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MECHANICAL ENGINEERING | RESEARCH ARTICLE

A structured index describing the ease of disassembly for handcrafted product

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Abstract: Both economic and environmental aspects significantly influence the design process since the early phases of preliminary design. The total Life Cycle Assessment (LCA) and the End of Life (EoL) of products have to be defined in the early design phases too but, for industrial products that are not feasible to automatic production, they are hard issues. However, the EoL of products can be assessed by evaluating the disassembly of joints assembling the product, even when the production process is subject to an important contribute of workmanship. In this paper, a useful method is proposed to analyze the disassembly plant of products, in order to optimize the design process in the early preliminary phases. The method quantitatively evaluates a Disassembly Index that describes the attitude of a product to be disassembled. A case study describes the disassembly attitude of structural subassemblies of a sailboat. In order to test the applicability of the model described to both manual and automated disassembly, a further application of the method is proposed on a Computer CPU. As result, the model demonstrated good sensitiveness to the testing of products quite different for dimensions, number of components, manufacturing processes and, in all cases, it quantified the disassembly easiness with good relevance.

Subjects: Industrial Design; Manufacturing & Processing; Mechanical Engineering Design; Mechanical Engineering Design; Ship Operations; Ship Building Technology & Engineering; Computer Aided Design; CAD; Life-Long Design; Machine Design; Industrial Design

Keywords: disassembly; handcraft; non-destructive; reusing; quantitative

1. Introduction

The Design for Disassembly (DfD) is part of the broader concept Design for X (DfX), which focused on each life cycle's step of the product development, in order to improve the quality and reduce the cost and the time of implementation of a project.

PUBLIC INTEREST STATEMENT

The paper proposed a method that can guide the designer in the early stages of product design. Some consideration about the disassembly of products can be helpful already in the preliminary design stage, because this can influence the economic and environmental aspects.

For industrial products that are not feasible to automatic production, this is hard issue.

This paper presents a smart method that aims at evaluating the disassembly of joints assembling a product, even when the production process is subject to an important contribute of workmanship. The method defines an index that describes the attitude of a product to be disassembled.

A case study proves the application of the method to structural subassemblies of a sailboat. Also a comparison to a mass product is provided, to confirm the soundness of the method.

Usually, the setting of a project considers first the production processes and suitable materials to be employed and then the practical aspects of the implementation, including machining cycles and machine tools. Following the traditional approach, the activities are carried out in sequence, rather than simultaneously, with consequent relatively long time in the development of the product. However, during any stage it may be necessary to go back, to repeat or modify an earlier stage, with further losses of time. Concurrent Engineering integrates the DfX techniques in the product development, thus suggesting a holistic view of the product. Holt and Barnes (2010) discussed some DfX techniques and the way they fit into the design process: this approach tries to break down the walls of the serial design, in order to lead to an integrated approach.

Concurrent and Simultaneous Engineering tend to an interdisciplinary approach, that is required for the collection and processing of large amounts of data related to the life cycle of a product and is aimed at improving the time and cost of production. In this context, a full co-operation between designers and engineers is needed and new technologies are required to make the team members communicating each other in a fast and efficient way at the same project and at the same time. Thus, the Design Process must be explicit and supported by modeling and simulation processes, already in the earlier phases of product design (Taha, Hadi, Sin Ye, & Mohamad et al., 2015). Many optimization methods based on QFD, TRIZ, can support the product design since the early phases (Caligiana, Francia, & Liverani, 2017; Caligiana, Liverani, Francia, Frizziero, & Donnici, 2017a, 2017b; Donnici, Frizziero, Francia, Liverani, & Caligiana, 2018a, 2018b, 2018c; Francia, Caligiana, Liverani, Frizziero, & Donnici, 2017; Frizziero et al., 2018; Frizziero, Francia, Donnici, Liverani, & Caligiana, 2018).

Among the aspects that influence the design of a product, the most relevant are the analysis of the market, the availability of materials, cost estimating and processing times, assembly and disassembly procedures. Last trends in Simultaneous Engineering suggest to support all phases of product's life cycle through the evaluation of the impact they produce on the environment. Sustainability may be known as meeting the desires of the present technology, without compromising the capability of future generations, to fulfill their very own wishes. Taha et al. (Will, 1991) proposed a new approach of evaluating sustainability at the product design stage. Through Analytic Hierarchy Process (AHP) they compared outputs obtained by evaluating production costs, carbon emission and ergonomic assessment.

Since 90', it was evident that what most influences the environment concerns is the manufacturing processes and the consequent manufacturing wastes and the consequent disposal of products at their end-of-life (Kriwet, Zussman, & Seliger, 1995).

Gungor & Gupta, (1999) defined the environmentally conscious manufacturing (ECM) as:

- understanding the life cycle of the product and its impact on the environment at each of its life stages;
- making better decisions during product design and manufacturing so that the environmental attributes of the product and manufacturing process are kept at a desired level.

These issues can be translated in some rules that pay particular attention to cunning solutions such as: long product life with the minimized use of raw materials, few different materials in a single product, few components within a given material in an engineered system, increased number of parts or subsystems that are easily disassembled and reused without refurbishing. Sakundarini, Taha, and Ghazilla et al. (2012) proposed a framework of integrated recyclability tool in order to optimize the life cycle decision that will ensure environmentally preferable materials during product design. The significance of the environmental factors, collectively with issues on value advantages and material shortage, has been translated in diverse environmental law all over the Europe and USA.

