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The Disassembly Map: A new method to enhance design for product repairability

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ABSTRACT

Designers and engineers need better tools and methods to create highly repairable products. Design for disassembly and reassembly is an important product related design feature that can enhance repair. In a highly repairable product, the components that fail most often should be easily accessible for repair or replacement. This paper describes the development of a method to visually map the disassembly of a product, showing different routes towards target components. These components can be those with a high potential failure rate (important for repair), embodied environmental impact (important for recycling) and economic value (relevant for component harvesting), depending on the circular strategy under consideration. The 'Disassembly Map' method is set up to guide product design and is aligned with the most recent research and standards on product repairability. The ease of disassembly is assessed on Four main design parameters are considered in this method to assess the ease of disassembly of: disassembly sequence/depth, type of tools, fastener reusability/reversibility, and disassembly time. In contrast to most of the related literature found, the Disassembly Map method is not based on the use of an algorithm for the automatic calculation of optimised disassembly sequences. It asks designers and engineers to analyse each disassembly step using standardized visual elements based on the ease of Disassembly Metric (eDiM) and the Maynard Operation Sequence Technique (MOST). Insights gathered from this analysis and the resulting visualisation can be used in an iterative product development process. The method was developed by analysing seven vacuum cleaners. Its effectiveness was then tested by redesigning one of them, enhancing its repairability.

1. Introduction

In the EU Circular Economy action plan released in 2020 (European Commission, 2020), the transition towards a Circular Economy is described as necessary to create new sustainable advantages, to protect businesses from future potential resource scarcity, and to boost the economy. Product design is seen as an important means of increasing product durability and to enhance repairability, upgradability and remanufacturing. New legislation resulting from this action plan is expected to compel companies to account for repairability and serviceability in product development.

Recently, many studies have been conducted on the subject of assessing product repairability. These were set up to define standards, protocols and scoring systems that can both help to create a new labelling system and to guide the redesign of more durable consumer products (Bracquené et al., 2018; CENELEC, 2020; Cordella et al., 2019; B. Flipsen, Bakker and van Bohemen, 2016; B. Flipsen, Huisken, Opsomer, Depypere, 2019; Peeters et al., 2018; Vanegas et al., 2016). They all emphasize the importance of the ease of disassembly. Product disassembly is an essential factor to ensure that End-of-life activity is both economically viable and interesting (Boothroyd and Alting, 1992; Fukushige et al., 2013; Kwak et al., 2009). The main factors known to influence the ease of disassembly are: disassembly depth/sequence and disassembly time (Fukushige et al., 2013; Ishii et al., 1994; Kroll, 1996; Kwak et al., 2009; Lambert and Gupta, 2008; Marks et al., 1993; Zussman et al., 1994); the reusability/reversibility of fasteners and the use of common tools (Bracquené et al., 2018; CENELEC, 2020; Cordella et al., 2019). However, there is a lack of easy-to-use design tools for the early stages of the design process, and that include all four parameters.

In this paper, we address designers, product architects, mechanical and production engineers who need to improve repairability and serviceability of consumer products. The research objective is to create

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and test a new method based on architecture structural model representation, which helps designers to assess the ease of disassembly and repair of household products. The aim is to create a clear, systematic and standardized representation of a product's architecture which can be used to facilitate the comparison and assessment of products' repairability and the ease of harvesting components and materials for reuse. This will facilitate product (re-)design by giving designers insights into the nature of each disassembly step in relation to the complexity of the overall product architecture.

Section 2 reviews existing analysis methods for product architecture optimization based on architecture structure modelling and standard methods for calculating disassembly time. Section 3 describes the method applied in this study for analysing the product architecture and ease of disassembly of seven vacuum cleaners. Section 4 describes how insights gathered from the literature and the products analysis were used to create a new architecture representation method, the Disassembly Map (Section 4.1). The successful application of this new mapping method to redesign one of the vacuum cleaners is presented in Section 4.2. The Discussion (Section 6), and Conclusions (Section 7) conclude the paper.

2. Background on product architecture mapping

Insights into product disassembly and reassembly are critical to the repairability of products. For designers, a visual representation of the disassembly process can be a powerful tool when making design decisions. We reviewed research into methods that enable the mapping of a product's architecture and assess the applicability of these methods in the early design stages; these are summarized below.

