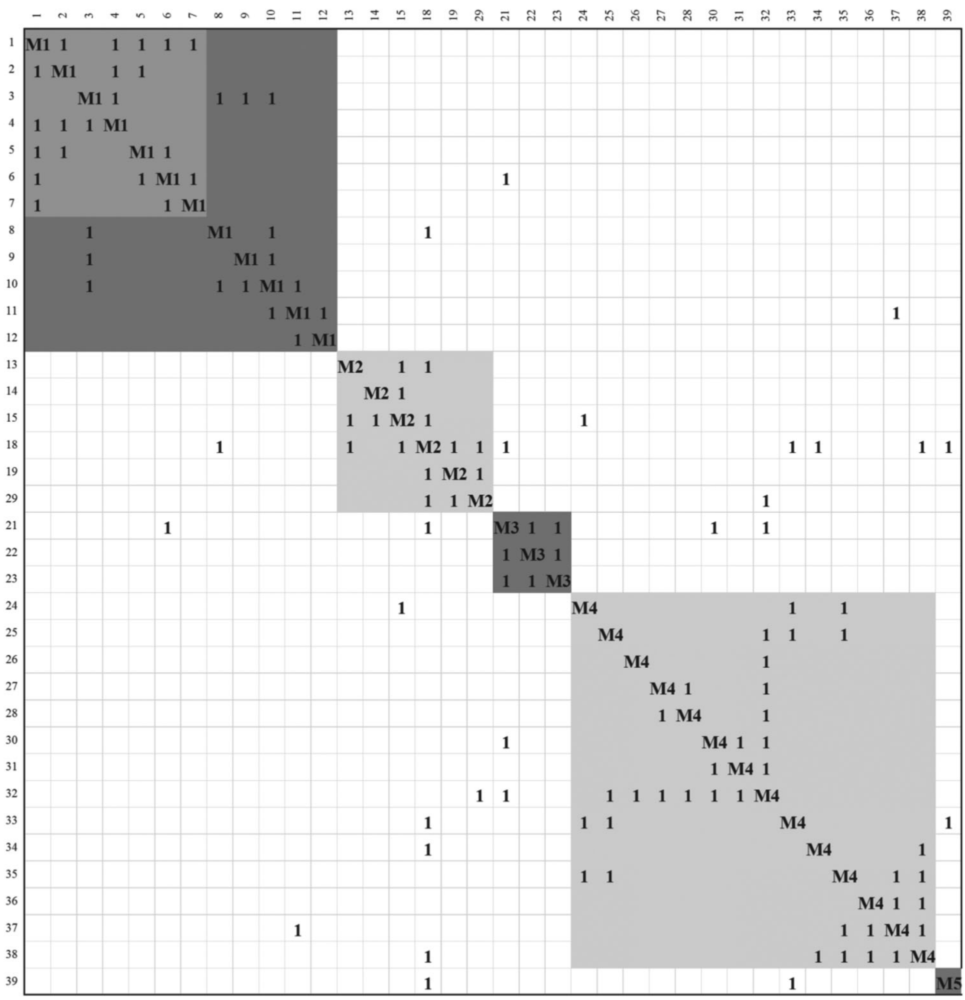


Figure 10. Interactions matrix after a modularity analysis. The final modules are denoted with the letter 'M'.

3.5. Measurement of assembly times before and after modularisation

This stage started with a careful review of the processes to note all necessary changes. To validate the changes made to the product, the assembly times of the original blender were measured (Table 3), the reductions caused by these changes were estimated and finally, both results were compared in the modules M1 and M2 and in the assembly of M4 in M2, since it was in these modules where time reductions occurred.

For the measurement of the assembly times, all the elements of the blender were placed near the work area, as per our initial assumption that the parts do not require storage away from this area due to their weight and/or size. Several practice assemblies were made to approach the times that an operator can reach, and the time of the last six assemblies was averaged (Table 3). This allowed reducing the assembly time variation between trials. Then they were compared with those obtained from the process of modularisation; times were separated by modules.