The expectation is to derive minimal energy and resources from the environment and discharge minimal amount of wastes during and after the life cycles. Stringent regulations obligate industry to assume responsibility for their products even after their useful life and in terms not only of reliability but also of recyclability.

At their end-of-life, products contain extensive amounts of reusable material that can be reused, recycled or dismantled, by means of remanufacturing processes or not. The goal is to encourage the disassembly of parts at the end of their life, in order to reduce costs and to preserve environment from emissions. Thus, the DfD can be considered a priority. Some relevant studies presented in literature about DfD are briefly cited in the following paragraphs: they mainly focus on disassembly sequence planning or economic analysis.

Chandra (1994) described product recovery in graphical terms by means of two curves: a cost curve and a revenue curve. The difference of these two curves is the profit that can be intended as a measure of emissions, energy, and money. The goal of the recovery issue is to find the optimal point of the profit curve. So as to discover this point for an explicit item, an improvement calculation was embraced that began from CAD information, by methods for a CAD instrument (ReStar), and found the base of a target work adopting the traveling “salesperson” methodology.

Taleb and Gupta (1997) offered algorithms to assess the disassembly of more than one product structures having commonplace elements. The aim became to compute the minimum disassembly order, by means of a core algorithm, and to determine a disassembly time table. They furnished a scheduling mechanism for disassembly that minimizes the disassembly cost.

Gungor and Gupta (1997) offered additionally a heuristic technique to pick out the first-class disassembly method via the assessment of the total time of disassembly once assigned a disassembly collection of a product.

Feldmann (1999) evaluated recycling costs and benefits for particular fractions of recovered substances by using the software program module “DisPlay” that determinates the most useful disassembly direction and individuates a recycling strategy. The overall profit become calculated, in terms of costs, as sum of the effort for disassembly steps and the earnings for the recycling. The most fulfilling answer gives as output a disassembly path to be pursued.

However, the principle disadvantage of disassembly evaluation, primarily based on financial criteria, is that there is not a approach to optimize disassembly. Lee (2001) proposed a multi-objective method for determining an End of Life disassembly chart in which the effect on the environment and the cumulative expenses of a disassembly method are evidenced. The feasible EoL options are evaluated in terms of costs, economic value and impact on the environment. Although the techniques proposed have a massive validity, the accompanied techniques are lacking a quantitative assessment of the mindset to disassembly in product design. Kroll and Hanft (1998) proposed to give quantitative evaluations taking into account the ease-of-disassembly of products. The methodology is based on the drawing up of a spreadsheet-like chart that simulates a disassembly process. In the columns are collected the information as the quantity, the task type, the required tools and the difficulty rates and in the rows are collected all the assembly components identified by a part number. By means of the disassembly chart two different index are calculated: the design effectiveness and the disassembly time. The combination of these indexes gives a quantitative evaluation of ease of disassembly of products.

Gungor (2006) proposed the evaluation of alternative connection types using the powerful analytic network process (ANP). The model presented tested alternative connectors with three main concerns: to make product disassembly friendly, to make product assembly efficient and to increase the product performance when it is in-use. The results obtained could guide designers in making better decisions on selecting connectors for a product.

Villalba, Segarra, and Chimenos et al. (2004) resumed the important aspects of the DfD as follows:

- to use as few parts as possible in the product both in repair and maintenance, because it reduces the time associated with accessing the desired part(s) of the product and in product recovery, it reduces the time to disassemble and helps selective separation of materials.
- to use connectors that are easily unfastened.

They proposed a model to decide if disassembly design lets in for material restoration, by means of a recyclability index. The recyclability index shows the capability of a material to regain its valued characteristics via a recycling process. It's also beneficial to decide the reasonable convenience to recycle a part. However, the feasibility of recycling depends on the feasibility of disassembly too, so the whole evaluation takes into account also the disassembly mindset of a product, even supposing from the completely low-priced point of view.

Most part of the research presented up to now are targeted on evaluations of the disassembly functionality that, even if quantitative, is all referred to fasteners and tools. The goal was to minimize the number of parts, increasing the use of common materials and choosing fastener and joint types easy to remove, in order to evaluate the recovery and recyclability convenience. For traditional products that ought to be produced in massive numbers or which can be addressed to mass production, assembly and disassembly plants are optimized (Abdullah et al., 2005; Afrinaldi, Zakuan, & Blount et al., 2010; Caligiana, Liverani, Francia, & Frizziero, 2017; Degidi et al., 2016; Desai & Mital, 2003; Masoumik, Abdul-Rashid, & Olugu et al., 2015; Said, Mitrouchev, & Tollenaere, 2016; Santochi, 2002) and, within the most a part of instances, disassembly operations are mechanized, also with the help of digital/augmented reality tools (Bajana, Francia, Liverani, & Krajčovič, 2016; Ceruti, Frizziero, & Liverani, 2016; de Amicis, Ceruti, Francia, Frizziero, & Simões, 2018; Kheder, Trigui, & Aifaoui, 2014; Mitrouchev, Wang, & Chen, 2016).

For such products, used suggestions as “design for automated disassembly”, “eliminate the need for specialized disassembly procedures”, “use simple and standard tools” match very well with ‘minimize the component count’, “optimize component standardization”, “minimize the use of different materials”, “use recyclable materials”, “minimize the number of joints”, “make joints visible and accessible”, “use joints ease to disassembly”, “use fasteners rather than adhesive”.

However, while the manufacturing is addressed to few samples and while the disassembly is mainly based on handy workmanships, these tasks emerge as a hard issue.