2.1. Analysis methods for product architecture optimization based on sequence mapping and structural modelling representation

In the first studies on product architecture optimization, diagrams were found to be useful for creating schematic models of product assembly and disassembly. Initially the focus was on design for assembly optimization, which later inspired research into design for disassembly and end-of-life (Boothroyd and Alting, 1992; Boothroyd et al., 2010).

Bourjault (1984) introduced the concept of 'liaisons'; user-defined relations connecting single components. In his liaison diagram, components like nodes and liaisons are indicated as lines connecting the nodes. Bourjault's representation was achieved through logic 'yes/no' questions, meant to define system relations and constraints. De Fazio and Whitney (1987) iterated on Bourjault's work by creating an algorithm that calculates all the possible assembly sequences for a given configuration. Their diagram is one of the first to use the vertical dimension of the graph to express the hierarchy between steps (in this case assembly steps). They indicated different layers of assembly in numbered "ranks". Later research used precedence diagrams together with the bill of materials to analyse product architecture and calculate optimised disassembly operations for End-of-life recovery (Gonzalez and Adenso-Diaz, 2005; Johnson and Wang, 1995). However, the structure of the disassembly tree obtained through these types of diagrams is rigid and does not permit representation and consideration of alternative disassembly sequences (Kwak et al., 2009). De Mello and Sanderson (1990, 1991) introduced the application of an AND/OR graph for assembly sequence representation. This allows a more optimised representation of multiple parallel and alternative disassembly sequences in the same graph. They used this representation system to develop an algorithm with a similar scope to the work of De Fazio and Whitney: calculating all possible assembly sequences of a product.

Marks et al. (1993) were the first to use architecture mapping to guide product disassembly optimization for End-of-life. In their representation method "Linker", based on connection diagrams, they clustered components sharing the same expected End-of-life in subassemblies using a technique referred to as "clumping". Similar clustering techniques have also been suggested in later research (Fukushige et al., 2013; Kwak et al., 2009; Lambert and Gupta, 2008).

The main limitation of the methods presented here is related to their limited practical applicability. Most are based on mathematical algorithms which calculate feasible sequences considering mainly geometrical constraints. However, the proposed solutions do not consider product stability, material properties, compatibility with the production line, or aesthetic requirements. In our study, we found these to be essential constraints for consideration in optimising product disassembly.

Ishii and Lee (1996) presented a more practical mapping approach, the Reverse Fishbone Diagram, meant to guide design for disassembly in the early design stages of a project. It is a qualitative product architecture representation diagram obtained by manually "walking through" the disassembly process (Ishii and Lee, 1996). The diagram is intended to be an effective analysis and communication tool to be used throughout the product development process by different stakeholders. Inspired by Marks et al. (1993), Ishii also suggests the use of component clustering based on the shared fate of components. Additionally, this diagram uses both the vertical and horizontal dimensions to represent sequence dependent and independent disassembly procedures. However, it shares similar limitations as already described for precedence diagrams.

The integration of disassembly time in a product architecture model was proposed by Fukushige et al. (2013). In this case, a precedence diagram was also used for the representation of disassembly sequences; disassembly time required for each step was calculated using the Disassemblability Evaluation Method (DEM) (Hiroshige et al., 1997 in Fukushige et al., 2013) and this amount of time was represented next to each component liaison. However, the representation of sequence dependent and independent operations through vertical and horizontal graph directions was completely lost in this structural model, resulting in an intricated and crowded diagram. Additionally, only disassembly duration is indicated, without indicating the related design features determining it.

2.2. Disassembly time assessment methods based on the MOST system

Disassembly depth only partially describes the complexity of the repairability process. What actually differentiates different types of steps is the nature of the operations carried out, which directly relates to the amount of time they require. Recent research (Bracquené et al., 2018; Cordella et al., 2019; Vanegas et al., 2016) suggests that the Maynard Operation Sequence Technique (MOST) (Zandin, 2002) is as an effective method for calculating disassembly time. MOST is a predetermined motion time system that describes the time required for basic actions, considering an averagely skilled worker working at normal pace and under supervised working conditions. These basic actions are represented using letters which express the type of activity, and indices that describe variation in activity time based on task conditions (e.g. force intensity required, component of the body involved in the movement, number of task repetitions). A sequence of basic actions can describe more complex motion sequences, also defined as sequence models, such as the use of a tool for the removal of a fastener (Table 1).

