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# Time-based disassembly method: how to assess the best disassembly sequence and time of target components in complex products

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## Abstract

Circular Economy (CE) is a new business model that is pressing manufacturing companies to think about closed loop scenarios for materials and products. Design for End-of-Life (DfEoL) and Design for Disassembly (DfD) are key enabling methods for the effective application of this model.

The paper presents a time-based method for the calculation of disassembly sequences, adopting basic theories and techniques in this topic and integrating new concepts for the assessment of the disassembly time. The method consists of five steps and starts from the documentations (e.g., CAD model) generally available early in the product development process. The first three steps encompass the product analysis by including (i) the definition of target components from the general assembly, (ii) the analyses of the virtual model, and (iii) the assessment of the so-called "level" matrix, which is based on the concept of disassembly levels and liaisons characterization among components. The last two steps allow for the assessment of the time-based disassembly sequence by including (iv) the analysis of feasible sequences and (v) the generation of the best disassembly sequence for target components. The method mainly overcomes two issues highlighted in the literature regarding the reliability of the disassemblability analysis using a time-based approach and the quality of results accounting for the real condition of the product at the time of disassembly. The calculation of the effective disassembly time is grounded on a specific repository developed to gather knowledge about the disassembly tasks and related disassembly time. This is the main contribution and novelty of the proposed approach.

By using the proposed method, different target components of a washing machine are analysed with the aim of demonstrating the robustness of the method and its consistency in the estimation of disassembly time. A maximum deviation of 10% between the estimated and measured disassembly times is noticed.

## Keywords

Design for Disassembly; Target Disassembly; Level Matrix; De-manufacturing; Disassembly time calculation; Disassembly Sequence Planning.

# 1 Introduction

During the past few years, the Circular Economy (CE) has been considered as a global economic model that decouples economic development from the consumption of finite resources. The CE forces companies to think about the whole product lifecycle from manufacturing to dismantling and to look for a solution to close the loop (Cradle to Cradle). In this context, Remanufacturing and Reusing represent potential new business opportunities for enterprises and industries.

Considering the service/maintenance operations and product dismantling, disassembly is a preliminary but fundamental phase. Disassembly can be defined as a systematic method for separating a product into its constituent parts, components and subassemblies [1]. Disassembly processes can be classified into: (i) complete (full product dismantling), and (ii) selective (disassembly of target components) [2]. Selective manual disassembly is usually the most common approach during de-manufacturing operations, such as maintenance, service, repairing, and End-of-Life (EoL) treatments [3].

Compliance with legislations or the pursue of CE business opportunities is pushing designers to consider product disassemblability during the design phase. The analytical evaluation of the product disassemblability passes through the analysis of the elementary activities required to remove components from a product. This analysis is mainly characterized by the solution of the Disassembly Sequence Planning (DSP) problem and the optimization of the disassembly path for target components [4].

The paper proposes a method to solve the disassembly problem by defining it as an objective function to minimize the disassembly time for a specific target component in a complex assembly. The method is developed according to well-known theories and techniques in this field, and it is grounded on an innovative procedure to calculate the effective disassembly time. Starting with the analysis of the product virtual model, it is possible to identify the disassembly levels and to assign liaisons to link each component or subassembly. The calculation of the effective disassembly time is based on a specific repository (called Liaison_DB), which classifies the assembly/disassembly liaisons in a structured manner and stores, for each liaison, a specific disassembly time retrieved by the direct observation and analysis of de-manufacturing activities. Disassembly time “penalties,” related to the condition of the product at the moment of disassembly (wear, rust, etc.), are accounted using corrective factors, defined on the basis of the knowledge and experiences of de-manufacturing centres. Using this method, designers can rapidly identify the most critical components from a disassembly point of view, with the aim of conceiving the correct product architecture or choosing the most appropriate joining methods. The possibility to achieve an estimation of the disassembly time for each sequence and target component represents the main contribution to the state of the art in the field of Design for Disassembly.

The paper is structured as follow. First, it gives an overview of the state of the art about the design for disassembly and DSP methods, highlighting the limitations of current methods. Then, the method and the related algorithms are presented in detail, including a step-by step procedure, with the aid of a simple example (car jack). The developed repository, with a link between the disassembly time and each specific assembly liaison, is described, as well as the approach to calculate corrective factors considering the real condition of the product at the moment of disassembly. Lastly, the paper presents a disassemblability analysis of a complex product (washing machine) as a case study. This example intends to demonstrate the reliability of the results, by comparing them with data gathered during de-manufacturing experimental tests.

## 2 Research background

Design for Disassembly studies began in the early 1990s when environmental concerns related to the disposal of industrial products became a new world challenge [5]. Literature in this field includes several aspects, such as the rules and guidelines to design products for easy dismantling, DSP, disassembly optimization algorithms, etc. [6][7][8].. Looking at the product development process (design phase), DSP is considered as a fundamental task to judge the component or subassembly accessibility, as well as the disassembly paths, which gives a quantitative measurement of product disassemblability [9]. Thus, the definition of the disassembly plan can be considered as the starting point for the target disassembly analysis [10]. Despite that the final goal of a DfD design project is the minimization of the disassembly time and cost, several objective functions are considered by researchers, such as the shortest disassembly path (minimum number of disassembly operations), minimum number of components to remove, and maximum recycling ratio [3].

The main deficiency highlighted by the literature review is related to the disassembly time, which is generally out of scope for the solution of the disassembly problem. The developed methods do not provide any indications on how to assess the effective disassembly time, which is the most useful and understandable indicator to consider during the design activities.

### *2.1 DSP methods and representations*

Several research activities have been focused on the development of algorithms and procedures to find the best disassembly sequence of target components using exact and heuristic/metaheuristic methods.

Exact or deterministic methods have been investigated at the beginning as a reverse problem of assembly sequence definition, starting from the product structure. Dewhurst [5] evaluated the depth of disassembly for particular components in a product, to establish the effective cost convenience for disassembly operations. Srinivasan et al. [11] developed a deterministic method based on the *“wave propagation”* model to determine the disassembly sequence with minimum component removals. Another important contribution in this context was proposed by Gungor and Gupta [12] through the definition of a *“branch-and-bound”* approach, which was subsequently optimized by Zhang and Zhang [13]. Other exact methods have been defined, such as the *“connectivity and interface relationship”* proposed by Ong and Wong [14], the *“shortest path algorithm”* proposed by Zwingmann et al. [15] or the *“connector-knowledge-based approach”* proposed by Li et al. [16]. Most of the mentioned methods aim to find the global optimum in the complete disassembly planning which is not the main goal of selective disassembly. Although feasible disassembly sequences can be obtained by using exact methods, they are not compliant with the design for disassembly purpose where the objective is the assessment of the disassembly time of specific components or subassemblies. In addition, exact methods are time-consuming and they have important limitations when the number of product components or subassemblies increases because of the combinatorial nature of the problem.

The use of heuristic and metaheuristic methods have been investigated to solve the DSP problem with the aim of decreasing the computational time, by searching the best sequence without analysing all the possible alternatives. These methods have focused on detecting the best sequence when a combinatorial explosion of sequences occurs, as in the case of complex industrial products. Petri net [17][18][19][20] and genetic algorithms [21][22][23][24][25][26] are the most popular methods in this field. Heuristic methods seem to be beneficial in terms of computational time, but they still focus on complete disassemblability analysis and do not solve the issue of time-based sequence generation.

Another way for reducing the complexity of the DSP problem and its representation consists of using simplification methods, such as graphs and matrices. AND/OR diagram was the first and a widely used method to represent assembly and disassembly sequences [27]. Precedence graph [28][2], Connection graph [29] and Extended process graph [30] provide different ways to represent and solve the DSP problem. Likewise, the use of disassembly matrices has been implemented.

Transition matrix is obtained from a disassembly graph and represents the transitions caused by the possible disassembly operations including the connections between components [31][32][33]. Precedence matrix is another representation method and is based on the analysis of geometric precedence relationships [34]. Interference matrix analyses the interferences among components along the extraction path (following a particular direction/axis) [14][35].

In all of the abovementioned methods (exact, heuristic and simplified), the objective function to minimize is usually the number of disassembly operations or the number of components to remove and not the disassembly time.

### *2.2 Computer aided systems for the recognition of geometrical and non-geometrical information*

Regardless of the objective function to minimize, the solution of the DSP problem requires the definition of useful information (e.g., constraints, precedencies, liaisons, and interfaces). The designers' input may be minimized by extrapolating data, both geometric and non-geometric, from the product virtual model (e.g., 3D CAD model) [36]. Geometric information allows the characterization of connectors (e.g., the number, type, size, and length). Connector's features influence the assessment of the effective disassembly time [37]. Kang et al. [38] set up a representation scheme for the recognition of mechanical joining types among components directly from the CAD model of the assembly. Only a few case studies of CAD-integrated time-based methods have been investigated in the literature. For example, Papakostas et al. [39] proposed a case study of car rear axles in which the extraction times were estimated starting from the assembly time, considering the component's weight and length of fasteners retrieved from the CAD model.

Non-geometric information (e.g., removal directions, constraints, contact surfaces, and neighbouring components) allows the characterization of component's mobility within the assembly. The knowledge of this information plays an important role for disassembly constraint analysis [16]. Kheder et al. [40] presented an automated DSP approach based on the ant colony algorithm starting from the product CAD model. Issaoui et al. [41] proposed an information model based on technological data (cover, fix components, elastic components, etc.) retrieved by the analysis of the CAD model.