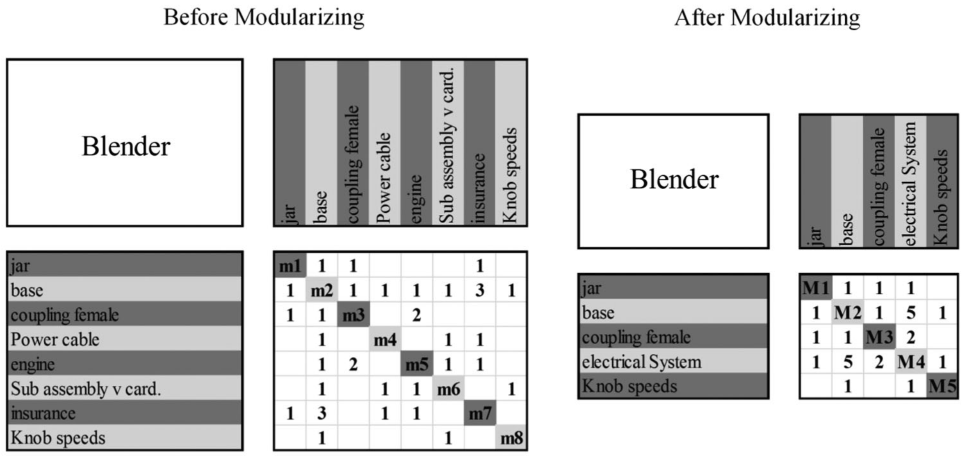


Figure 11. Simplified comparison of the matrices before and after the process of modularising: the first row and the first column show the names of the modules. The grey boxes in the matrix correspond to the modules. And the numbers of the matrix in white boxes denote the quantity of interactions between modules. To the left is the matrix before modularisation and to the right is the matrix after modularisation.

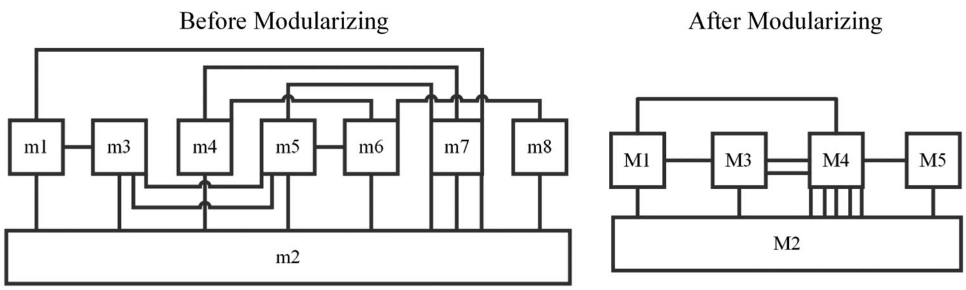


Figure 12. Outline of the manner in which modules interact. The boxes represent the modules and the lines that connect boxes' interactions. The left presents the outline before modularising and the right after modularising.

Table 3. Initial assembly times of the blender separated by modules.

Module	Assembly time (s)
m1	49.07
m2	33.97
m3	20.72
m4	214.60
m5	
m6	
m7	
m8	–
m4 with m2	150.20
m3 with m2m4	40.50
m8 with m4	19.89
Total (s)	528.95

Table 4. Theoretical assembly time for the electrical part of the blender.

Operations	Time (s)	No. of cables	Total time (s)
Stripping the cable	7	12	84
Weld	9	8	72
Pressing	13.9	4	55.6
Total			211.6

In our case study, a theoretical calculation of the assembly times was estimated for the whole electrical part based on the theory DFA (Boothroyd, Dewhurst, and Knight 2002), and using the experimental time presented in the graphs (160–162) (Table 4). Evaluating the adjustments that were made to make the product more modular, the following results were obtained in the reduction of the assembly time.

3.5.1. First change: eliminating cable clamp (16) and two cable clamp screws (17)

The elimination of these three parts means that the two cable clamp screws (17) and the cable clamp do not have to be tightened (16); these implied a reduction of 23.63% in time. When performing this change, the function of the cable clamp was integrated to the lower base (15), modifying the injection mould to make a parallel-sided slot in a small part of the lower base (15), tying a knot into the power cable (24), and thus be able to hold the cable through it (Figure 7).

3.5.2. Second change: modification of the motor subassembly (32) and changing the motor side rubber support (29) to the base

Modifying the motor subassembly (32) and arranging the motor side rubber support (29) in the blender base (18) facilitates assembly, reducing the time by 2 s, a decrease of 5.89% in this operation.

3.5.3. Third change: extension of the walls of the fastener of the jar base (8) and transferring the safety activator of the jar to the same fastener

Making the walls of the bottom cover fastener higher (8) and transferring the safety activator from the jar to the fastener of the bottom cap involve modifying the injection moulds. However, this change makes the assembly of the bottom cover fastener (8) to the jar (10) easier and increases the benefits not only for the operator but also for the user of the blender. This increase in the ease of assembly was assessed in a reduction in time by a second (it decreases 2.04% the assembly time in this operation).

3.5.4. Fourth change: unification of motor supports

Making the motor supports identical saves time in defining which supports to use and where to put it. This procedure reduces the overall assembly time by 3 s, corresponding to a decrease of 8.83%.