In a few industrial instances, as the nautical subject mainly, complex and manual manufacturing procedures are nonetheless hired, that provide no opportunity to the economic process to be automatized.

Furthermore, the very limited variety of items that are realized each year and the difficulty to handle with products of huge dimensions do not inspire the upgrading of the manufacturing process.

In such instances, each attempt to an analytic approach aimed to the design process optimization can be helpful and come to be applicable in an effort to reduce costs and time to marketplace.

In this paper, a very simple and powerful method is proposed to support the evaluation of the disassembly functionality of products not addressed to automate manufacturing, that are referred inside the paper as non-traditional/non-conventional products. Outcomes highlight the amount of components, faced to the full elements of the assembled product, that may be recovered after the disassembly of the product and, therefore, encourage careful concerns on it.

2. The model

For traditional items, whose manufacturing procedure can be automatized, some general rules in the assembly and disassembly optimization have been suggested in the literature (Kroll & Hanft, 1998).

Generally good principles are: to minimize number of union elements, to use elements of union detachable or easy to destroy, to prevent change of direction for disassembly, to make the joining procedures simple and standardized, to make conceivable synchronous detachment and dismount, to provide access for tools with dismount.

These general principles are not immediate to be pursued when products are subject to handcrafted assembly operations that cannot be standardized or generalized. For these categories of products, a detailed analysis is necessary to schedule the disassembly operations and to make them quantifiable.

Depending on the complexity of products, all the information about the number and the kind of the relative joints have to be investigated and even arranged by subassemblies.

This paper presents a model applied to a very complex product, assembled by handcrafted operations and composed by a large variety of elements. The goal is to define a method that makes it easy to collect all the data about the parts of the product and all the information about them, concerning the materials and the connections employed. Finally, some parameter has been defined in order to describe and to manage the disassembly features in order to evaluate the easiness of disassembly the product.

Figure 1 shows a possible structured data collection where in the first column an ID number is assigned to each joint (in general the joint assembles two parts). For each joint, the model specifies which structural elements of the product have been joined, how many times the same kind of joint is repeated into the same product, how many connections are used for the junction and how the junction is realized.

Some significant parameters have to be identified that can describe the disassembly plants, following the guidelines suggested by the DfD principles. Moreover, these parameters have to be chosen in order to fit a large variety of products.

This model is based on the management of three parameters that can describe the disassembly of products, even the non-conventional ones (Francia, Caligiana, & Liverani, 2016).

The first parameter describing the disassembly process is concerned to how many different materials are employed in each joint of the product (or of a product significant subassembly); a second parameter have been chosen in order to take into account the time necessary to disassemble each specific joint; finally, a third parameter would account for the reusability of parts, after the disassembly has been completed.

Figure 1. Data collection and classification.

ID	Structural elements to be joined	N. of joints	N. of connecting elements	Specifications on the kind of joint realized
1				
2				
etc.				

The three parameters are useful to define a Disassembly Index that can describe the attitude of a product to be efficiently disassembled. This index has been formulated in order to assume values that will vary from near to 0 to 1, giving a feedback on whether the parts of a product could be easily disjoined, reused, recycled or dismantled.

They are referred in the text as z , k and h . All the parameters will vary in the range of 0.1 to 1, each following a proper variation scale that strictly depends on the working conditions. More in detail, parameter z depends on the number of materials employed in the junction, parameter k varies in function of time and describes the time necessary to disassemble a joint and parameter h depends on the reusability of parts after they have been disassembled and is evaluated depending whether the reuse is complete or partial and whether is immediate or it needs refurbishing.

Parameter z assumes a specific value depending on how many different materials have been used. In order to optimize the dismantling, the use of different materials employed in a joint has to be minimized (Ljungberg, 2007). For this reason, it is 1 when, for the connectors of the joint, a unique material has been employed, while, when the number of materials employed are varies from 2 to 5, it can range from 0.75 to 0.1 following the variation scale shown in Table 1.

Parameter k has been defined following an exponential trend that is plotted in Figure 2. More in particular, in the argument of the exponential function, the disassembly time t , calculated in minutes, is related to the assembly time t_0 through a normalizing factor f . Through it, the disassembly time t is allowed to vary from a minimum value of $0.4 t_0$ to a maximum value as the total assembly time t_0 . It takes care for a slow decreasing of the function depending on the time. The parameter k is calculated in (1) as follows, in function of the time:

$$k(t) = e^{-f\left(\frac{t}{t_0}\right)} \quad (1)$$

The factor f is defined as follows:

$$f = \frac{t_0}{t_{max} - t_{min}} \quad (2)$$

The variation scale adopted for parameter k is shown in Table 2, where the time is calculated in minutes.

Parameter h describes the behavior of the disassembly: in particular, a non-destructive behavior is considered when parts can be reused after they have been disassembled. The reuse can be easily achieved if parts are intact and they can be directly employed in a further joint. A destructive behavior is considered when some parts of the joint cannot be reused or when they cannot, not at all. A partial reuse is also considered, depending on the refurbishing is need or not. As destructive behavior can be considered non-reversible operations such as cutting, breaking and tearing whereas non-destructive methods require the use of smart connectors that can be easily unfasten. The variation scale adopted for parameter h is shown in Table 3, as follows. Ranges for parameter h have been set by considering all the principal behaviors of parts after their disassembly and the

Table 1. The variation scale adopted for parameter z

z	No. of materials
1	1
0.75	2
0.5	3
0.25	4
0.1	5

Figure 2. The trend of Equation (1).