The definition of numerical approaches coupled with CAD systems favours the development of computer-aided design tools to be able to assess the product disassemblability during the early design phase. CAD-integrated methods and tools are surely interesting even though the potential in this field is still limited and incomplete. In particular, due to the nature of manual de-manufacturing operations, disassembly constraints require to be manually analysed and judged by experts.

### *2.3 Characterization of disassembly time for assembly liaisons*

The literature shows a particularly broad set of equations and methods to estimate the assembly time considering the liaison features [42], which starts from the representation of the product architecture [43]. Some authors considered the disassembly as an inverse process of assembly, even if this hypothesis is not supported by the standard practices and studies in this field.

The product disassembly time depends on several factors such as component shape, size and weight, joining element, joining direction, disassembly tools, and equipment [44]. Furthermore, it is influenced by the product work load (life cycle stress), working environment, chemical and physical degradation (aging), deformation, cleanness, material type, coating/painting process, etc. [45]. The condition of the product and its constituent components could be uncertain when disassembly occurs and this kind of information needs to be processed systematically in order to develop any realistic and credible disassembly plan [46]. For this reason, the well-known equations adopted for the estimation of assembly time cannot be used to estimate the disassembly time for a product.

The knowledge of disassembly time is essential information for designers and engineers, but its evaluation is generally performed at the dismantling and de-manufacturing centres [47]. The time gap between the design phase and the disassembly activities (maintenance, EoL, etc.) is the main issue to face if designers want to use disassembly time data when the product is conceived [48].

From the disassembly perspectives, different classifications have been proposed for mechanical connections and part interfaces [49][50][51]. Even if the proposed classifications can be considered as the basis for the development of a complete characterization of assembly/disassembly liaisons, they have some limitations. First, they are not complete and do not propose an effective disassembly time for each category or item. Second, they do not consider the ageing effect caused by the product lifecycle. Lastly, they are based on a theoretical framework and not on experimental analyses.

In conclusion, a literature review highlights that current approaches for DSP optimization consist of minimizing the disassembly paths (or tasks) rather than minimizing the effective disassembly time. This research study aims to go beyond the current state of the art by presenting a structured method, based on a set of novel and known steps, for analytically estimating the disassembly time for each target component in a complex assembly. The main novelty is certainly related to the definition of a repository containing essential time-based data of the main assembly liaisons and corrective factors that are used for the disassembly time estimation. These data are retrieved by the experimental analysis of de-manufacturing activities in order to guarantee reliability and robustness in the estimated times.

# 3 Proposed disassembly time calculation method

The main goal of the proposed method is the assessment of the disassembly time, estimated by using an exact DSP approach and a structured repository (called Liason_DB) for the classification of knowledge about elementary disassembly tasks. In particular, this study encompasses well-known concepts and techniques in this topic and proposes a structured procedure for the calculation of the best disassembly sequence based on the effective disassembly time.

Fig. 1 depicts the general workflow of the proposed method, while each step is described in detail in the next five subsections.

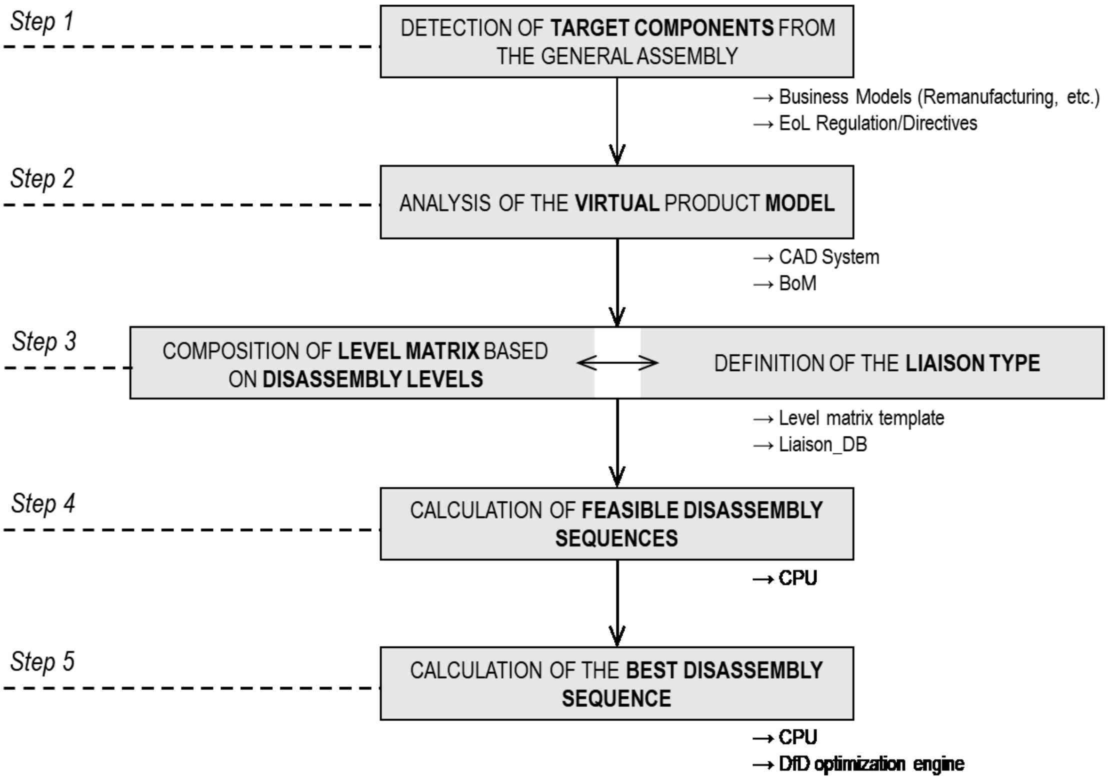


Fig. 1: workflow of the proposed DSP approach.

## *3.1 1$^{st}$ step – Detection of target components from the general assembly*

The approach starts with the detection of target components to remove from the product general assembly. Target components can be single parts (product components) or groups of parts (product subassemblies). The choice of target components is based on different aspects:

- Compliance with the maintenance/service plan during the use phase;
- Compliance with the EoL regulations/directives;
- Possibility to create new business models (Reuse, Remanufacture, etc.).

In the case of complex industrial products, target components can be located in a very deep position; hence, several disassembly paths are feasible to reach the target. For this reason, it is important to know the optimized one that guarantees the minimum disassembly time.

### *3.2 2nd step – Analysis of the virtual product model*

The second step of the method encompasses the analysis of the product structure starting from the virtual model. The latter can be available with its geometrical representation (i.e., CAD model) or with its structure (i.e., BoM – Bill of Material). Both models are useful to retrieve necessary data and the following information can be extracted:

- Quantity and name of components;
- Component geometry;
- General arrangement and physical obstructions among components and subassemblies;
- Dimensions, weights and materials;
- Geometrical features of components and subassemblies (cutting edges, holes, tapered geometry, etc.).

In particular, when design tools (e.g., the CAD system) support the product model analysis, the user can "navigate" the model by using the software features such as model rotation, zoom-in, zoom-out, as well as the possibility to hide/show components. This manual activity helps to set obstructions and precedencies among components, while the extraction paths and/or directions (±x, ±y, or ±z) are not limited. Indeed, users can consider combinations of extraction directions and/or extraction paths.

Using the BoM, instead, a complete list of components is available, as well as the constituent materials. BoM components are generally organized in subassemblies, facilitating the definition of the relations between components and subassemblies. However, most of the information related to geometry and physical obstructions are not available in the BoM; thus, the analysis is generally time-consuming and less accurate. When only the BoM is available, approximations are necessary for the analysis. For example, the component's geometrical features need to be simplified by using the component bounding box (envelope), thus losing useful information.

### *3.3 3rd step – "Level" matrix and liaison types*

The aim of this step is the identification of disassembly levels, precedence relations and liaisons among components and subassemblies. The starting point is represented by the component list, extrapolated during the 2nd step of the method and used to initialize the "level" matrix template, i.e., an NxN square matrix, where N is the total number of components. The "level matrix" is manually defined by the end-user and each row/column of the "level" matrix represents a component/subassembly of the general assembly. It is important to highlight that the liaison and joining elements (screws, rivets, connectors, etc.) are not counted as components in the "level" matrix so they do not need to be extrapolated from the virtual models.

#### *3.3.1 Composition of "level" matrix based on disassembly levels*

A key aspect of the proposed approach is the notion of disassembly level. A *disassembly level* is defined as "*the level in which one or more components/subassemblies connected to other components/subassemblies can be disassembled without any physical obstruction*." The definition of disassembly levels allows limiting the number of feasible paths for the selected target component, avoiding time-consuming calculations of non-optimum disassembly sequences (i.e., sequences with higher disassembly time).