After making the four changes described, a reduction in the assembly time of 8.70% per assembled blender was obtained (Table 5). This means an increase in the production of blenders and, of course, an increase in the anticipated sales of the manufacturing enterprise. In other words, if a single operator works 8 h a day, there will be an increase of five blenders per day, equivalent to an increase of 1820 blenders in a year for each operator.

Table 5. Time reductions and total assembly time for modularised blender.

Module	Assembly time (s)	% of decrease by modules
M1	48.07	2.04
M2	28.97	14.72
M3	20.72	
M4	214.60	
M5	–	
M4 with M2	110.20	26.63
M3 with M2M4	40.50	
M5 with M4	19.89	
Total (s)	482.95	8.70

Out of the measurement of the assembly times, another form of assessment was used to validate the changes made to our example product. The indexes of two different methodologies of DFA were measured: the design efficiency (Lucas Engineering & Systems Ltd. and University of Hull 1989) and the assembly efficiency (Boothroyd, Dewhurst, and Knight 2002). Both indexes were calculated for the initial product and the modularised product.

The design efficiency is defined as the number of type A parts over the total number of parts, where the number of type A parts are the ones essential for the proper functioning of the product, and therefore they are not susceptible to change. These parts were chosen according to the rating questions of parts schematised in Figure 13, which shows a procedure in which these two methods were combined on the same diagram. The questions in the first row are those proposed by Boothroyd, Dewhurst, and Knight (2002) and the rest were proposed by Lucas (1989) (Figure 14).

The efficiency of the assembly is determined by the number of type A parts multiplied by 3 s, and divided by the actual assembly time. These 3 s is an average assembly time for a part that has no operating, insertion or fixing problems (Boothroyd, Dewhurst, and Knight 2002, 94) (Figure 15).

When the indexes for design efficiency (Lucas Engineering & Systems Ltd. and University of Hull 1989) and assembly efficiency (Boothroyd, Dewhurst, and Knight 2002) were calculated before and after the modularisation of the blender, an increase of 2.79% and 3.80%, respectively, was noted, which validates the changes made to the product. If the design efficiency was 100%, we would have a product in which all its parts are 100% necessary, and if the assembly efficiency was 100%, we would have a product with an optimal assembly process; for this reason, any increase in these two indexes leads to a more efficient product. It is important to clarify that since the proposed changes are aimed to modularise the product and not to redesign it from an assembly viewpoint, these rates could be increased if DFA (Boothroyd, Dewhurst, and Knight 2002) was implemented in each of the modules separately.

In conclusion, changes performed in the blender in function of DFA with a modular perspective increased the design efficiency, assembly efficiency and the daily number of blenders produced (Table 6). This means that the implementation of this methodology in the products of a company can increase the profitability mainly by increasing the number of blenders produced. Furthermore, these changes performed from a modular perspective influence the organisation of the production plant as evidenced below.