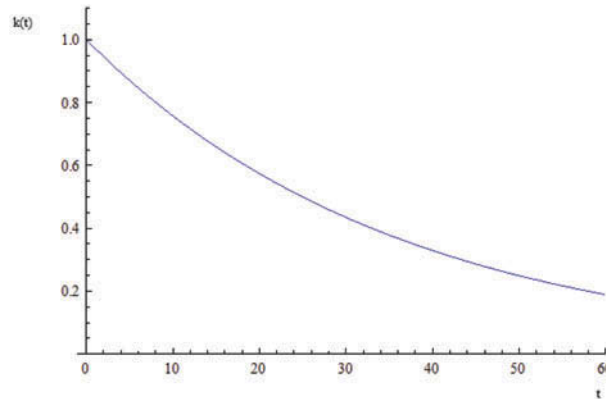


Table 2. The variation scale adopted for parameter k

k	Disassembly time
1	1' to 4'
0.9	5' to 7'
0.8	8' to 10'
0.7	11' to 15'
0.6	16' to 20'
0.5	21' to 27'
0.4	28' to 35'
0.3	36' to 47'
0.2	48' to 60'
0.1	Beyond 60'

Table 3. The variation scale adopted for parameter z

h	Reuse
1	Complete
0.75	Complete whit refurbishing
0.5	Partial
0.25	Partial with refurbishing
0.1	Null

values have been assigned starting from the most promising condition, complete reusing of parts, and then by decreasing by 25% the following even worse behaviors.

All parameters above described contribute to the formula (3) that computes the Disassembly Index as the ability of a product to be easily disassembled:

$$DI = \frac{\sum_{i=1}^{N_u} k_i(t) * h_i(r) * z_i(m) * n_i}{N} \quad (3)$$

where n_i is the number relative to how many times the same kind of junction is repeated, N_u quantifies the different kind of joints employed to assemble the whole product, N is the number of total junctions considered. The formula gives, as output, a value that can vary from a minimum near to 0 to 1. The output of the simulation is useful to quantify the ability of a product to be disassembled in terms of

recoverability, dismantling, time saving. On the other hand, it can be interpreted as the percentage of recovered parts faced to the whole product.

3. The model application to a sail boat

As case study to test the model proposed, this paper introduces a sailboat, the Sly 38, which is object of studies in the project “Econaut”, whose scientific partner is the Nautical Technopole (2015), for simulation and optimization of the geometries and materials. The realization of the project and the product is led by a new way of thinking, dedicated to enjoy sailing and minimize environmental impact, keeping the same comfort, improving safety and giving the superior performances in the tradition of Sly yachts. The goal is to get, through the gradual implementation of new methodologies, at the version 38 of the Sly, shown in Figure 3, which can be defined as the forerunner of a new generation of Green-Boats. Thus, this case study entails all the focusing aspects discussed in the previous paragraphs and it supports the attractiveness of the model proposed in this paper, tested through a huge analysis of all the product connections.

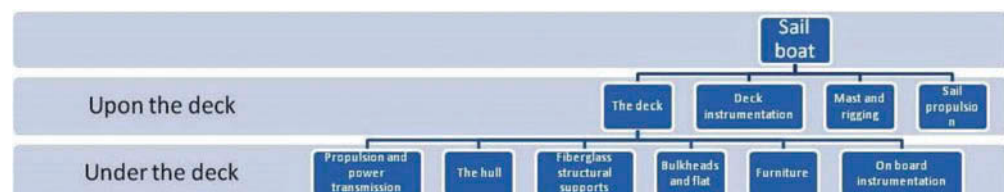
In this context, a DfD analysis have been carried on, starting from considerations on the main blocks assembling the Sly 38. The macro-blocks that can be considered for the Sly 38 are listed as follows and are illustrated in Figure 4:

- hull and deck;
- fiberglass structural supports;
- bulkheads and flat;
- furniture;
- on-board instrumentations;
- propulsion and power transmission;
- deck instrumentations;
- mast and rigging;
- sail propulsion;
- appendices.

Figure 3. The Sly 38 sailboat.



Figure 4. The Sly ‘38’s macro-blocks to be assembled.



In the present study, only some blocks under the deck have been analyzed and they are, more in particular, the hull-deck, the fiberglass structural supports, the bulkheads, the flat and the furniture block, as evidenced in Figure 5. The remaining blocks are separate entities that are mounted on board in a second time; for them only a possible disassembly for maintenance has been considered.

3.1. The macro-blocks of the sly 38

The hull and deck block is the most relevant in terms of weight of material of the whole product. It can be considered as a box in which the walls represent the hull and the deck its top cover. They can be realized in different materials, such as metal, glass-vinyl ester resin, glass-epoxy or carbon-epoxy, requiring different manufacturing processes such as hand lay-up, vacuum, or vacuum infusion. For the Sly 38 the hull and deck are made of glass-vinyl ester resin in hand lay up of skins.

The hull and the deck are made of single blocks. Therefore, they are single bodies without chemical or mechanical connections of any kind. Even where the product is made of multiple parts, these are joined together again, with the help of fiberglass, and then the final product will be a homogeneous single block. The union between hull and deck, shown in Figure 6, allows the closure of the boat and realizes the housing area. It is obtained by a structural bonding able to transfer loads from one part to another, without allowing relative movement. The two surfaces are maintained in position, until the complete hardening of the adhesive, through a series of rivets along the whole edge. Currently the rivets, which are embedded in the glue and which remain under the gunwale of the boat, have no structural purpose.

Figure 5. The main blocks considered for the Sly 38 assembly.