For the definition of the disassembly level, the following general rule (*hypothesis #1*) can be followed:

If *component A* obstructs one or more components (e.g., *component B*) which are in relation only with *component A*, in case *component A* is removed at *level n*, the other components (e.g., *component B*) are free to be removed at *level n+1.*

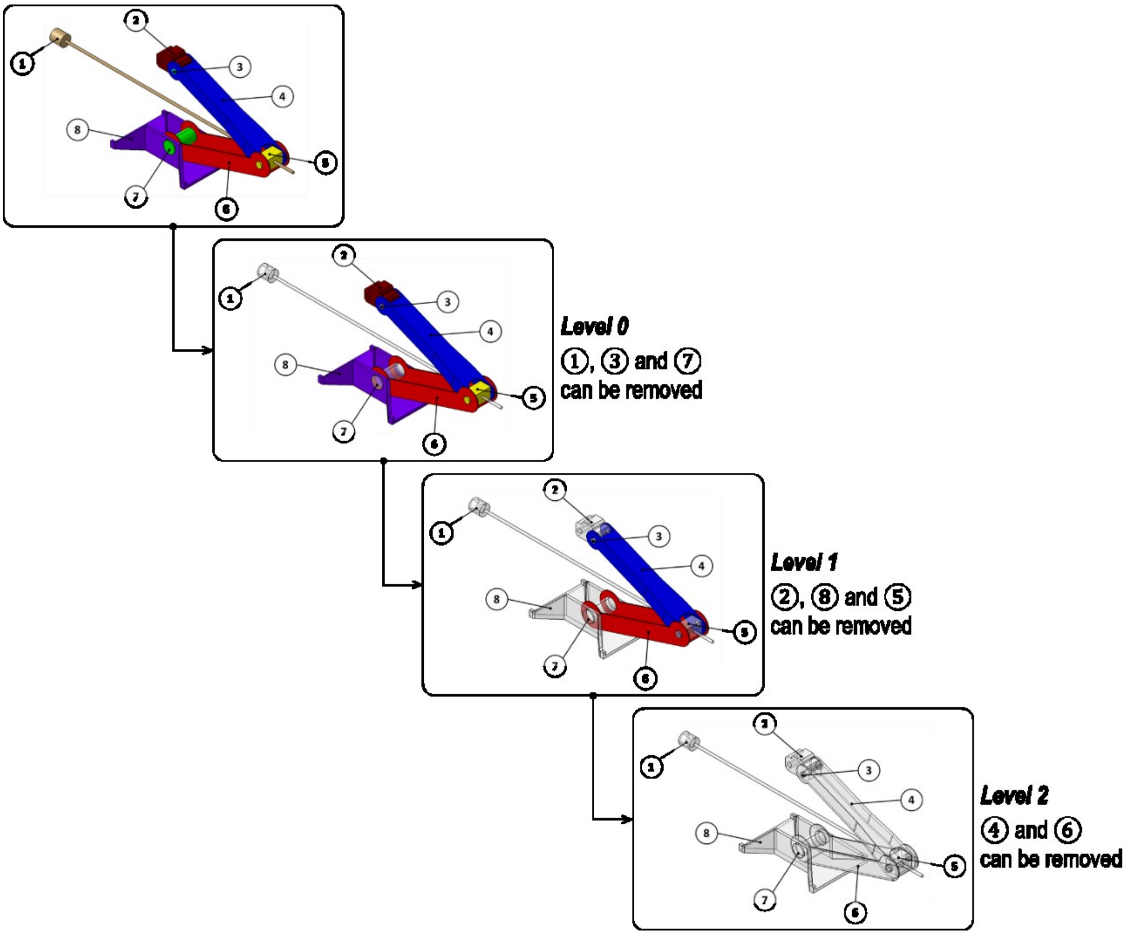
Following this rule, *level 0* contains all the components that can be first removed from the general assembly, without any precedence, while components belonging to *level n* can be removed only after removing one or more components of *level n-1*. The method does not foresee the assignment of the level for all of the components because the procedure can be stopped when all of the target components have been reached.

Another important rule to define is related to the concept of inherited precedencies (*hypothesis #2*):

If *component C* obstructs *component B* and *component B* obstructs *component A*, then *component A* is free to be removed after *component B* (direct precedence) and *component C* (inherited precedence).

The definition of the disassembly levels can be assisted by computer-aided tools (e.g., CAD system), which permit the navigation of the virtual model for easy identification of the levels, while considering the target components. Components or subassemblies removed in previous levels can be hidden in the CAD viewer to facilitate the definition of disassembly levels and precedencies. As described in the previous section, the user sets the way to extract the component without limitation in terms of directions (±x, ±y, or ±z) and/or paths.

Fig. 2 shows the application of such rules and the related definition of disassembly levels for a simple assembly (car jack).



Level 0
①, ③ and ⑦
can be removed

Level 1
②, ⑧ and ⑤
can be removed

Level 2
④ and ⑥
can be removed

Fig. 2: example of the definition of disassembly levels for a car jack.

The identified precedence relations among the product components are used to fill the "level" matrix template. In the "level" matrix, each cell of a row/column identifies the relation between two components/subassemblies of the general assembly. The cells of the matrix are filled using two possible values as follows:

- "1" for those components in the column which require to be disassembled before the component in the row under analysis;
- "0" for all other cases.

For example, if *component A* is not in any relation with *component B*, the cell in row A and column B is set to "0." If *component A* must be removed after *component C*, the cell in row A and column C is set to "1."

An example of a “level” matrix for the example in Figure 2 (car jack) is proposed below (Fig. 3).

| | ① | ② | ③ | ④ | ⑤ | ⑥ | ⑦ | ⑧ |
|---|---|---|---|---|---|---|---|---|
| ① | | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| ② | 0 | | 1 | 0 | 0 | 0 | 0 | 0 |
| ③ | 0 | 0 | | 0 | 0 | 0 | 0 | 0 |
| ④ | 1 | 1 | 1 | | 1 | 0 | 0 | 0 |
| ⑤ | 1 | 0 | 0 | 0 | | 0 | 0 | 0 |
| ⑥ | 1 | 0 | 0 | 0 | 1 | | 1 | 1 |
| ⑦ | 0 | 0 | 0 | 0 | 0 | 0 | | 0 |
| ⑧ | 0 | 0 | 0 | 0 | 0 | 0 | 1 | |

Fig. 3: “level” matrix for the car jack example.

The “level” matrix can be easily read by following each row. Considering the matrix in Fig. 3, component ④, for instance, can be removed after the disassembly of two components positioned in level 1 (components ② and ⑤), as well as the two components inherited from level 0 (components ③ and ①). On the other hand, component ⑧ can be removed after the disassembly of only one component (component ⑦) which is positioned at level 0. An important consideration is that the sum of the items in each row identifies the number of components/subassemblies to remove before reaching the target component. This sum is called “disassembly depth.”

### *3.3.2 Definition of the liaison types*

Another important task of the 3rd step of the method, which requires to be performed concurrently to the levels definition, is the assignment of liaisons types between components/subassemblies in the general assembly. While a level identifies which components can be removed in a specific disassembly step, the liaison identifies the relations between components and thus the physical links between them. A *liaison* is defined as “*the type of connection (mechanical, electrical, etc.) between two components which can be removed by a specific disassembly operation.*”

This step leverages on a comprehensive database (Liaison_DB) containing the typical liaisons (assembly connections), which are properly classified and characterized, with the relative standard disassembly times (Favi et al. 2016). A list of liaisons (Liaison_class) is noted based on the most common mechanical, electrical and physical connections in the context of mechatronic products. Each class contains one or more liaison types (Liaison_type), as described in Fig. 4.

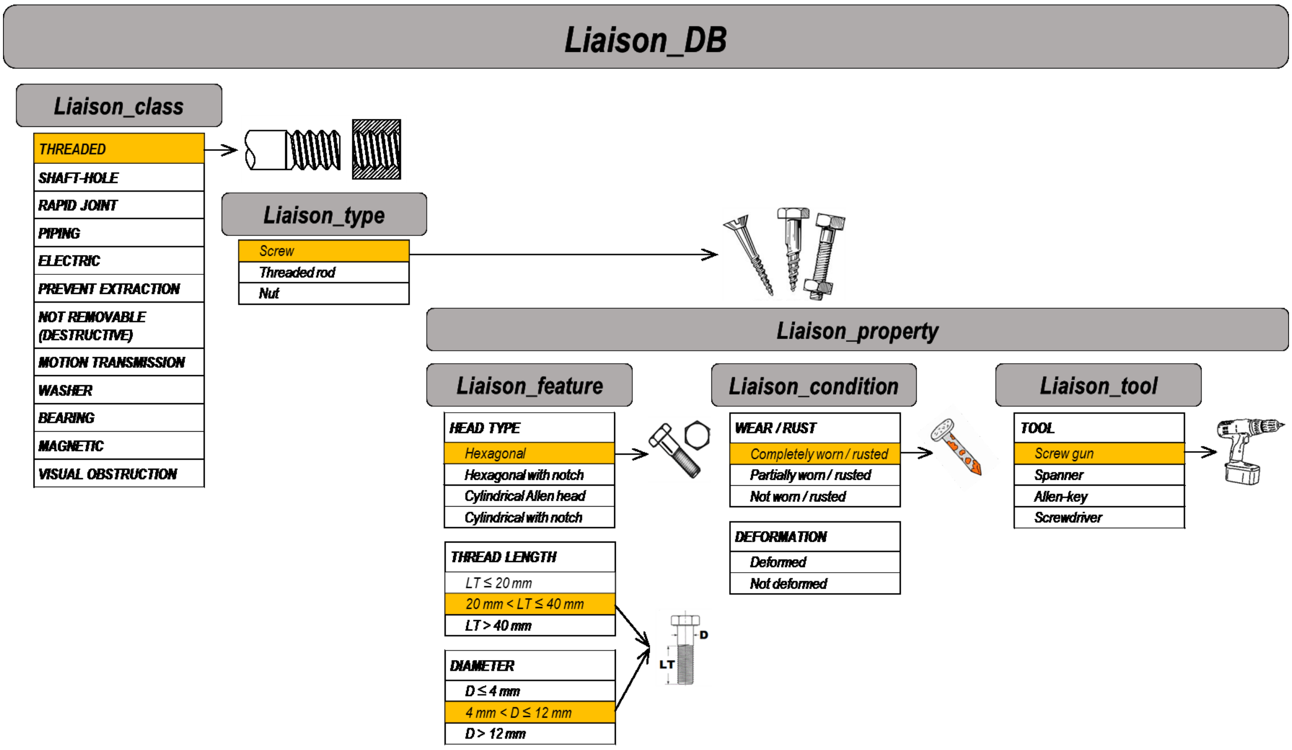


Fig. 4: structure of the Liaison_DB.