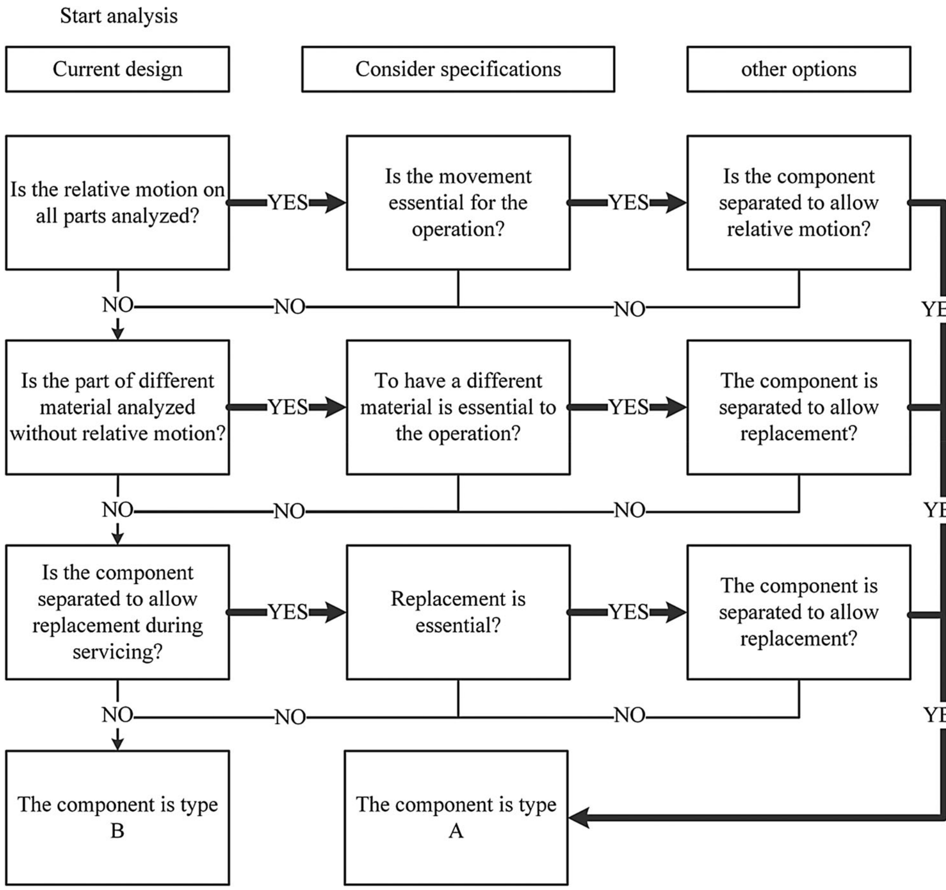


Figure 13. Classification of type A parts. The diagram shows the classification questions of type A parts, obtained by integrating questions from Boothroyd, Dewhurst, and Knight's (2002) methodology and Lucas Engineering & Systems Ltd. and University of Hull's (1989) methodology.

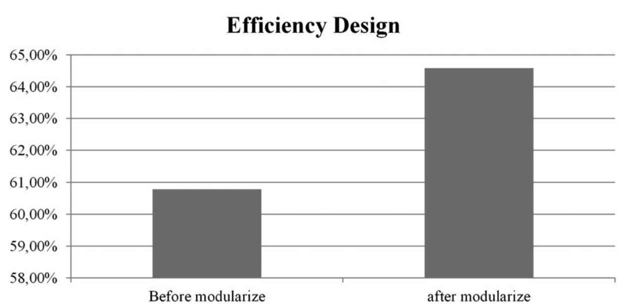


Figure 14. Design efficiency (Lucas Engineering & Systems Ltd. and University of Hull 1989) before and after the product modularising. Shows an increase of 2.79%.

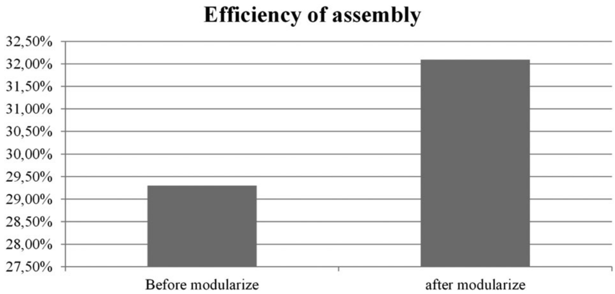


Figure 15. Assembly efficiency (Boothroyd, Dewhurst, and Knight 2002) before and after product modularising. Shows an increase of 3.8%.

Table 6. Increase in the efficiency of design, increase in the assembly efficiency and increase in the production of blenders.

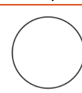
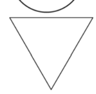
Increased efficiency of design	2.79%
Increased efficiency of assembly	3.80%
Percentage reduction in assembly time	8.70%

3.6. Operation chart before and after product modularisation

To continue the study and give guidance for plant layout, an operation chart was generated, as proposed by García (2006), in which the operations necessary to assemble the product were schematised.[3] These diagrams are composed of five main symbols of which only three were used for this investigation: the ones corresponding to operations, storage and transport (Table 7). Operations were taken as the necessary procedures for the product to be assembled, stored as the meeting point where the parts are arranged to achieve the operations and transported as the action of moving a part from the point of storage to the point where the product is assembled.

To construct the operations diagram, the order in which the blender was assembled was taken into account, meaning that each part begins to be stored, then transported to the place of assembly and finally assembled through an operation, which in the case of the blender is to insert, screw and/or bond. To better understand the flowchart scheme, the module jar assembly (m1) is exploded along with the numbering of the operations required to assemble this module (Figure 16, left); the ovals in each diagram represent operations of the modules discussed above.

Table 7. Symbolism used in the operation chart (García 2006, 54).

Operation	Description	Symbol
Operation	'Occurs when an object is being changed in its characteristics, it is being created, adding something or it is being prepared for another operation'	
Storage	'Occurs when an object or a group of them are retained and protected for a later use or to not misuse them'	
Transport	'Occurs when an object or a group of them are moved from one place to another except when this movement is part of another operation'	