Two quantitative tools based on MOST for the assessment of disassembly operations required to reach certain product components are the Disassembly Evaluation Chart (Kroll, 1996) and the ease of Disassembly Metric (eDiM) (Peeters et al., 2018; Vanegas et al., 2016). Kroll (1996) calculates sequence models taking into account fastener accessibility, tool positioning, force applied, and action base time. These parameters are used to score disassembly operations on a ten-point 'difficulty' scale. Vanegas et al. (2016) developed the eDiM spreadsheet (ease of Disassembly Metric/Method) to map disassembly tasks and calculate operation time required. They identified six typical tasks: tool change, connector identifiability, product manipulation, tool positioning, fastener disconnection, and removal of disassembled component.

Table 1
MOST sequence model used to describe the operation of unfastening and removing a screw.

MOST sequence for screw unfastening and removal						Meaning of actions and indexes
A1B0G1	A1B0P6	L16	A1B0P1	A1B0G1	A1B0P1	
Get tool	Put tool in place action	Tool action	Put tool aside	Reach and grab the screw	Remove the screw	A1 = Reach to a screw driver within reach B0= No body motion occurs in vertical direction G1 = Gaining control of the screw driver A1 = Move the screwdriver to a fastener within reach B0= No body motion occurs in vertical direction P6= Place the screwdriver with adjustments to engage the fastener L16 = Twist the screw driver with hand (around 9 motion repetition) to run out the threads A1 = Remove the screw driver to a storage area within reach B0= No body motion occurs in vertical direction P1= Place the screw driver in the storage area A1 = Return the hand to the assembly within reach B0= No body motion occurs in vertical direction G1 = Grab the screw from the screw hole A1 = Remove the screw from the screw hole P1= Place the screw in the storage area
Basic actions A = Horizontal motion B = Vertical motion G = Gaining control P = Placement/positioning L = Loosening action						

Standard sequences are proposed for five of these (Table 2) while the sequence for 'fastener disconnection' changes in accordance with the specific type of fastening and tool involved. Both methods quantify disassembly difficulty based on time calculation. However, they do not integrate information directly relevant to designers about disassembly dependencies of components, types of disassembly interdependencies, location of target components in the overall product architecture, use of uncommon tools and non-reusable fasteners.

This overview shows a variety of interesting and insightful methods for product architecture mapping. Although these methods address disassembly depth/sequence and disassembly time, reversible use of fasteners, and the use of common tools, none of these integrates all four parameters needed for a highly repairable product design. The Disassembly Map method presented in this paper builds on the reverse Fishbone Diagram (Ishii and Lee, 1996), integrating a more elaborate representation of disassembly operations inspired by previous literature (Bourjault, 1984; De Fazio and Whitney, 1987; De Mello and Sanderson, 1990; Fukushige et al., 2013) and introducing new standard visual elements to communicate parameters related to the calculation of disassembly time, based on MOST (Zandin, 2002; Kroll, 1996; Vanegas et al., 2016).

2.3. Criteria for the creation of a new method

Based on the literature introduced above, seven criteria for the creation of a new method have been defined:

C.1. The method should be based on standard representation models, following precise rules which can ensure reproducibility and comparability
C.2. The method should clearly communicate the depth of disassembly of each component required to be disassembled to reach the most valuable components
C.3. The method should be flexible enough to represent even the most intricate and complex component precedence relations and disassembly dependencies
C.4. The method should clearly indicate which components are the most valuable and relevant, by considering different plannable End-of-life strategies
C.5. The method should clearly indicate how different design features have an effect on disassembly time
C.6. The method should clearly indicate the type of tools required for the disassembly, and highlight when the use of uncommon tools is required
C.7. The method should provide specific information about the fasteners used to connect each component and highlight when fastener reusability/reversibility is not ensured

Table 2
Standard disassembly tasks, proposed by Vanegas et al. (2016), used in this study.