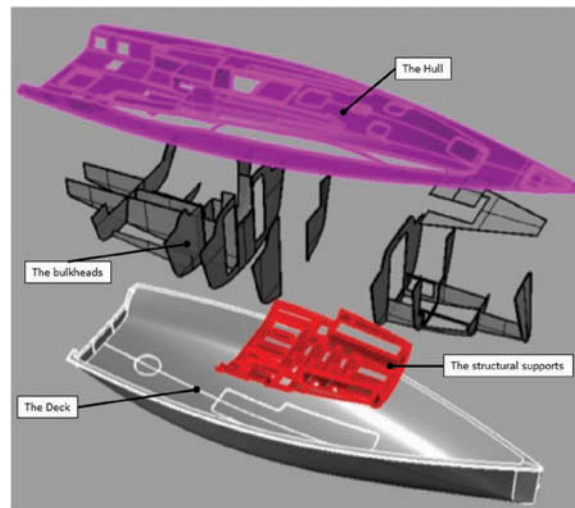
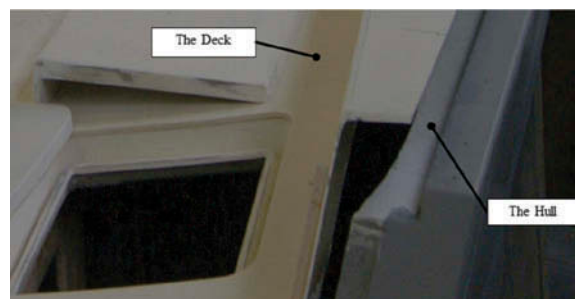


Figure 6. The hull-deck assembly.



The structural strength of the hull of the boat is ensured by reinforcing structures, suitably dimensioned, positioned on the bottom of the hull. These structures can be the floor frame that form a reinforcing structure, together with the spar. In some cases, the reinforcement structures have already been realized in a unique block. These structures can be joined to the hull by a manual layered fiberglass (VTR) reinforcement, i.e. with the lamination of a glass resin piece throughout their edge, or by gluing them with structural adhesive.

The Sly 38 has a central basement where floor frames and spars are merged into a single structure. The basement also has the function of guide for the transverse bulkheads, which together with the basement have the task of sustain the hull and deck in the load conserving.

The inner spaces of the boat is divided by means of the bulkheads that can have a structural function or not. The bulkheads, the hull and the deck are connected by the manual layered VTR reinforcement each other.

Figure 7 shows the manual layered VTR reinforcement application to join a vertical bar: it can be seen the skin of fiberglass not yet trimmed. The darker area under the fiberglass is due to the plaster that is applied to remove the right angle between the bulkhead and the hull, which would cause an accumulation of resin and the presence of air bubbles.

All bulkheads, plains and components in contact with the hull and deck, as the union with the inner part of the deck, have been manually VTR reinforced to guarantee a good quality of the joint.

In Figure 8 the positioning of the bulkheads in the hull can be seen, all realized through the manual layered VTR reinforcement.

Figure 7. An example of junction by means of manual layered VTR reinforcement.

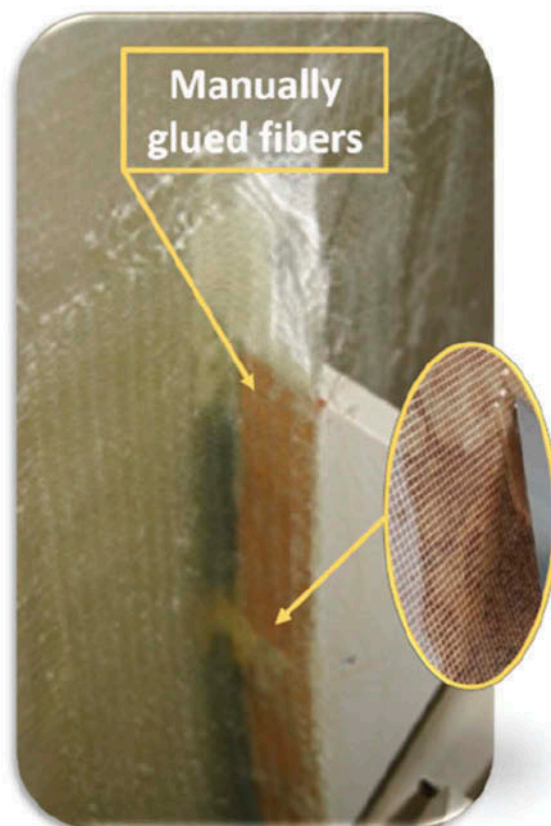


Figure 8. The bulkheads junction to the hull by means of manual layered VTR reinforcement.



A different kind of junction has been adopted for the cabin ceiling of the living area: this junction is made of fiberglass gel coat and upon it, built-in grooves are arranged to guarantee a good bulkheads positioning. These grooves are filled with structural adhesive that will be shaved once the deck has been placed.

In Figure 9 it can be seen the cabin ceiling joined to the bulkhead by means of the fiberglass gel coat, realized with a very good grade of accuracy.

The furniture of sailing boats significantly varies for cruise boats or racing boats. While for cruise boats the design criterion is focused the on-board comfort, aesthetics and ease of rigging, for the racing boats it is focused on the sailing speed, the lightness and the thinness, neglecting factors such as the internal volume and the simplicity of operation. For the same sailboat model, usually several layouts for the interior of the boat are available, increasing or decreasing the cabins and/or bathrooms on the boat.

For interior furniture, materials such as okumé, albasia, oak, teak are used among the woods, steel and aluminum for the profiles and glass or plexiglass for the bathroom's accessories.