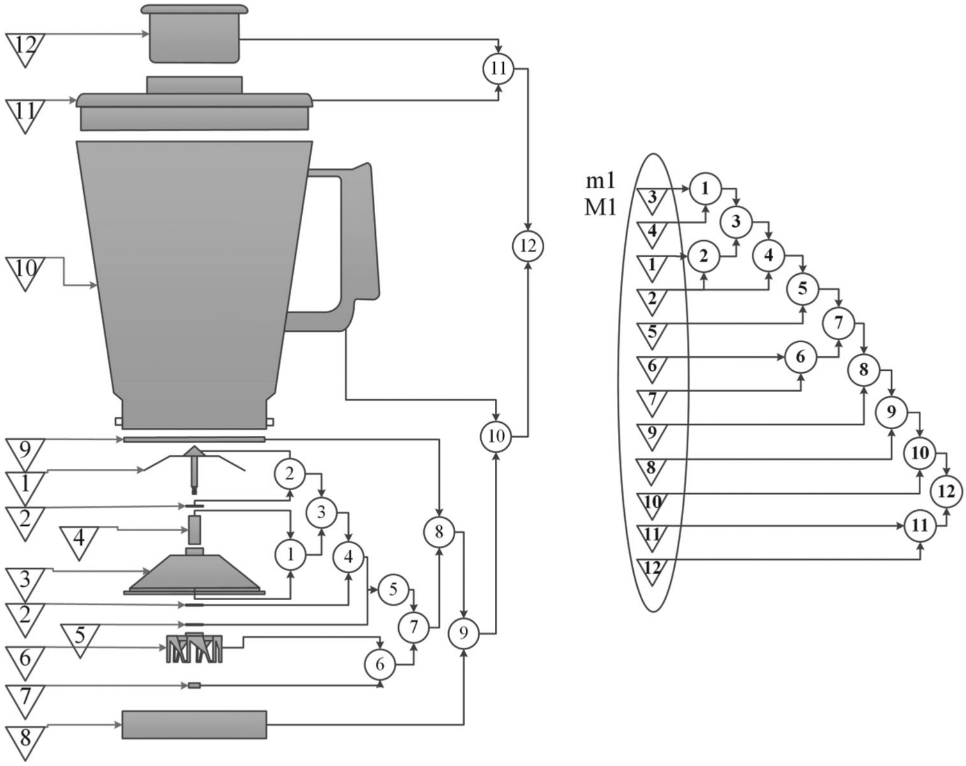


Figure 16. Flow chart for the blender jar. Left side: scheme of the original jar assembly module (m1) exploded with the operations. Right side: operations diagram of the redesigned module jar assembly (m1, M1).

The simplicity of the flow chart showed an overview of product assembly and allowed to determine which parts and subassemblies could be assembled simultaneously. Generally, in a production process subassemblies are assembled with pre-assembled subassemblies and usually not individual parts together. For the case of the blender, parts 35, 36, 37 and 38 were previously assembled by means of operations 19, 20 and 21 that can run simultaneously with operations 16, 17 and 18 (Figure 17).

As the diagram of operations shows how parts are organised schematically in a sequential order according to the order of assembly operations, it is important to observe how the modules are distributed. Considering that an assembly process is more efficient if modules are assembled separately, which also implies a higher level of modularity (Ericsson and Erixon 1999), it was shown in the flow chart of the blender base before modularising that modules were intersecting others in the assembly process, and that they presented operations that did not allow the assembly of modules separately (Figure 17). This is unlike the flow chart after modularising (Figure 18) in which it is clearly outlined that M4 was transformed into a totally independent module.

3.7. *Distribution of plant in the assembly process*

In the final part of this investigation, it was proposed to redistribute the plant, according to the assembly process and the new modules proposed. As a starting point, an initial