A specific disassembly time is assigned to each specific liaison (Liaison_type) and thus to each specific disassembly task (Table 1). The standard disassembly time is relative to a reference liaison, in a standard condition (length, diameter, tool, etc.) and without damages. This last assumption is particularly important because the purpose of selective disassembly, both in the cases of services and EoL, is the possibility to recover products or components without destructive actions. For instance, in the case of a screw liaison type, the reference is set to a new screw (not used or damaged) with a hexagonal notch head, a length of 20 mm or less, a diameter between 4 mm and 12 mm and disassembled with a pneumatic screwdriver. In this case, the standard disassembly time (4 seconds) equals the assembly time. The standard disassembly time for each liaison type classified in the Liaison_DB is reported in the following Table 1.

Table 1: standard disassembly times for the liaison types stored in the Liaison_DB.

| **Liaison class** | **Liaison type** | **Standard disassembly time [s]** |
|---|---|---|
| Threaded | Screw | 4 |
|  | Threaded rod | 4 |
|  | Nut | 4 |
| Shaft-hole | Pin | 3 |
|  | Linchpin | 3 |
| Rapid joint | Snap-fit | 2 |
|  | Guide | 3 |
|  | Dap joint | 2 |
| Piping | Rubber hose | 2 |
|  | Spring Clip | 4 |
| Electric | Coaxial cable | 4 |
|  | Electric plug | 2 |
|  | Screw terminal | 2 |
|  | Ribbon cable | 2 |
| Prevent extraction | Circlip | 4 |
|  | Split pin | 4 |
| Not removable (destructive operation) | Nail or Rivet | 6 |
|  | Welding | 10 |
|  | Adhesive | 6 |
| Motion transmission | Tang or Key | 3 |
|  | Spline profile | 3 |
| Washer | Washer | 2 |
| Bearing | Bearing | 5 |
| Magnetic | Magnetic | 2 |
| Visual obstruction | Visual obstruction or contact | 1 |

Based on the specific liaison type, a set of features affecting the disassembly time is classified (Liaison_feature in Fig. 4). Afterwards, the conditions of the liaison at the time of disassembly (worn, rusted, deformed, etc.) and the tools used for the disassembly task are also defined (respectively Liaison_condition and Liaison_tool in Fig. 4). As a result, for instance, if the product service life is particularly long, perhaps in a severe working environment, rust and oxides formation, wear deposition, etc., can increase the disassembly difficulties and subsequently the time necessary for the specific activity (e.g., unscrewing). Concerning the peculiarity of the liaisons, each variation from the standard condition must be addressed for the calculation of the disassembly time. It includes variation in geometrical features (screw length, screw diameter, screw head type, etc.) and variation in assembly/disassembly tools available during the disassembly operations (manual screwdriver, allen key, etc.). A corrective factor is associated with each particular condition (e.g., the kind of tool used directly influences the disassembly time). These values are used to adjust the stored standard disassembly times, obtaining the effective disassembly times, according to the following equation (1):

$$Te = Ts \cdot \prod_k CF_k \qquad (1)$$

where

- $Te$ is the effective disassembly time,
- $Ts$ is the standard disassembly time, and
- $CF_k$ is the corrective factor for the *k-th* liaison property related to the chosen de-manufacturing conditions.

Standard disassembly times and corrective factors are defined according to an in-depth literature review, several empirical case studies and analysis of different products in collaboration with expert stakeholders involved in the EoL management (i.e., dismantling centres). In the latter case, surveys, interviews and direct observation/video recording of dismantling operators' activities are used to collect relevant knowledge about liaisons (duration of each disassembly task, needs of special tools, difficulties of the disassembly or extraction operation, etc.). Successively, by using spreadsheets and/or a video annotation software, the collected knowledge is reused to establish the value of the standard disassembly time and each corrective factor.

Corrective factors related to features and disassembly tools (respectively Liaison_feature and Liaison_tool in Fig. 4) are derived by measuring five times the same task in order to have robust data for the correct characterization of each condition and to take into account the uncertainties related to the disassembly operations (e.g., operators' skills). The values stored are the mean of PDF (Probability Density Function) with a normal distribution, assessed by experimental measures of disassembly operations considering the various liaison features.

Corrective factors related to the liaison condition (Liaison_condition in Fig. 4) are established by simply observing the issues and difficulties for each disassembly task, in the case of worn and/or deformed liaisons. Even if these corrective factors are more qualitative than the factors related to the liaison features, they allow taking into account the condition at the time of disassembly and thus differentiate the disassembly tasks from the assembly tasks.

A complete example of the corrective factors defined for the screw liaison types and features is proposed in the following Table 2.

Table 2: Corrective factors for a screw liaison type

| **Liaison class** | **Liaison type** | **Standard disassembly time [s]** | **Liaison property** | **Liaison corrective factors** |
|---|---|---|---|---|
| Threaded | Screw | 4 | Wear | Completely worn / rusted = 2<br>Partially worn / rusted = 1.3<br>Not worn / rusted = 1 |
| | | | Deformation | Deformed = 2<br>Not deformed = 1 |
| | | | Head type | Hexagonal = 1.2<br>Hexagonal with notch = 1<br>Cylindrical = 1.2<br>Cylindrical with notch = 1<br>Cylindrical with hex notch = 1.1 |

| | | | | |
|---|---|---|---|---|
| | | | Length | L ≤ 20 mm = 1<br>20 mm < L ≤ 40 mm = 1.1<br>L > 40 mm = 1.2 |
| | | | Diameter | D ≤ 4 mm = 1.2<br>4 mm < D ≤ 12 mm = 1<br>D > 12 mm = 1.2 |
| | | | Tool | Screw gun = 1<br>Spanner = 1.2<br>Screwdriver = 1.4 |

An example of a rusted screw is reported below to better understand the influence of corrective factors. For this liaison type, the parameters are as follows:

- Standard disassembly time ($Ts$) = 4 [s]
- Liaison properties:
  - ✓ Head type: cylindrical with notch → $CF_1 = 1$
  - ✓ Length: > 20 mm, < 40 mm → $CF_2 = 1.1$
  - ✓ Diameter: < 4 mm → $CF_3 = 1.2$
  - ✓ Wear: partially worn / rusted → $CF_4 = 1.3$
  - ✓ Deformation: not deformed → $CF_5 = 1$
  - ✓ Tool: spanner → $CF_6 = 1.2$
- Effective disassembly time ($Te$) = $Ts * CF_1 * CF_2 * CF_3 * CF_4 * CF_5 * CF_6 = 8.24$ [s]

The relevant gap between the standard and the effective disassembly times highlights the importance of corrective factors in modelling the specificity of each analysed liaison. It represents an essential feature of the proposed approach with the aim of guaranteeing a high reliability in the time estimation. Moreover, additional time contributions can be considered to model the needed tool changing operations or product re-positioning.

### *3.4 4th step – Calculation of feasible disassembly sequences*

Disassembly "level" matrix and disassembly levels are the two mathematical models required for the definition of feasible disassembly sequences. Through the definition of the disassembly levels, it is possible to discard some sequences from the combinatorial calculation. This is a consequence of the intrinsic rule defined below (*hypothesis #3*):

Considering a generic level *n*, only components belonging to the same level (*n*) or to the subsequent level (*n+1*) are considered for the calculation of the feasible disassembly sequences. After the removal of a component at level *n*, the removal of components which belong to level *n-1* is not considered in the calculation.

This rule generates an important limitation in the explosion of the combinatorial sequences, thus permitting a drastic reduction of the computational time while keeping the quality and the accuracy of the result.

The disassembly levels for the car jack example are reported below in Fig. 5.

Fig. 5: disassembly levels for the car jack example.

The knowledge of the disassembly levels allows calculating the feasible disassembly sequences to reach each target component. Fig. 6 highlights two feasible disassembly sequences for the car jack example, considering ④ as the target component.

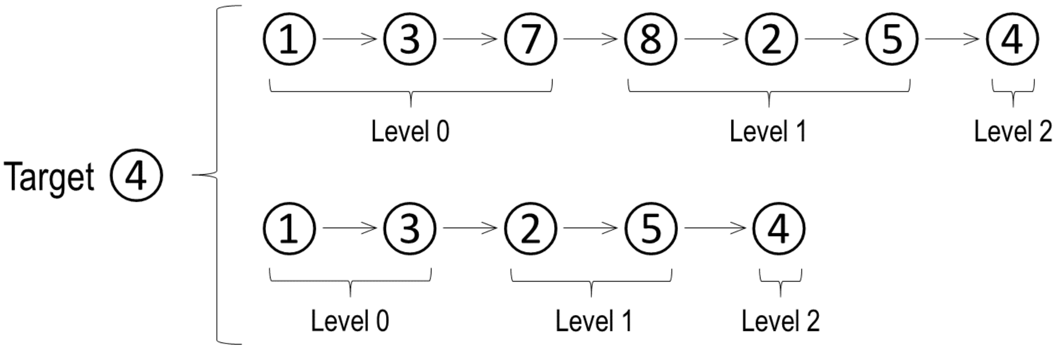


Fig. 6: Examples of feasible disassembly sequences for target component ④.