Disassembly task	Description	Sequence	TMU	Time (s/task)
Tool Change	Fetch and Put back	A1B0G1+A1B0P1	40	1.4
Identifying	Localising connectors			
	Visible area > 0.05 mm^2			0
	Hidden: visible area < 0.05 mm^2	T10	100	3.6
Manipulation	Product handling to access fasteners	A1B0G1+L3	50	1.8
Positioning	Positioning tool onto fastener	A1B0P3A0	40	1.4
Removing	Removing separated components	A1B0G1+A1B0P1	40	1.4

3. Method

The Disassembly Map method was developed by design professionals in the context of a research project on design for repair (De Fazio, 2019), in collaboration with a manufacturing company. The product related parameters proposed by Cordella et al. (2019) for the assessment of repair, were used to guide the analysis of the seven vacuum cleaners and the subsequent creation of the Disassembly Map method. These are:

- Disassembly depth/sequence
- Disassembly time
- Type of tools
- Fasteners reusability

Safety, although of critical importance, was not within the scope of this paper.

The Disassembly Map method was developed during multiple iterations, by combining the insights from literature, presented in Section 2, and the analysis of the seven products. The method obtained and its application are presented in Section 4.

3.1. Selection of products

Vacuum cleaners were chosen because, like most household appliances, they have a fairly simple product architecture and include both electrical and mechanical components. This makes it possible to compare the outcomes of this assessment with other household appliances. Furthermore, in recent years, the European Commission often used vacuum cleaners as a starting point for new eco-regulations, as indicated also in Cordella et al. (2019). Three different kinds of vacuum cleaners were chosen (Table 3):

- Different product types with different architectures (bag canisters, bagless canisters, and stick vacuum cleaners).
- Different price ranges, to investigate how architecture and repairability may change based on price.
- Different brands, to investigate to what extent different manufacturers take repairability into account in the product architecture of their vacuum cleaners.

3.2. Identification of target components

Ease of product disassembly is important to improve the accessibility of the most important (i.e. 'target') components. Target components in this research are defined based on the different End-of-life strategy for which the product architecture needs to be assessed or optimised. These are the components that fulfil one of the following criteria:

1. Regular need for repair or replacement (if the aim is to facilitate repair operations);
2. High embodied environmental impact (if the aim is to facilitate recycling operations);
3. High economic value (if the aim is to facilitate refurbishment or component harvesting).

Components relevant for repair and upgrade activities are determined by their functional importance, frequency of failure, and upgrades happening during the average life-span of the product group (Cordella et al., 2019). Based on the literature, an average lifespan of 8 years for vacuum cleaners was taken as starting point (Bracquené et al., 2018; Kemna and Boorn, 2016; Rames et al., 2018). The same list of priority parts proposed by Cordella et al. (2019) for vacuum cleaners was used in this study for those components with the highest failure/functional importance. Target components based on embodied environmental impact and embodied economic value were identified by using the HotSpot Mapping tool (Flipsen et al., 2020). Table 4 shows an overview of the target components identified in this study for the vacuum cleaner #1 (low end canister, brand A).

3.3. Research protocol

Each product disassembly was repeated three times. The disassembly process was recorded by top-view and side-view video. Furthermore, images were taken of all disassembly operations, and for each component, the weight and material composition were noted and used in the HotSpot Mapping spreadsheet. If multiple ways of disassembling a part were possible, the fastest disassembly sequences were considered. The eDiM calculation sheet was filled in and a "user questions" approach inspired by Bourjault (1984) and De Fazio and Whitney (1987) was used at the end of each step to correctly describe disassembly dependencies

Table 3
Type of products analysed.

Type of vacuum cleaner	Price range	Brand
1. Bagless canister	Low-end (up to 150 euros)	A
2. Stick	High-end (over 250 euros)	A
3. Bag canister	High-end (over 250 euros)	A
4. Bagless canister	High-end (over 250 euros)	A
5. Bagless canister	Low-end (up to 150 euros)	B
6. Bagless canister	Low-end (up to 150 euros)	C
7. Bag canister	Low-end (up to 150 euros)	D

and precedence between components:

1. Which next disassembly step is required to reach the target component?
2. Is this disassembly operation absolutely necessary to reach the target component?
3. Is there any other operation that could be carried out first?
4. Is there any other operation that could be carried out in parallel with the one just completed?