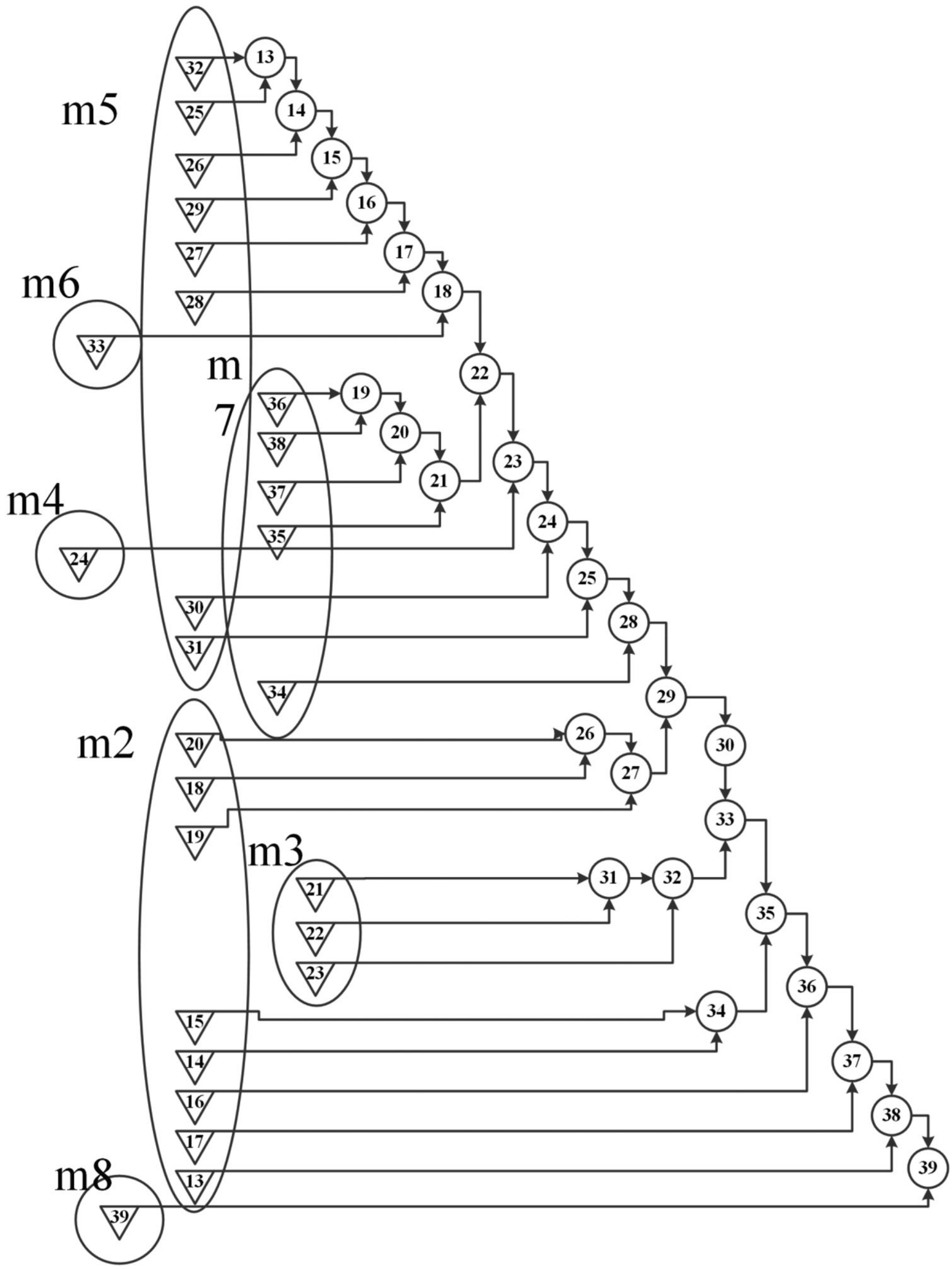


Figure 17. Flow chart of the blender base before modularising. The flow chart of the blender base before modularising is presented.

distribution of a plant with two workstations was considered, one to assemble the blender jar and another to assemble the rest of the blender. The proposed distribution of the plant was made according to the chosen initial modules. This initial plant distribution produces a total of 60 blenders daily, based on the speed of assembly of the slower workstation; it is

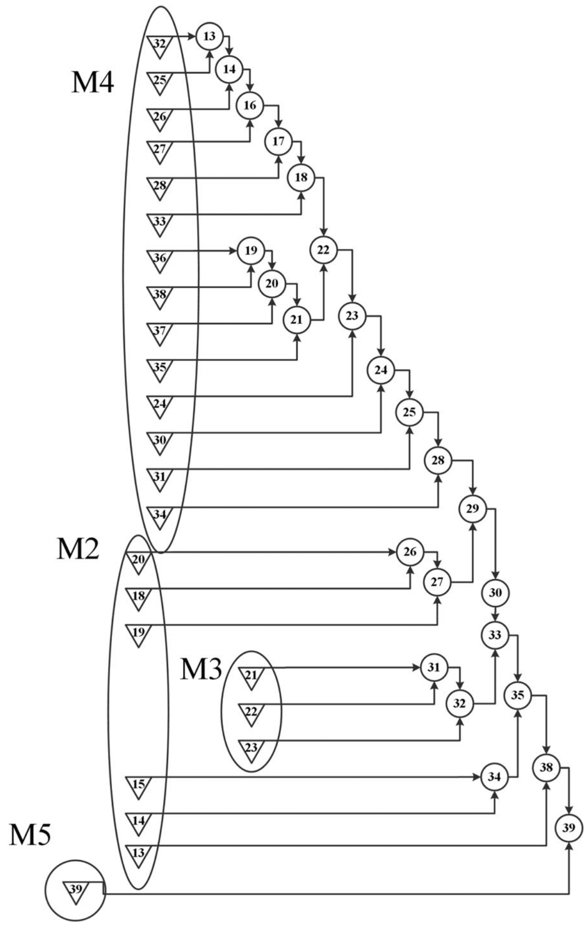


Figure 18. Flow chart of the blender base after modularising. The flow chart of the blender base after modularising is presented. The blender jar module (M1) was omitted because after modularising, its flowchart did not change.

the one operating with modules m2–m8 which takes 479,88 s for its assembly (Figure 19, initial).