All the furniture such as dinette table, kitchen furniture, and chart table is generally preassembled outside the boat, as shown in Figure 10, and then inserted in blocks into the interior of the boat. Connections between the furniture and bulkheads are realized by gluing and screwing further.

Figure 9. The cabin ceiling junction to the bulkhead by means of gel coating.

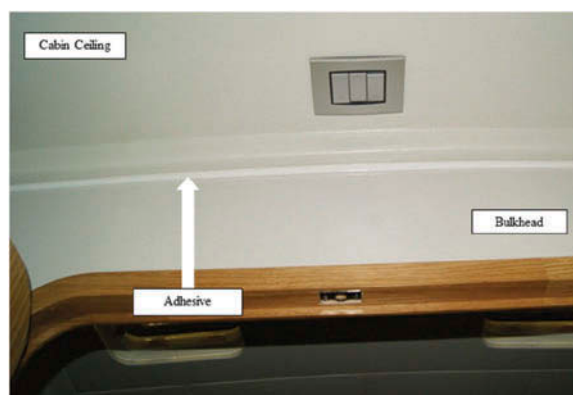


Figure 10. The preassembled furniture.



Upon the bulkheads, some fiberglass is covered using panels that are anchored by clips, as shown in Figure 11.

3.2. The manufacturing operations description and quantification

All the assembly operations carried out in the assembly of the Sly 38 are mainly handmade: handmade operation are not univocally quantifiable and the attribution of values to parameters that analytically define each operation entails an approximation anyway. In particular, the time necessary for assembly and disassembly each junction is strongly influenced by the operator ability, so the assignment of a value to the parameter k is not univocal and can be considered with good approximation. As previously remarked, many attempts in literature have been made in order to define some universal methods that can make robust the disassembly time evaluation (Kroll, 1996; Kroll & Carver, 1999; Kroll & Hanft, 1998), but the conclusion is that there is no standardized method to evaluate the ease of disassembly in an unambiguous manner (Vanegas et al., 2018) for products that needs handcrafted assembly connections. In this case study, the values for k have been calculated assuming the disassembly time for each junction varying from 10 to 60 min, depending on the operation considered.

The manufacturing operations are listed in Table 4, where parameters k , z and h assume a value quantified as discussed in the model description. Each kind of junction is evidenced by a color, in order to make immediate the interpretation of data, especially in the following Tables.

For example, the manual layered VTR reinforcement is made by the progressive lay up of fiberglass skins glued each other through resin and plaster. The number of fiberglass layers and the quantity of resins vary depending on the load that the junction has to support. In this case, assembly and disassembly time depends also on the dimensions of the junction that has to be realized. To realize the junction of the Sly 38 for the hull-basement block, in particular, the disassembly time k required is more than 1 h. For single fasteners and positioning of parts, a disassembly time of 5 min has been considered (more in particular for fasteners associated to hinges or to silicon gluing a disassembly time of 10 min has been considered). For structural gluing, a disassembly time

Figure 11. In the picture are visible the clips glued to the hull; after is shown the placement of the paneling.

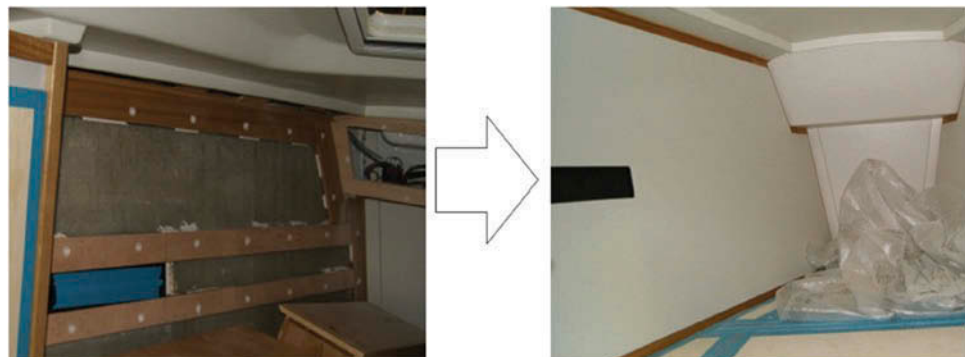


Table 4. The parameters k , z and h quantification

Kind of junction	k	h	z
Manual layered VTR reinforcement	0.1	0.25	0,5
Fasteners	0.9	1	1
Structural gluing	0.3	0.1	1
Silicone gluing	0.5	0.5	1
Plastic clips	0.5	0.75	0,5
Just posed	0.9	1	1

of 40 min has been considered and finally, for silicone and plastic clips, a disassembly time of 20 min has been considered. All these data have been defined by the advice of expert operators.

For parameter z , a value of 0.5 has been assigned for three different materials employed in the junction, the two elements that have to be joined apart. This is the case of manual layered VTR reinforcement and plastic clips.

For parameter h , values varying from 0.1 to 1 are assigned, depending on the reusing of parts after the disassembly. In particular, for manual layered VTR reinforcement, the parts to be joined can be recovered after refurbishing operations. Fasteners and positioning allow recovering as parts as the joining elements; plastic clips allow a complete recovery of parts that however need refurbishing operations; silicone gluing allows a partial recovery of parts, because parts to be joined can be reused, but no recovery is possible for the junction elements; structural gluing does not allow any recovery.

3.3. The sly 38 joints global classification

In this paragraph, all the data considered for the Disassembly Index computation are reported and they collected in Tables 5 and 6.