In accordance with the EN45554, in this study a step is defined as an operation that finishes with the removal of a part, and/or with a change of tool. On the other hand, grabbing a tool, putting a tool down and removing a fastener were not considered as a step. A disassembly sequence was considered to be the number of steps required to reach and remove a target component. The mapping of a few small components, such as small metal springs or plastic inserts, has been neglected to simplify the analysis. These did not influence the disassembly operation of target components, and their failure rate was negligible. De-soldering was not considered as a valid operation for components disassembly.

The final Map obtained for the product disassembly was drawn digitally, including information about the tools used, the operations involved, and the target components. The representativity of the Map was then discussed with the manufacturer's product architects and production engineers. The value of the Disassembly Map methodology for design for repairability was then tested by redesigning one of the products, enhancing its ease of disassembly.

4. Results

4.1. Disassembly Mapping method

Based on the literature review presented in section 2, the analysis of the disassembly of seven vacuum cleaners, and on the use of the eDiM, we created a new method: the Disassembly Map, a representation method that can be used to map the architecture of a product in order to provide guidance to (re-)design for repair. The following section presents the main features of this new method: general logic representations, action blocks, action block coding, penalties, and target indicators. The creation of the method was guided by the application of MOST; for this reason and to enable result reproducibility, the main MOST sequences used for the creation of the Map are presented throughout the text.

General logic representations

Components are represented by a circle, containing a component number. The Disassembly Map always starts with a circle representing the entire assembed product. Each circle is connected to the other with arrows that communicate the disassembly direction. Each component circle is indicated only when a component is completely removed. The Disassembly Map is based on three main logic representations:

1. Sequential dependency. Sequence-dependent disassembly is the least optimised configuration, since it requires sequential and singular disassembly of each component. As shown in Fig. 1, in this case the disassembly of any component requires the disassembly of the upper one (first A, then B, and finally C). This dependency generally determines high disassembly time, increasing the procedure's difficulty. The representation of sequence-dependent steps is always vertical, communicating a sense of depth.
2. Sequential independency. Sequence-independent disassembly is the preferable configuration as it does not require sequential and singular disassembly of each component. In Fig. 2, B and C can be independently disassembled, after the removal of A. This means that a repairer could just pick and immediately remove the component of choice. In this case, the disassembly time of one component does not influence the disassembly time of the other. This configuration is

Table 4
Target components identified in this study for vacuum cleaner number 1.

Part	**High failure/functional importance** (based on Cordella et al., 2019)	**High embodied environmental impact** (Based on HotSpot Mapping tool)	**High embodied economic value** (Based on HotSpot Mapping tool)
Motor	Target	Target	Target
PCBA	Target	Target	Target
Power cable/cord winder	Target	Target	Target
Motor brushes	Target		
Filter	Target		
Nozzle	Target		
Hose	Target		
Power slider PCBA		Target	Target
Metal hose attachment		Target	

represented in the Map by placing independently removable components at the same depth level (on the horizontal axis - e.g. B and C). Independently disassembled components are represented using a branching, or by a second arrow starting from the last component removed before the independent sequence.

3. Multiple dependency. If the disassembly of a component (e.g. C) requires the previous disassembly of two or more components (e.g. A and B), where the disassembly is independent of each other, this is represented using an '&' (and) connection. In Fig. 3, A and B can be disassembled independently from each other (neither of them requires the previous disassembly of the other). However, the disassembly of C requires that both A and B are removed. The correct use of arrow pointers is important to communicate the correct sequence direction and precedence, and to facilitate readability.

Representation of cluster blocks

Expanding on the logic described above, it is possible to depict even more complex disassembly scenarios. For example, according to the methodology developed by Ishii, K., & Lee, B. (1996) the number of steps required to remove component D in Fig. 4, would be four: sequentially removing components A, then B, followed by C and finally D. This sequence however does not depict reality. In fact, the shortest way to component D is to remove components A, B and C simultaneously, as a cluster of components. Clusters of components are represented by a single component circle containing all the components' name/number, separated by commas. The representation of such clusters is important as correctly grouping components which share similar End-of-life processes or failure rates can significantly improve the repair or recycling of the cluster.

Representation of alternative disassembly sequences

If component D is the target, Fig. 4 depicts the preferred scenario. However, if component C is also a target component, a representation of its complete disassembly would be required as well, showing the disassembly of components A, B, and C. Both sequences should be represented in the Disassembly Map as they show the fastest sequences to two different but related target components, but which require a different disassembly sequence. This can be achieved by depicting alternative paths in the Disassembly Map as shown in Fig. 5.