By implementing the process of modularisation for the blender, we split workstations by modules in order to have 'products within the product, small factories within the factory' (Ericsson and Erixon 1999, 102–105). With this new distribution of the plant, the production rate increased by 116.67%, since the slower workstation, which in this case is that corresponding to M2, M3 and M5, is 259,60 s faster than the slowest module in the initial distribution (Figure 19, 1).

The modular design and specifically the newly defined modules in the product allowed different plant layouts to select the best option, efficiently assemble more blenders and achieve an increase in productivity. For example, the formation of four operators where modules M2, M3 and M4 are assembled only by two of them will allow an increase of 123% compared to the initial distribution (Figure 19, 2). This configuration could be optimised through maximising the working time of the workers. If the operator of the faster

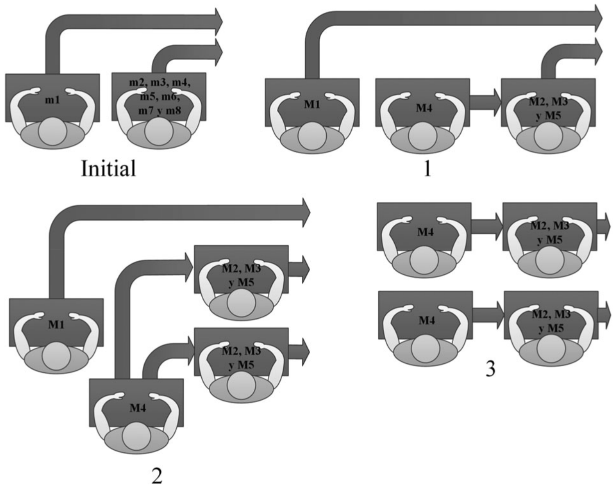


Figure 19. Layout of plant before and after the process of modularisation. After making a modular analysis of a product, other layouts of the plant can be proposed that allow a further increase in the production of that product, in this case blenders.

module, which in this case is M1, assists in the assembly of M4 after finishing the assembly of 217 blender jars, this would increase the number of blenders to 217. Expressed in working hours, working for 3 h in formation 2 and for 5 h in formation 3, an increase of 262% in the daily production of blenders (Figure 19, 3) would be implemented. This shows that the modular redesign has high implications for optimising the assembly time, the use of the work area, the elimination of rework, the flexibility of the company and therefore the productivity of a company.

4. Conclusions

This research proposed using procedures based on tools that are normally used for designing and were adapted for redesigning of products, specifically to work based on principles of modularity, since the existence of methodologies to work in redesigning products is scarce in the literature. It was shown how the adaptation of these tools in existing product can generate changes in the layout of a plant, facilitating organisation in the areas of assembly, increasing flexibility and increasing production levels of a company. In addition, the methodology can help implement a modular platform in cases where a company has products.

The proposed method comes from the complete knowledge of the product. As a first step, disassembly and functional analysis of the product are made. In the disassembly process, the initial modules are chosen and the first interaction matrix is generated for an analysis from the DFA and the modularising of the product. This modularisation is performed by reducing the number of interactions between modules, resulting in a new interaction matrix, which is built in each step of the DFA methodology and the functional analysis of the modules. Finally, to improve the distribution of the plant, implementing a flow chart is proposed to display the jobs and propose different distributions of the plant from which it is possible to choose the most efficient for the company.

To evaluate the benefits of the changes made by the interaction matrix assembly, times were measured before and after modularising and the function of each module was revised. Specifically, by applying the method to a blender, an increase in modularity of 39.13% was obtained, along with a reduction in assembly times (8.70% by blender), an increase in the efficiency of design and an efficiency of assembly (2.79% and 3.80%, respectively); with the new plant layout produced according to the modules obtained, the production of blenders was increased by 116.67%; and finally by using the modules to their maximisation with four operators, production increased by 262%.

Given the established modules, various formations in the distribution of the plant may be considered and chosen according to the number of operators, the displacement time and modules assembly time, among other important variables, which best suits the needs of the company.

In this research, a modularisation methodology that is easy to implement on any product is proposed, because it allows the analysis of the product abstractly with the interaction matrix and functional analysis, and tangibly with DFA, to permit a decrease in assembly time and manufacturing costs, and an increase in production. Thus, the plant becomes more flexible and this helps to improve the processes. It is a methodology that enables to retrace the steps already taken in order to make the product that is being studied progressively more modular, which then allows another type of analysis on each of the modules, such as design for quality, DFA and design for robustness, among other designs for X that exist.