Table 5 lists 32 identification numbers, IDs, that correspond to all the structural elements of the blocks assembled in the Sly 38. More in particular, an ID number is relative to two structural elements, specified in the second column, that are joined as described in the final column "Kind of junction". The third column n_j entails the number of junctions of the same kind. The fourth column "number of joining parts" entails how many elements are employed to realize the junction.

In Table 6, that follows, for each ID the three parameters k , z and h are defined. Except for the manual layered VTR reinforcement's parameters, whose evaluation takes into account the dimensions and the assembly time, the values k , z and h assumed a unique value, depending only on the manufacturing operation and not on the dimensions of the elements to be joined. In Table 6, each kind of junction is evidenced by the same color proposed in Table 4, in order to make immediate the interpretation of data. In the described conditions, the computation of the Disassembly Index, as defined in the formula (3), gives back a value of 0,392.

4. A comparison with a mass product

In order to test the applicability of the model described to both manual and automated disassembly, a second case study is proposed. The object of the comparative case study is a Computer CPU. This is a product addressed to mass/automated production, which has been proposed as typical case study in many dissertations.

Table 5. The values assigned to parameters k , z and h for the Sly 38

ID	Structural elements	n_i	No. of joining parts	Kind of junction
1	Hull-basement	1		Manual layered VTR reinforcement
2	Basement-fixed undercarriage	2	4	Fasteners
3	Basement- just posed undercarriage	5		Just posed
4	Hull-principal bulkheads	7		Manual layered VTR reinforcement
5	Hull-secondary bulkheads	6		Manual layered VTR reinforcement
6	Hull-separation bulkheads	13		Manual layered VTR reinforcement
7	Principal bulkheads—cabin top coat	7		Manual layered VTR reinforcement
8	Secondary bulkheads—cabin top coat	6		Manual layered VTR reinforcement
9	Fiberglass cabin top coat -deck	1		Structural gluing
10	Cabin top coat -deck	5	20	Plastic clips
11	Cabin top coat -deck	2		Silicone gluing
12	Cabin ceiling -deck	3	7	Plastic clips
13	Lateral panels	7	30	Plastic clips
14	Dinette lateral panels	1	6	Silicone gluing
15	Skylight	12	20	Bolt
16	Anchor compartment	1	2 + 6	Hinge+ fasteners
17	Fixed table	1	4	Fasteners
18	Mobile table	1	4	Fasteners
19	Dinette cabinet	4	2	Fasteners
20	Dinette cabinet	3	2	Fasteners + silicone gluing
21	Fixed refrigerator	1	2	Fasteners + silicone gluing
22	Mobile refrigerator	1	6	Fasteners
23	Chart table and side	1	6	Fasteners + silicone gluing
24	Kitchen cabinet	1	4	Fasteners + silicone gluing
25	Cabin and bathroom closet	3 + 1		Silicone gluing
26	Seatback bench	2		Silicone gluing
27	Footing	2		Just posed
28	Bathroom washbasin	1		Silicone gluing
29	Long bench panel	2	6	Plastic clips
30	Short bench panel	1	4	Plastic clips
31	Door	4	2 + 6	Hinge + fasteners
32	Boarding ladder	1	2 + 4	Hinge + fasteners

In Kroll and Hanft (1998), the disassembly plant of this product has been analyzed in order to validate a method for evaluating the ease of disassembly of products. The evaluation method was based on the filling of an evaluation chart that described the disassembly process by means of some entries such as the quantity, the task types and repetitions, the required tools to disassemble parts, the difficulty rating to the disassembly process. Finally, it evaluated the ease of disassembly in terms of the design effectiveness and the disassembly time.

Table 6. The parameters k , z and h assigned to each ID for the Sly 38

ID	k	h	z
1	0.1	0.25	0.5
2	1	1	1
3	1	1	1
4	0.2	0.25	0.5
5	0.3	0.25	0.5
6	0.3	0.25	0.5
7	0.2	0.25	0.5
8	0.3	0.25	0.5
9	0.8	0.75	1
10	0.8	0.75	0.5
11	0.8	0.5	1
12	0.8	0.75	0.5
13	0.8	0.75	0.5
14	0.8	0.5	1
15	1	1	1
16	0.8	1	1
17	1	1	1
18	1	1	1
19	1	1	1
20	0.8	0.5	0.75
21	0.8	0.5	0.75
22	1	1	1
23	0.8	0.5	0.75
24	0.8	0.5	0.75
25	0.8	0.5	1
26	0.8	0.5	1
27	1	1	1
28	0.8	0.5	1
29	0.8	0.75	0.5
30	0.8	0.75	0.5
31	0.8	1	1
32	0.8	1	1

As data collected for the previous case study, Table 7 describes all the parts and all the joining elements of the CPU, as follows; in Table 8, for each ID, parameters k , z and h are defined.

The operations that occur in the assembly of the computer CPU are as follows: screwing, fasten, gluing, posing, filling, pulling, flipping, and removing. They are very simple operations that do not require any contribute of workmanship or rather they can be easily automatized and completed in few minutes. This entails that the values for k have been calculated assuming the disassembly time for each junction varying from 1 to 10 min at most, depending on the operation considered. Two different values for parameter k have been calculated, relative to the operation of screwing, depending on the screwing had to be combined with other operation such as pulling, filling or removing, operation that required higher disassembly time.