In Fig. 6, each arrow identifies a disassembly operation, i.e., the process to disassemble one component, by removing all the liaisons that link the analysed component with the rest of the assembly. The calculation of the disassembly time for each operation is achieved by considering the different liaisons between components, together with the relative conditions and corrective factors. The disassembly time for each feasible sequence is then calculated as the sum of the different disassembly operations involved in a specific disassembly sequence (equation (2)).

$$Seq\_i_{Tx} = \sum_m Op\_m_{Tx} \tag{2}$$

where

- $Seq\_i_{Tx}$ is the disassembly time of the *i-th* sequence to reach the target component *Tx*, and
- $Op\_m$ is the disassembly time of the *m-th* operation belonging to the $Seq\_i_{Tx}$ sequence.

### *3.5 5th step – Calculation of the best disassembly sequence*

The optimization problem uses a simple mathematical model in which the purpose of the optimization is the minimization of the disassembly time for the selected target component. In fact, for complex products, an inconsistency can arise during the solution of the disassembly problem. It can be found that the shortest path (i.e., minimum number of disassembly operations) is not the best way to reach the target (i.e., minimum disassembly time). Using the proposed approach, the disassembly path that minimizes the disassembly time is noted as the best disassembly sequence.

The mathematical model used for the minimization of disassembly time is a pairwise comparison among the feasible disassembly sequences, realized step by step during the calculation of each feasible disassembly sequence. The sequence with the minimum value of disassembly time is finally selected, as reported in the following equation (2).

$$BDS_{Tx} = \min(Seq\_1_{Tx}, Seq\_2_{Tx}, Seq\_3_{Tx}, \dots\ Seq\_i_{Tx}, \dots\ Seq\_n_{Tx}) \tag{2}$$

where

- $BDS_{Tx}$ is the Best Disassembly Sequence for the target component $Tx$,
- $Seq\_i_{Tx}$ is the *i-th* feasible disassembly sequence for the target component $Tx$, and
- $n$ is the overall number of feasible disassembly sequences for the target component $Tx$.

## 4 Method testing

The adoption of the proposed method in real context supports the product development process by improving disassemblability performances. The method is applied in a washing machine case study with the aim of testing different aspects:

- the relevance of the method in the case of complex products,
- the ability of the method in the calculation of feasible disassembly sequences and to derive the best one,
- the reliability of the obtained result (disassembly time) compared with experimental tests.

This example provides a comprehensive analysis of the disassemblability of target components, considering the assessment of disassembly times and disassembly sequences. The following subsection details the workflow and the results obtained, while the one after discusses the reliability, potentialities and drawbacks of the method.

### *4.1 Washing machine case study*

The case study is an old model of a washing machine manufactured and assembled by an Italian company (Candy) with an estimated life of 15 years. The product has clear signs of rust both in the external case (cabinet) and internal components (e.g., fasteners). Fig. 7 shows the simplified 3D model used in the analysis, as well as the picture of the real disassembled product.

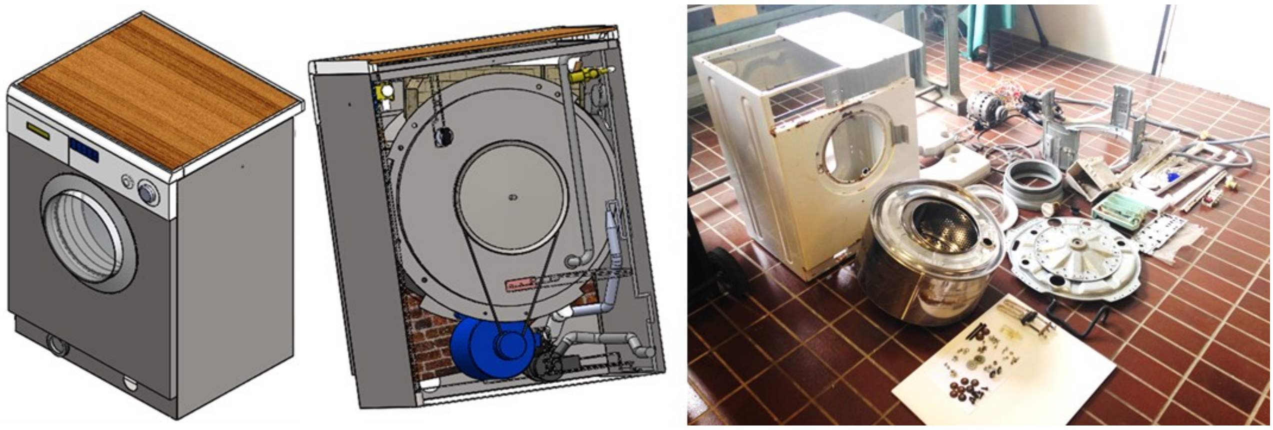


Fig. 7: washing machine 3D model (left) and real disassembled product (right).

The 1st step of the method allows for the identification of target components from the general assembly. Five *Target Components* are detected considering the specific aim (EoL and/or maintenance):

- *Capacitor*: according to the European directive on Waste Electrical and Electronic Equipment (WEEE), it must be removed at EoL before proceeding with product dismantling or shredding, due to the potential presence of hazardous substances and materials (such as lead or polychlorinated biphenyls);
- *Water pump*: it can be disassembled for maintenance/failure or it can be recovered at EoL for remanufacturing purpose (second-hand component);
- *Electric motor*: it is selected as the target component for legislation (WEEE), maintenance/failure and remanufacturing purposes;
- *Heating element*: first, it is a critical component identified by the WEEE directive, and second, it can be substituted due to corrosion and calcium deposition;
- *Drum*: since it is made from stainless steel (AISI 430), it is economically convenient to separate it from other carbon steels before shredding.

The *Virtual product model analysis* (2nd step) is carried out to set *Precedencies, Disassembly levels and Liaisons among components* (3rd step). The following Table 3 illustrates the 20X20 “level” matrix calculated for the washing machine.

Table 3: “level” matrix for the washing machine.

| | | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S | T | | Disassembly depth |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Tank pipe** | **A** | | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | → | 3 |
| **TOP back cover** | **B** | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | → | 0 |
| **Motor support** | **C** | 0 | 1 | | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | → | 12 |
| **Electric motor** | **D** | 0 | 1 | 1 | | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | → | 13 |
| **Electric wires** | **E** | 0 | 1 | 0 | 0 | | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | → | 10 |
| **Wood panel** | **F** | 0 | 1 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | → | 2 |
| **Belt** | **G** | 0 | 1 | 1 | 0 | 1 | 1 | | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | → | 13 |

| | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Tank back cover** | **H** | 0 | 1 | 1 | 1 | 1 | 1 | 0 | | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | → | 16 |
| **Cabinet** | **I** | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | → | 11 |
| **TOP front cover** | **J** | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | → | 6 |
| **Tank support** | **K** | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | → | 14 |
| **TOP guide DX** | **L** | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | → | 3 |
| **Tank + Drum** | **M** | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | → | 17 |
| **TOP guide SX** | **N** | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | 0 | 1 | → | 3 |
| **Detergent box** | **O** | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | | 1 | 1 | 0 | 0 | 1 | → | 8 |
| **Control Panel Assembly** | **P** | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | | 1 | 0 | 0 | 1 | → | 7 |
| **Concrete weight** | **Q** | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | 0 | 0 | 1 | → | 3 |
| **Pulley** | **R** | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | | 1 | 1 | → | 14 |
| **Electro-mec. Assembly** | **S** | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | | 1 | → | 8 |
| **Back cover** | **T** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | → | 0 |

In the last right-hand column of Table 3, the disassembly depth values for each washing machine component/subassembly are shown. This value allows for easy identification of the minimum number of disassembly operations to perform to reach the target component.

Components/subassemblies with disassembly depth equal to “0” can be disassembled at first; thus, they belong to disassembly level “0” (this is the case for components B and T, highlighted in Table 3 with green colour). In addition, all 20 components/subassemblies are grouped into 13 different disassembly levels (from “0” to “12”) according to the method, in order to have a complete view of the disassembly model. Fig. 8 reports the graph of disassembly levels. It shows which component/subassembly can be removed at each level (big circles), listing for each one, the components/subassemblies that have precedence (small circles) in the disassembly plan. For instance, component J, belonging to level “3”, has to give precedence to three components, belonging to level “2”: L, N and Q. The disassembly levels graph is a simplified representation of the “level” matrix, containing only aggregated information (i.e., the direct disassembly precedencies are represented).

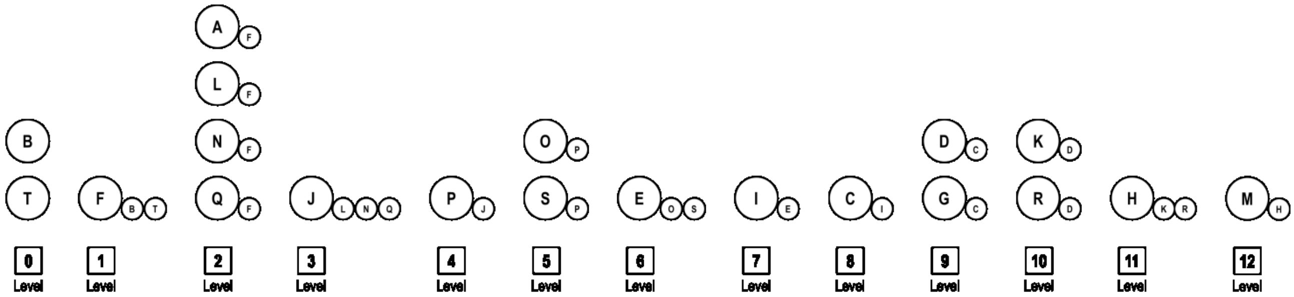


Fig. 8: washing machine disassembly levels graph.