Disassembly action blocks

The degree of difficulty of separate disassembly actions influences

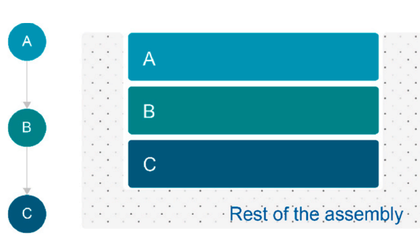

Fig. 1. Representation of sequence dependent disassembly.

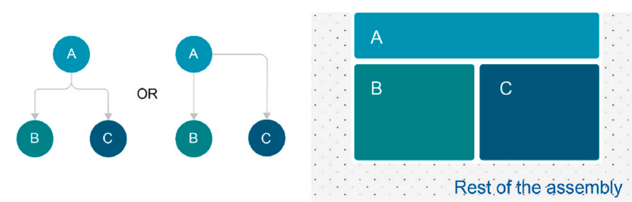

Fig. 2. Representation of sequence independent disassembly.

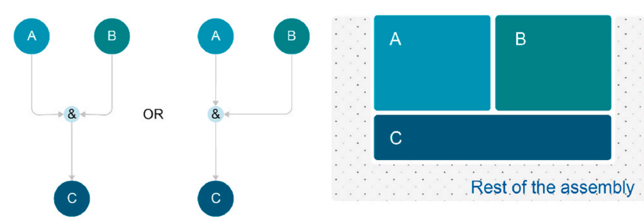

Fig. 3. Representation of multiple dependency.

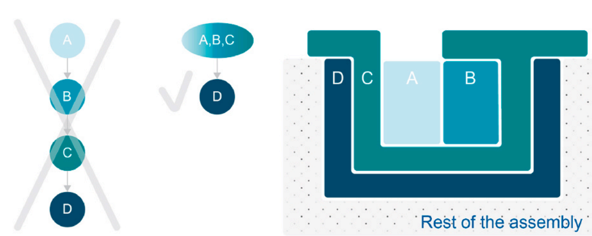

Fig. 4. Representation of cluster blocks.

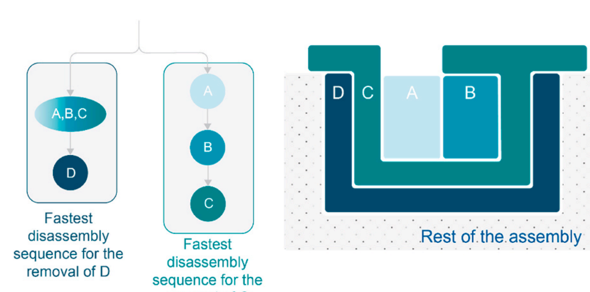

Fig. 5. Representation of two alternative disassembly paths for the optimal removal of two different components, involved in each other disassembly.

disassembly time and hence the overall ease of disassembly. Disassembly difficulty depends on the nature of the actions required to remove a component, and thus completing a step in the disassembly process. Based on MOST, the eDiM method, and Kroll's evaluation chart, two main features were identified that influence disassembly time (and thus difficulty): 'type of disassembly motion' and 'intensity of the required force'. The Disassembly Map uses 'action blocks' to symbolize these features. Action blocks are placed next to the line between the component circles. If the same disassembly action (same fastener type and same tool used) is repeated multiple times, the number of repetitions can be indicated next to the block, facilitating the count of tool changes.(Fig. 6).

A preceding action can be shared by different components. For example, in Fig. 7, the shared action can be opening the lid of a product (e.g. A), to be able to extract two different and independent internal components (e.g. B and C). The lid is not disassembled, but simply opened. Therefore, it cannot be indicated in the Map using a component circle, but the action of opening the lid is represented before B and C, since it is required for their disassembly.

Another example is the action of dividing a cluster in two components: in Fig. 8, the cluster 'A,B' is disassembled in a single dividing action into two components, A and B.

In most cases, the time required for component removal (after all connectors have been opened/removed) does not change as the component is simply extracted (MOST sequence $A_1B_0G_1 + A_1B_0P_1$). To avoid redundancy, the final action of component removal/extraction by hand is not indicated by an action block, but by the component circle itself.