Table 7. The values assigned to parameters k , z and h for the computer CPU

ID	Structural elements	n_i	No. of joining parts	Kind of junction
1	Motherboard—housing	1	4	Screws
2	Drives subassembly—housing	1	4	Screws
3	Motherboard—housing	1	5	Fasteners
4	Foot—housing	1	4	Gluing
5	Printer port—housing	1	2	Screws
6	Power supply—housing	1	4	Screws—pull-remove
7	Speaker- housing	1	1	Flip- pull- screws
8	Hard drive cover panel—housing	1	2	Screws
9	Port—housing	1	4	Screws
10	I/O card	3	1	Posed
11	Front bezel—housing	1	6	Screws
12	Drives subassembly side	1	6	Screws
13	Drives subassembly bottom	1	4	Flip—screws
14	Floppy disk drive—connector plate	2	2	Screws

Table 8. The parameters k , z and h for each ID for computer CPU

ID	k	h	z
1	0.9	1	1
2	0.9	1	1
3	0.9	1	1
4	0.9	0.75	1
5	0.9	1	1
6	0.6	1	1
7	0.6	1	1
8	0.9	1	1
9	0.9	1	1
10	1	1	1
11	0.9	1	1
12	0.9	1	1
13	0.8	1	1
14	0.9	1	1

The computation of the Disassembly Index for the Computer CPU, in the above-described conditions, gives back a value of 0.86.

5. Discussion

Two simulations have been carried on different products to test the model proposed in this paper. The first simulation evaluated the disassembly of a sailboat, which is a product of large

dimensions, composed by many parts, assembled by manual operations and addressed to hand workmanship production. The second simulation concerned a computer CPU, which is a product addressed to mass production, of standard dimension and assembled by automated operations.

The assembly/disassembly plants of the two products are very different in the two cases and the Disassembly Index calculated are quite different, as well. More in particular, the DI for the sailboat assumed a value of 0.39: this value evidences that less than a half of the total assembled elements of the main blocks of the Sly 38 can be efficiently disassembled and that the reusing of parts is not optimized through the choice of adequate assembly manufacturing processes. However, the DfD analysis highlighted that the assembly process most influencing the index is the manual layered VTR reinforcement, whose two parameters describing the disassembly time and the recovery are very poor. Furthermore, in order to check the model validity and the sensibility of the model to the parameters variation, a second simulation on the same product has been performed, that considered a different kind of junction instead of the manual layered VTR reinforcement. It has been supposed to replace the manual layered VTR reinforcement with a junction by fasteners and the DI has been recalculated: it assumed the value of 0.7. This significant variation of the DI validated the model sensitiveness and confirmed the assumption that the manual layered VTR reinforcement process mostly influenced the global simulation.

The facing product, the computer CPU, is addressed to mass/automated production; often, in literature, it has been taken as typical application in disassembly plants evaluations, as a product that can be efficiently reused. However, it is not directly comparable to the sailboat in terms of dimensions, complexity of the assembly of parts and disassembly manufacturing processes. The computation of the DI for the computer CPU gave back a value of 0.86: this value can be explained pointing out that in Table 8 quite all the parameters assume high values, because of the disassembly operations are standardized and rather automatized.

6. Conclusion

The results about the DI evaluation in both cases of the handcrafted product faced to a mass product highlighted some important conclusions:

- this model is easy to employ because is based on the definition of only three parameters, describing the number of materials, the time necessary to disassembly operations and the integrity of parts after their disassembly, that in some cases are quantified by simple considerations on facts (number of material employed and reusing of parts) and, in other cases, by the use of a mathematical expression to calculate the time necessary to disassemble a joint (disassembly time); the model demonstrated good sensitiveness to the variation of parameters k , z , h , that have been hypothesized in two parallel simulations for the same product, depending on the manufacturing processes described;
- this method allows to give quantification to key aspects of dissemblability. In the literature, this is known as a very hard issue, especially for handcrafted products because, usually, assembly/disassembly operations strictly depend on the ability of the operator and, in general, on human factors and are not easily and objectively quantifiable;
- the parameter k , that is the most influenced by human factors for handcrafted products, is quantified with good reliability and widespread applicability, being defined through an exponential equation that correlates the disassembly time to the assembly time by means of a normalizing factor that control the fast decreasing of the function;
- the model has been tested on products quite different for dimensions, number of components, manufacturing processes (automated vs handcrafted), giving back two results very different, as expected, and in both cases good relevance can be observed for the disassembly index.

Thus, the method described in this paper allows the testing of DfD plants for a large variety of products, by means of a simple model that quantifies the attitude of products to be disassembled,

in terms of recovery, recyclability, gain of time. However, this model does not take into account other aspects as the cost of operations to disassemble parts, the hierarchic level number, that corresponds to the relative positioning of the components of the product, and the sequence of operations. This latter aspect considers that many components can be decomposed via a multitude of sequences and its optimization becomes a crucial issue. All these factors, which actually influence the easiness of a product to be disassembled efficiently, could be integrated in further enhancement of the model.

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Author statement

This research group is involved in Industrial and Mechanical Design.

The focus research activities are centered on innovative methodologies just like QFD, TRIZ, Design For Six Sigma, Bench Marking, Top-Flop Analysis.

Among the innovative methodologies are investigated also the strategies of Design for X, with a main focus on Design for Assembly, Design for Disassembly, Design for Additive Manufacturing, Design for Six Sigma.

This paper proposed a method to guide the designer to optimization of products already in the early stages of design.

By Design for Disassembly criteria, it aimed at evaluating the efficiency of dissemblability of products, by means of an index that can be applied not only to mass product, but especially to handcrafted products.

Up to now, the state of art missed criteria to estimate the DfD efficiency of not automated products.

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