The 3rd step of the method encompasses the definition of liaisons between components, which is performed concurrently with the definition of precedence relations. The complete set of precedence relations, liaisons and features necessary to reach the Electric motor target is provided in the Appendix. The definition of disassembly levels and the calculation of the "level" matrix allow for the generation of the *Feasible disassembly sequences* for the five chosen Target Components (4th step). By analysing Table 3 and Fig. 8, it emerges that all of the disassembly sequences have to start with one of the following components: B (TOP back cover) or T (Back cover).

Supposing the disassembly of component B (1st disassembly operation), it is possible to reduce the initial "level" matrix (Table 3) by eliminating the row and column corresponding to component B. Therefore, the disassembly depth for each component has to be updated, as shown in Table 4. After the 1st disassembly operation, the only component free from obstruction and thus ready to be disassembled (i.e., disassembly depth equal to "0") is component T (belonging to level "0"). After the disassembly of component T (2nd disassembly operation), instead, the group of components with disassembly depth equal to "0" will contain component F (see Table 5). By iterating this process, it is possible to calculate all of the feasible disassembly sequences for specific target components, as well as for the entire product.

Table 4: Reduced "level" matrix for the washing machine, after the disassembly of component B.

| | | **A** | **C** | **D** | **E** | **F** | **G** | **H** | **I** | **J** | **K** | **L** | **M** | **N** | **O** | **P** | **Q** | **R** | **S** | **T** | | **Disassembly depth** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Tank pipe** | **A** | | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | → | 2 |
| **Motor support** | **C** | 0 | | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | → | 11 |
| **Electric motor** | **D** | 0 | 1 | | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | → | 12 |

| | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Electric wires** | **E** | 0 | 0 | 0 | ▨ | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | → | 9 |
| **Wood panel** | **F** | 0 | 0 | 0 | 0 | ▨ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | → | 1 |
| **Belt** | **G** | 0 | 1 | 0 | 1 | 1 | ▨ | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | → | 12 |
| **Tank back cover** | **H** | 0 | 1 | 1 | 1 | 1 | 0 | ▨ | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | → | 15 |
| **Cabinet** | **I** | 0 | 0 | 0 | 1 | 1 | 0 | 0 | ▨ | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | → | 10 |
| **TOP front cover** | **J** | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | ▨ | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | → | 5 |
| **Tank support** | **K** | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | ▨ | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | → | 13 |
| **TOP guide DX** | **L** | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | ▨ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | → | 2 |
| **Tank + Drum** | **M** | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | ▨ | 1 | 1 | 1 | 1 | 1 | 1 | 1 | → | 16 |
| **TOP guide SX** | **N** | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | ▨ | 0 | 0 | 0 | 0 | 0 | 1 | → | 2 |
| **Detergent box** | **O** | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | ▨ | 1 | 1 | 0 | 0 | 1 | → | 7 |
| **Control Panel Assembly** | **P** | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | ▨ | 1 | 0 | 0 | 1 | → | 6 |
| **Concrete weight** | **Q** | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | ▨ | 0 | 0 | 1 | → | 2 |
| **Pulley** | **R** | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | ▨ | 1 | 1 | → | 13 |
| **Electro-mec. Assembly** | **S** | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | ▨ | 1 | → | 7 |
| **Back cover** | **T** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | ▨ | → | 0 |

Table 5: Reduced "level" matrix for the washing machine, after the disassembly of component B and component T.

| | | **A** | **C** | **D** | **E** | **F** | **G** | **H** | **I** | **J** | **K** | **L** | **M** | **N** | **O** | **P** | **Q** | **R** | **S** | | **Disassembly depth** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Tank pipe** | **A** | ▨ | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | → | 1 |
| **Motor support** | **C** | 0 | ▨ | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | → | 10 |
| **Electric motor** | **D** | 0 | 1 | ▨ | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | → | 11 |
| **Electric wires** | **E** | 0 | 0 | 0 | ▨ | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | → | 8 |
| **Wood panel** | **F** | 0 | 0 | 0 | 0 | ▨ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | → | 0 |
| **Belt** | **G** | 0 | 1 | 0 | 1 | 1 | ▨ | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | → | 11 |
| **Tank back cover** | **H** | 0 | 1 | 1 | 1 | 1 | 0 | ▨ | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | → | 14 |
| **Cabinet** | **I** | 0 | 0 | 0 | 1 | 1 | 0 | 0 | ▨ | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | → | 9 |
| **TOP front cover** | **J** | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | ▨ | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | → | 4 |
| **Tank support** | **K** | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | ▨ | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | → | 12 |
| **TOP guide DX** | **L** | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | ▨ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | → | 1 |
| **Tank + Drum** | **M** | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | ▨ | 1 | 1 | 1 | 1 | 1 | 1 | → | 15 |
| **TOP guide SX** | **N** | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | ▨ | 0 | 0 | 0 | 0 | 0 | → | 1 |
| **Detergent box** | **O** | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | ▨ | 1 | 1 | 0 | 0 | → | 6 |
| **Control Panel Assembly** | **P** | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | ▨ | 1 | 0 | 0 | → | 5 |
| **Concrete weight** | **Q** | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | ▨ | 0 | 0 | → | 1 |
| **Pulley** | **R** | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | ▨ | 1 | → | 12 |
| **Electro-mec. Assembly** | **S** | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | ▨ | → | 6 |

The *Best disassembly sequences* are derived by considering the disassembly path which minimizes the disassembly time, calculated on the basis of input information and data stored in the Liaison_DB (5th step). Corrective factors are set based on the product condition to have a realistic modelling of the analysed product. In addition, disassembly tools are set for each liaison to properly estimate the disassembly time.

As an example, Table 6 reports the details of the best disassembly sequence estimated for the Electric motor and a comparison with the real disassembly time measured for each operation considering the same disassembly path.

Table 6: best disassembly sequence for the Electric motor

| **Operation N°** | **Removed component** | **Estimated disassembly time [s]** | **Measured disassembly time [s]** | **Error [%]** |
|---|---|---|---|---|
| 1 | TOP back cover | 14.4 | 14 | -3% |
| 2 | Back cover | 28.8 | 27 | -7% |
| 3 | Wood panel | 9.8 | 10 | 2% |
| 4 | TOP guide DX | 9.6 | 9 | -7% |
| 5 | TOP guide SX | 9.6 | 9 | -7% |
| 6 | Concrete weight 1 | 13.8 | 12 | -15% |
| 7 | TOP front cover | 11.8 | 11 | -7% |
| 8 | Control Panel Assembly | 14.4 | 16 | 10% |
| 9 | Detergent box | 33.4 | 36 | 7% |
| 10 | Electro-mec Assembly | 148 | 160 | 8% |
| 11 | Electric wires | 74.1 | 85 | 13% |
| 12 | Cabinet | 29.6 | 33 | 10% |
| 13 | Motor support | 4.4 | 5 | 12% |
| 14 | Electric motor | 14.7 | 16 | 8% |
| **Total** | | 416.4 | 443 | 6% |

Fig. 9 illustrates the corresponding graph of the cumulative disassembly times for the same disassembly sequence (Electric motor).

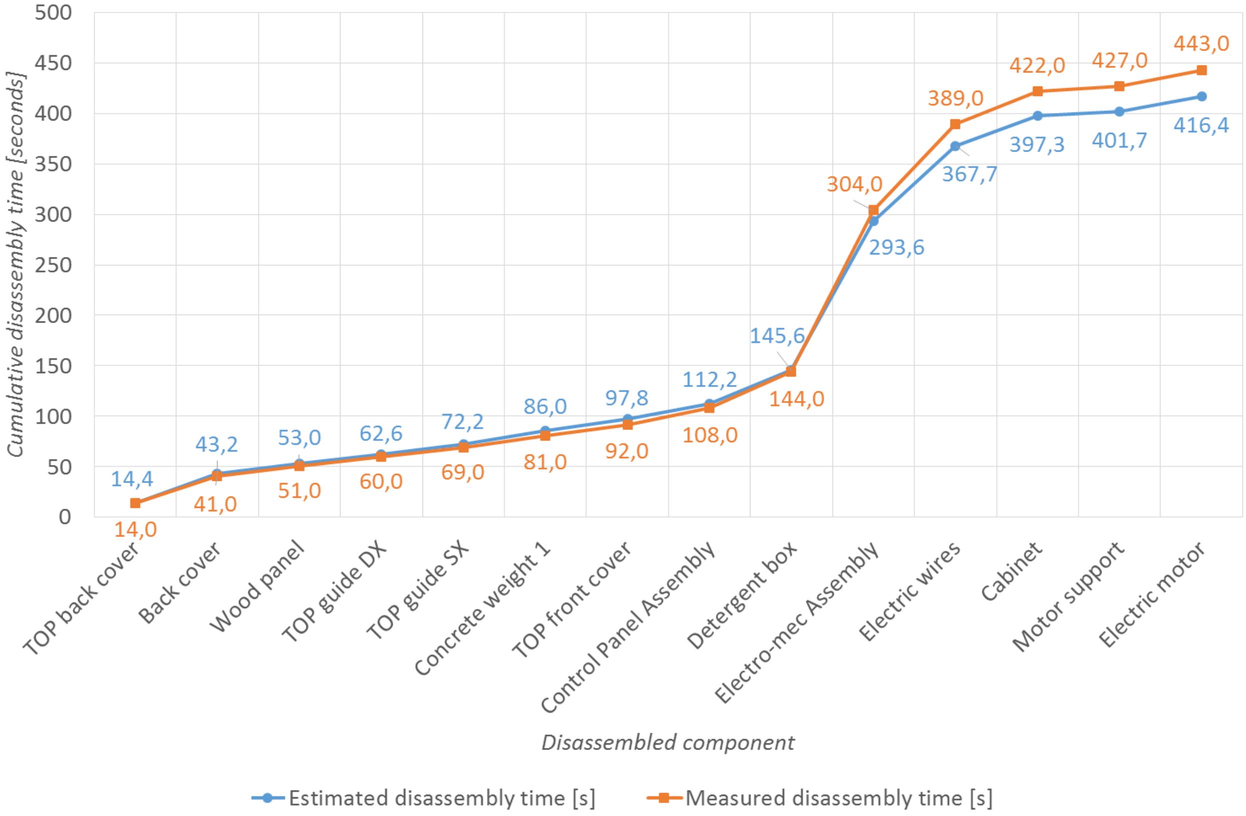


Fig. 9: cumulative disassembly time graph for the Electric motor.