Notes

1. For 'more modular' we understood a product with fewer interactions between modules. Throughout the article, the process of modularisation is evidenced in the decrease in interaction between modules.
2. The literature shows that the SMI can be used to measure modularity (Hölttä-Otto and De Weck 2007); however, this index is highly dependent on the size of the matrix, implying that two arrays of different size cannot be compared, and that as matrices tend to be larger, the SMI values will tend towards zero.
3. As a result of using the operation chart, a product can be more modular. Therefore, it is recommended to integrate the operation chart in the modularisation process of the product.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Andreasen, M. M., S. Kähler, T. Lund, and K. G. Swift. 1988. *Design for Assembly*. 2nd ed. Berlin: Springer-Verlag.

Boothroyd, G., P. Dewhurst, and W. Knight. 2002. *Product Design for Manufacture and Assembly*. 2nd ed. Boca Raton, FL: CRC Taylor & Francis.

Daniilidis, C., V. Enßlin, K. G. Eben, and U. Lindemann. 2011. "A Classification Framework for Product Modularization Methods." DS 68–4: proceedings of the 18th international conference on Engineering Design (ICED 11), Impacting Society through Engineering Design, Vol. 4: Product and Systems Design, Lyngby/Copenhagen, August 15–19.

Eder, W. E., and S. Hosnedl. 2008. *Design Engineering a Manual for Enhanced Creativity*. Boca Raton, FL: CRC Press.

Eder, W. E., and S. Hosnedl. 2010. *Introduction to Design Engineering: Systematic Creativity and Managment*. Leiden: CRC Press/Balkema.

Ericsson, A., and G. Erixon. 1999. *Controlling Design Variants: Modular Product Platforms*. 1st ed. Dearborn, MI: Society of Manufacturing Engineers.

Erixon, G. 1996. "Design for Modularity." In *Design for X*, 1st ed., edited by G. Q. Huang, 356–379. London: Chapman & Hall.

García, R. 2006. *Study of Work: Engineering Methods and Measurement of Work*. 7th ed. México: McGraw-Hill.

Gupta, G. E. 2013. "Analysis of Modularity Implementation Methods from an Assembly and Variety Viewpoints." *International Journal of Advanced Manufacturi Technology* 66 (9–12): 1959–1976.

Hölttä-Otto, K. 2005. "Modular Product Platform Design." Doctoral diss., University of Technology, Laboratory of Machine Design, Helsink, 151.

Hölttä-Otto, K., and O. De Weck. 2007. "Degree of Modularity in Engineering Systems and Products with Technical and Business Constraints." *Concurrent Engineering* 15 (2): 113–126.

Hölttä-Otto, K., E. S. Suh, and O. De Weck. 2005. "Tradeoff Between Modularity and Performance for Engineered Systems and Products." In *ICED 05: 15th International Conference on Engineering Design: Engineering Design and the Global Economy, August, 15–18*, edited by A. Samuel and W. Lewis. Barton: Engineers Australia.

Huang, C. C., and A. Kusiak. 1998. "Modularity in Design of Products and Systems." *IEEE Transactions on Systems, Man, and Cybernetics* 28 (1): 66–77.

Hubka, V., and W. E. Eder. 1988. *Theory of Technical System: A Total Concept Theory for Engineering Design*. 2nd ed. New York: Springer-Verlag.

Hubka, V., and W. E. Eder. 1996. *Design Science: Introduction to the Needs, Scope and Organization of Engineering Design Knowledge*. London: Springer-Verlag.

Lucas Engineering & Systems Ltd., and University of Hull. 1989. *Design for Assembly Practitioners Manual*. 5th ed. Hull: University of Hull.

Nonaka, I. 2000. "The Knowledge-creating Company." *Harvard Business Review* 69 (6): 96–104.

Otto, K., and K. Wood. 2001. *Product Design: Techniques in Reverse Engineering and New Product Development*. 1st ed. Upper Saddle River, NJ: Prentice Hall.

Pahl, G., W. Beitz, J. Feldhusen, and K. H. Grote. 2007. *Engineering Design: A Systematic Approach*. 3rd ed. London: Springer.

Pedroza, A. R., and S. Ortiz. 2008. "Technology's Strategic Management in the Pre-development of New Products." *Journal of Technology Management & Innovation* 3 (3): 100–111.

Steward, D. V. 1993. *Using the Design Structure Method*. NSF Report. Washington, DC: NSF.

Ulrich, K. T., and S. Eppinger. 2012. *Product Design and Development*. 5th ed. New York: McGraw-Hill.

Vokurka, R. J., and S. W. O'Leary-Kelly. 2000. "A Review of Empirical Research on Manufacturing Flexibility." *Journal of Operations Management* 18 (4): 485–501.