Action block coding

Both the type of disassembly motion used for every disassembly procedure and the force intensity of loosening the connection greatly influence disassembly time, and are represented by the appearance of the action blocks (using different block shapes, colours, colour tones and labels) in order to visually provide relevant design information. The following analysis, based on the use of MOST and eDiM, shows how these parameters have been categorized and how they are linked to the appearance of the action blocks.

1. The type of disassembly motion depends on the type of tool needed:
   a) *Hand motion*: in some cases, fasteners can be disconnected by hand and no tool is needed. The simple use of hands saves the time of fetching and replacing a tool from the workstation (MOST sequence $A_1B_0G_1+A_1B_0P_1$). Examples of connectors that can be disassembled by hand are friction fits, snap fits, hinges, cable connectors, knobs, and buttons; these are represented by a green rounded rectangle (Table 5).
   b) *Tool single motion*: this category requires the use of a tool and a single loosening motion, expressed by the MOST action L. The tool is positioned on the fastener and force is applied. The level of force determines the MOST index and hence the amount of disassembly time (MOST sequence $A_1B_0P_3+L_{force\text{-}based\text{-}index}$). Examples of single action tools are spudger, cutting plier, and hammer; these are represented by an orange rectangle.
   c) *Tool multiple motion*: this category requires a tool and multiple loosening motions in order to unfasten a connector. Examples are screwdrivers and wrenches which, after being positioned on the fastener, are turned multiple times. In this case the index of the MOST action L is not only defined by the level of force applied, but also by the number of loosening action repetitions. This category of tools usually requires the highest disassembly time (Kroll, 1996) and they are represented by a pink hexagonal shape.

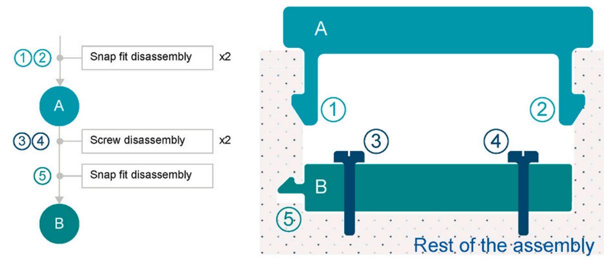

Fig. 6. Representation of action blocks.

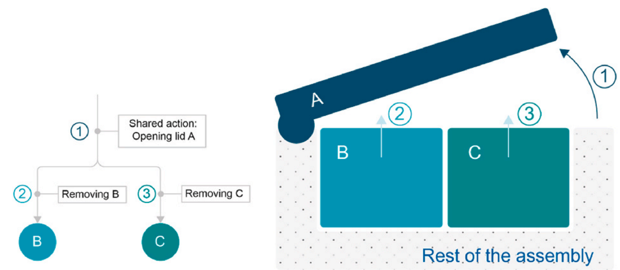

Fig. 7. Representation of a shared action: opening lid A to remove component B and C.

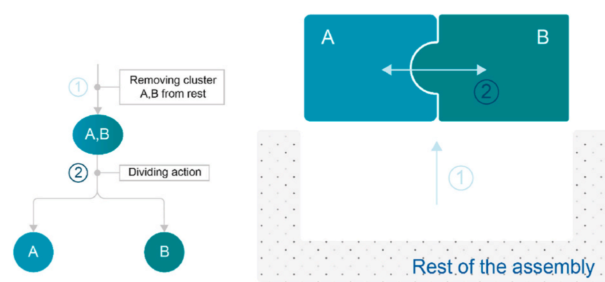

Fig. 8. Representation of the action of dividing two components from each other.

The specific type of tool used is indicated in the action block using an abbreviation in brackets (Fig. 9).

2. The loosening force intensity is another aspect that affects disassembly time and overall difficulty, in particular for hand loosening and single action tools. Three levels of force intensity are defined based on the MOST:
   a) *Low force intensity* (MOST sequences considered L_1, M_1): between 0 and 5 N; the action can be carried out using fingers and by applying a light force.
   b) *Moderate force intensity* (MOST sequences considered L_3, M_3): between 5 and 20 N; the action can be carried out using the entire hand (wrist action), applying a moderate force.
   c) *High force intensity* (MOST sequences considered L_6, M_6): exceeding 20 N; the action requires considerable force and the use

of both hands or moving the entire arm. If applied to less robust connectors, this force is likely to lead to fastener damage.