### *4.2 Results discussion*

To verify the reliability of the estimated disassembly times, a comparison with experimental data (measured during non-destructive product disassembly operations) is performed on the abovementioned washing machine. A skilled operator from an authorized WEEE dismantling centre is involved in this activity, and a full-range of equipment (e.g., table, crane, electric screwdrivers, keys, allen-keys, pliers, hammer, and gloves) is provided to him. For each target component (capacitor, water pump, electric motor, heating element, drum), the operator follows the best disassembly sequence calculated by the method to be fully compliant with the retrieved sequences. Disassembly times are measured, step after step, using a stopwatch, and every step is documented to have a detailed feedback on each disassembly operation in terms of time, observed difficulties and notes. In addition, alternative disassembly paths for the selected Target Components are investigated in order to verify the validity of the retrieved best disassembly sequences. The following Table 7 reports a summary of the obtained results.

Table 7: comparison between the estimated and the measured disassembly times

| **Target component** | **Estimated disassembly time [s]** | **Measured disassembly time [s]** | **Error %** |
|---|---|---|---|
| Capacitor | 45 | 48 | -6,3% |
| Water pump | 51 | 57 | -10,5% |
| Electric motor | 416 | 443 | -6,1% |
| Heating element | 420 | 466 | -9,9% |
| Drum | 466 | 496 | -6,0% |

A gap of approx. 6% to 10% is determined by this analysis. In detail, the experimental times are systematically higher than the estimated ones, as reported in Table 6, for the electric motor example. The differences mainly arise from the following two reasons: (i) differences in wear/rust conditions of components/liaison inside the washing machine (not all component have the same condition) and (ii) inaccuracies of the method in predicting accessibility problems due to components obstructions, product re-orientation or the use of large disassembly tools. However, the error calculated, which is almost always below 10%, can be considered as acceptable during the design process, when the objective is to identify criticalities to guide the decision-making process towards the implementation of the most suitable corrective actions.

The data plotted in Fig. 9 show the reliability of the method and related data. By evaluating the slope of the curves, it is possible to see that the method clearly establishes the most critical disassembly operation (operation #10). The error committed by the method in estimating the cumulative disassembly time after the most critical operation is below 3%.

## 5 Conclusions

This paper presents a method for the analytical evaluation of the product disassemblability, based on the estimation of the disassembly times of target components. The estimation of the disassembly time, considering the actual conditions of a component at its end of life through a list of corrective factors, represents the main contribution to the state of the art in the field of Design for Disassembly.

By using the knowledge (experience of de-manufacturing centres) stored in the Liaison_DB repository, a designer can easily understand if the disassembly times of the components are within the target values set by the Chief Technical Officer. Moreover, the method supports designers in finding the most critical (time consuming) disassembly operation (operation with the highest slope within the cumulative disassembly time graph, Fig. 9). These results support designers in defining the most effective re-design strategy oriented towards disassembly (change of materials, change of liaison types, simplification of product architecture, etc.). This is particularly relevant in the case where companies are directly involved in the management of product maintenance or product EoL (e.g., remanufacture scenarios), since disassembly costs are directly paid by the company itself.

All of the needed information and the required inputs for the implementation of the method are derived from the product virtual models, which are available during the product development process (design phase). The availability of design documentation (3D models and BoMs) bounds the required time to perform a complete product disassembly analysis and reduces the impact on the traditional design workflow, although the quantity of data to manage remains the same.

The proposed approach has been used for evaluating the disassemblability of a washing machine. Through this case study, the authors wanted to evaluate the ability of such method in finding the best disassembly sequence for complex products and the reliability of the estimated disassembly times in comparison with experimental tests. The deviations between the disassembly time, estimated by this method, and from the experimental tests range from 6% to 10%. Although this paper presents only one case study, the proposed method is flexible and upgradable. It is flexible because the method is independent from the product in which it is applied, and upgradable since the knowledge related to the liaisons and relative properties and factors can be increased, while maintaining the same database structure.

The proposed method belongs to the category of the analytic/exact approaches for estimating the disassembly time. It is a flexible method which can be used during the product embodiment design and does not require any preliminary background or preparation work (apart from database tuning for widening the liaisons types, if required). However, it requires knowledge of the product virtual representations. The heuristic methods discussed in the state of the art are approaches more general than the analytic ones, which can be used even during the conceptual design phase, when the 3D CAD model does not yet exist. The main limitation of such method is related to the low applicability during the conceptual design. A future work will consist of developing a scalable solution integrating analytic/exact methods for the calculation of the product disassemblability (i.e., the method presented in this paper) with heuristic methods. The analytic method, which does not depend on the products, can be applied during the product embodiment design phase to create a repository of product disassemblability analyses. Subsequently, the latter can be used as the basic knowledge for developing a heuristic method (specifically for the product realized by the company) to be used during the conceptual design stage. This combination makes product disassemblability evaluation possible both during the conceptual and embodiment design stages. Another interesting research outlook will be the gap assessment between the proposed time-based approach and the available methods based on the minimization of disassembly operations. This analysis will lead to demonstrate the effectiveness of the proposed approach in de-manufacturing industries where the main driver is the minimization of disassembly time which is directly linked with the disassembly costs.

Moreover, the application of the proposed method during the design stages can be fostered by implementing algorithms for the automatic identification of disassembly levels based, for example, on collision analysis or Gaussian spheres. In this way, manual inputs can be reduced as well as the time required for the analysis of the virtual model (2nd and 3rd steps of the approach).

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# Appendix

| **Disassembly level** | **Component** | **Components with precedence relations** | **Joint components** | **Liaison Type** | **Liaison properties** |
|---|---|---|---|---|---|
| 0 | Back cover | - | Cabinet | 6 Screws | Wear = not worn / rusted<br>Deformation = not deformed<br>Head type = Hexagonal<br>Length = $\leq 20$ mm<br>Diameter = $> 4$ mm, $\leq 12$ mm<br>Tool = Screw gun |
|  | TOP back cover | - | Cabinet | 3 Screws | Wear = not worn / rusted<br>Deformation = not deformed<br>Head type = Hexagonal<br>Length = $\leq 20$ mm<br>Diameter = $> 4$ mm, $\leq 12$ mm<br>Tool = Screw gun |
| 1 | Wood panel | Cabinet<br>TOP back cover | TOP guide DX | 1 Guide | Wear = partially worn /rusted<br>Deformation = not deformed<br>Length = $> 300$ mm<br>Typology = U-shape<br>Tool = Manual |
|  |  |  | TOP guide SX | 1 Guide | Wear = partially worn /rusted<br>Deformation = not deformed<br>Length = $> 300$ mm<br>Typology = U-shape<br>Tool = Manual |
| 2 | TOP guide DX | Wood panel | Wood panel | 1 Guide | Wear = partially worn /rusted<br>Deformation = not deformed<br>Length = $> 300$ mm<br>Typology = U-shape<br>Tool = Manual |
|  |  |  | Cabinet | 2 Screws | Wear = not worn / rusted<br>Deformation = not deformed<br>Head type = Hexagonal<br>Length = $\leq 20$ mm<br>Diameter = $> 4$ mm, $\leq 12$ mm<br>Tool = Screw gun |
|  | TOP guide SX | Wood panel | Wood panel | 1 Guide | Wear = partially worn /rusted<br>Deformation = not deformed<br>Length = $> 300$ mm |

| | | | | | |
|---|---|---|---|---|---|
| | | | | | Typology = U-shape<br>Tool = Manual |
| | | | Cabinet | 2 Screws | Wear = not worn / rusted<br>Deformation = not deformed<br>Head type = Hexagonal<br>Length = ≤ 20 mm<br>Diameter = > 4 mm, ≤ 12 mm<br>Tool = Screw gun |
| | Concrete weight | Wood panel | Tank support | 2 Screws | Wear = not worn / rusted<br>Deformation = not deformed<br>Head type = Hexagonal<br>Length = > 40 mm<br>Diameter = > 12 mm<br>Tool = Screw gun |
| 3 | TOP front cover | TOP guide DX<br>TOP guide SX<br>Concrete weight | Cabinet | 2 Screws | Wear = not worn / rusted<br>Deformation = not deformed<br>Head type = Hexagonal<br>Length = ≤ 20 mm<br>Diameter = > 4 mm, ≤ 12 mm<br>Tool = Screw gun |
| | | | Control Panel Assembly | 1 Snap-fit | Wear = not worn / rusted<br>Deformation = not deformed<br>Geometry = Rectangular<br>Tool = Manual |
| 4 | Control Panel Assembly | TOP front cover | Cabinet | 3 Screws | Wear = not worn / rusted<br>Deformation = not deformed<br>Head type = Hexagonal<br>Length = ≤ 20 mm<br>Diameter = > 4 mm, ≤ 12 mm<br>Tool = Screw gun |
| | | | TOP front cover | 1 Snap-fit | Wear = not worn / rusted<br>Deformation = not deformed<br>Geometry = Rectangular<br>Tool = Manual |
| 5 | Detergent box | Control Panel Assembly | Tank pipe | 1 Pin | Wear = not worn / rusted<br>Length = ≤ 10 mm<br>Diameter = > 10 mm, ≤ 100 mm<br>Grooves = No<br>Play = ≤ 0.01 mm<br>Conicity = No<br>Notch = No |

| | | | | | |
|---|---|---|---|---|---|
| | | | | | Tool = Pliers |
| | | | Cabinet | 3 Screws | Wear = not worn / rusted<br>Deformation = not deformed<br>Head type = Hexagonal<br>Length = ≤ 20 mm<br>Diameter = > 4 mm, ≤ 12 mm<br>Tool = Screw gun |
| | | | | 1 Snap-fit | Wear = not worn / rusted<br>Deformation = not deformed<br>Geometry = Other<br>Tool = Manual |
| | | | | 1 Pin | Wear = not worn / rusted<br>Length = ≤ 10 mm<br>Diameter = > 10 mm, ≤ 100 mm<br>Grooves = No<br>Play = ≤ 0.01 mm<br>Conicity = No<br>Notch = No<br>Tool = Pliers |
| | | | Tank back cover Assembly | 1 Pin | Wear = not worn / rusted<br>Length = ≤ 10 mm<br>Diameter = > 10 mm, ≤ 100 mm<br>Grooves = No<br>Play = ≤ 0.01 mm<br>Conicity = No<br>Notch = No<br>Tool = Pliers |
| | Electro-mec Assembly | Control Panel Assembly | Electric wires | 30 Electric plugs | Wear = completely worn / rusted<br>Connected with = Rigid support<br>Tool = Manual |
| | | | Cabinet | 5 Screws | Wear = not worn / rusted<br>Deformation = not deformed<br>Head type = Hexagonal<br>Length = ≤ 20 mm<br>Diameter = > 4 mm, ≤ 12 mm<br>Tool = Screw gun |
| | | | Cabinet | 1 Screw | Wear = not worn / rusted<br>Deformation = not deformed<br>Head type = Cylindrical with notch<br>Length = ≤ 20 mm<br>Diameter = > 4 mm, ≤ 12 mm |

| | | | | | |
|---|---|---|---|---|---|
| | | | | | Tool = Screw gun |
| 6 | Electric wires | Detergent box<br>Electro-mec Assembly | Tank back cover Assembly | 8 Electric plugs | Wear = partially worn / rusted<br>Connected with = Rigid support<br>Tool = Manual |
| | | | Electro-mec Assembly | 30 Electric plugs | Wear = completely worn / rusted<br>Connected with = Rigid support<br>Tool = Manual |
| | | | Cabinet | 13 Electric plugs | Wear = partially worn / rusted<br>Connected with = Rigid support<br>Tool = Manual |
| | | | | 1 Pin | Wear = not worn / rusted<br>Length = ≤ 10 mm<br>Diameter = > 10 mm, ≤ 100 mm<br>Grooves = No<br>Play = ≤ 0.01 mm<br>Conicity = No<br>Notch = No<br>Tool = Pliers |
| | | | Electric motor | 5 Electric plugs | Wear = partially worn / rusted<br>Connected with = Rigid support<br>Tool = Manual |
| 7 | Cabinet | Electric wires | TOP back cover | 3 Screws | Wear = not worn / rusted<br>Deformation = not deformed<br>Head type = Hexagonal<br>Length = ≤ 20 mm<br>Diameter = > 4 mm, ≤ 12 mm<br>Tool = Screw gun |
| | | | Back cover | 6 Screws | Wear = not worn / rusted<br>Deformation = not deformed<br>Head type = Hexagonal<br>Length = ≤ 20 mm<br>Diameter = > 4 mm, ≤ 12 mm<br>Tool = Screw gun |
| | | | TOP guide SX | 2 Screws | Wear = not worn / rusted<br>Deformation = not deformed<br>Head type = Hexagonal<br>Length = ≤ 20 mm<br>Diameter = > 4 mm, ≤ 12 mm<br>Tool = Screw gun |
| | | | TOP guide DX | 2 Screws | Wear = not worn / rusted<br>Deformation = not deformed |

| | | | | | |
|---|---|---|---|---|---|
| | | | | | Head type = Hexagonal<br>Length = ≤ 20 mm<br>Diameter = > 4 mm, ≤ 12 mm<br>Tool = Screw gun |
| | | | TOP front cover | 2 Screws | Wear = not worn / rusted<br>Deformation = not deformed<br>Head type = Hexagonal<br>Length = ≤ 20 mm<br>Diameter = > 4 mm, ≤ 12 mm<br>Tool = Screw gun |
| | | | Control Panel Assembly | 3 Screws | Wear = not worn / rusted<br>Deformation = not deformed<br>Head type = Hexagonal<br>Length = ≤ 20 mm<br>Diameter = > 4 mm, ≤ 12 mm<br>Tool = Screw gun |
| | | | Detergent box | 3 Screws | Wear = not worn / rusted<br>Deformation = not deformed<br>Head type = Hexagonal<br>Length = ≤ 20 mm<br>Diameter = > 4 mm, ≤ 12 mm<br>Tool = Screw gun |
| | | | | 1 Snap-fit | Wear = not worn / rusted<br>Deformation = not deformed<br>Geometry = Other<br>Tool = Manual |
| | | | | 1 Pin | Wear = not worn / rusted<br>Length = ≤ 10 mm<br>Diameter = > 10 mm, ≤ 100 mm<br>Grooves = No<br>Play = ≤ 0.01 mm<br>Conicity = No<br>Notch = No<br>Tool = Pliers |
| | | | Electric wires | 13 Electric plugs | Wear = partially worn / rusted<br>Connected with = Rigid support<br>Tool = Manual |
| | | | | 1 Pin | Wear = not worn / rusted<br>Length = ≤ 10 mm<br>Diameter = > 10 mm, ≤ 100 mm<br>Grooves = No |

| | | | | | |
|---|---|---|---|---|---|
| | | | | | Play = ≤ 0.01 mm<br>Conicity = No<br>Notch = No<br>Tool = Pliers |
| | | | Tank support Assembly | 2 Pin | Wear = completely worn / rusted<br>Length = > 10 mm, ≤ 300 mm<br>Diameter = > 10 mm, ≤ 100 mm<br>Grooves = No<br>Play = ≤ 0.01 mm<br>Conicity = No<br>Notch = No<br>Tool = Pliers |
| | | | | 2 Snap-fit | Wear = not worn / rusted<br>Deformation = not deformed<br>Geometry = Other<br>Tool = Manual |
| | | | Tank | 1 Snap-fit | Wear = not worn / rusted<br>Deformation = not deformed<br>Geometry = Other<br>Tool = Manual |
| | | | | 1 Nut | Wear = not worn / rusted<br>Deformation = not deformed<br>Head type = Common<br>Length = > 10 mm<br>Diameter = > 4 mm, ≤ 12 mm<br>Tool = Screw gun |
| | | | | 1 Pin | Wear = not worn / rusted<br>Length = ≤ 10 mm<br>Diameter = > 10 mm, ≤ 100 mm<br>Grooves = No<br>Play = ≤ 0.01 mm<br>Conicity = No<br>Notch = No<br>Tool = Pliers |
| | | | Electro-mec Assembly | 5 Screws | Wear = not worn / rusted<br>Deformation = not deformed<br>Head type = Hexagonal<br>Length = ≤ 20 mm<br>Diameter = > 4 mm, ≤ 12 mm<br>Tool = Screw gun |
| | | | | 1 Screw | Wear = not worn / rusted |

| | | | | | |
|---|---|---|---|---|---|
| | | | | | Deformation = not deformed<br>Head type = Cylindrical with notch<br>Length = ≤ 20 mm<br>Diameter = > 4 mm, ≤ 12 mm<br>Tool = Screw gun |
| 8 | Motor support | Cabinet | Electric motor | 1 Nut | Wear = not worn / rusted<br>Deformation = not deformed<br>Head type = Common<br>Length = > 3 mm, ≤ 10 mm<br>Diameter = > 4 mm, ≤ 12 mm<br>Tool = Screw gun |
| 9 | Electric motor | Motor support | Motor support | 1 Nut | Wear = not worn / rusted<br>Deformation = not deformed<br>Head type = Common<br>Length = > 3 mm, ≤ 10 mm<br>Diameter = > 4 mm, ≤ 12 mm<br>Tool = Screw gun |
| | | | Tank support Assembly | 2 Screws | Wear = not worn / rusted<br>Deformation = not deformed<br>Head type = Hexagonal<br>Length = > 40 mm<br>Diameter = > 4 mm, ≤ 12 mm<br>Tool = Screw gun |
| | | | Electric wires | 5 Electric plugs | Wear = partially worn / rusted<br>Connected with = Rigid support<br>Tool = Manual |
| | | | Belt | 1 Guide | Wear = partially worn /rusted<br>Deformation = not deformed<br>Length = ≤ 300 mm<br>Typology = U-shape<br>Tool = Manual |