The force intensity is represented by the action block colour tone. A single colour tone was used for all screws as this study focused on vacuum cleaners where, on average, all the screws required the same amount of force and number of turns (around 9 turns, MOST sequence used L_{16}).

The type of connector is the main factor determining which tool and force intensity is required. Indicating the type of connector in the Map is fundamental to inspire possible design optimization solutions. The main types of fasteners encountered during the disassembly of vacuum cleaners are friction fits (also defined as press or interference fits), snap fits, screws, knobs, push buttons, hinges, and cable plugs. Except for screws, all these connectors can be disassembled by a single disassembly action, described by the MOST sequences for controlled movement parameter "M $(_{1,3,6})$" or tool action movement "L $(_{1,3,6})$". Tool change sequence must be considered if a tool is required. The type of connector is also indicated in the action block (Fig. 9). If a component is fastened by multiple connectors of the same type (i.e. two screws), their number is indicated next to the action block. Table 5 shows how different force intensity and tools influence overall operation time, by referring to the MOST sequence models used to describe different disassembly activities. If the connector type changes, but the tool used and force intensity are the same, time remains unchanged.

Disassembly penalties

Penalties indicate design features preferably avoided from a disassembly perspective, as they negatively affect disassembly time and increase overall difficulty. Four aspects that negatively affect disassembly are:

1. *Product manipulation* (MOST sequence $A_1B_0G_1+L_3$): this penalty was first presented by Vanegas et al. (2016), and describes the need to manipulate a product of small to medium dimension on a working surface in order to reach certain fasteners. This penalty can also be used to indicate the need for walking around the product in order to reach a connector (up to 2 steps, MOST sequence $A_3B_0G_1$), if the product is too heavy to be moved (e.g. washing machines).
2. *Low visibility/identifiability* (MOST sequence T_{10}): this penalty was also introduced by Vanegas et al. (2016) and describes the additional disassembly time required to disassemble hidden connectors which are difficult to find or to reach.
3. *Uncommon tool*: this penalty cannot be quantified with a MOST sequence. However, it can compromise product repairability and disassembly, since the disassembler might not be equipped with an uncommon tool (Cordella et al., 2019). A complete list of commonly available tools can be found in the standard EN 45554:2020 (CEN-ELEC, 2020); any other tool is considered uncommon.
4. *Non-reusable connector*: connectors that cannot be reused do not affect the disassembly time. However, they have a negative effect on design for re-assembly because they require the availability of new connectors or spare components (Cordella et al., 2019).

These aspects are presented in the Disassembly Map using penalty icons (Table 6) which can be positioned next to action blocks.

Target component indicators

Indicators have been used to facilitate the localization of target components (Table 7). These indicators identify those components that are more likely to fail or with functional importance, those with the highest embodied environmental impact and those with the largest economic value. A more extensive assessment and component list is presented by De Fazio (2019).

Table 5
Overview of the visual representation of the action blocks, which are based on type of disassembly motion and force intensity, and lead to different disassembly times. These have been studied and calculated using MOST sequence models and eDiM standard disassembly tasks. Also shown are examples of how different disassembly actions have been represented through colour, colour tone and shape.

					Disassembly				**Assembly**				**Total tool time**
	Force intensity	Fastener type	Tool	Action block representation	Tool Change Time (s)	Tool Positioning Time (s)	Tool action Time (s)	Disassembly Total Time (s)	Tool Change Time (s)	Tool Positioning Time (s)	Tool action Time (s)	Reassembly Total Time (s)	Total Operation Time (s)
Single motion disassembly action	Force < 5N	Snap fit	Hand		0,0 s	1,4 s $A_1B_0P_3A_0$	0,4 s L_1	1,8 s	0,0 s	1,4 s $A_1B_0P_3A_0$	0,4 s F_1	1,8 s	3,6 s
			Spudger		1,4 s $A_1B_0G_1+A_1B_0P_1$	1,4 s $A_1B_0P_3A_0$	0,4 s L_1	3,2 s	1,4 s $A_1B_0G_1+A_1B_0P_1$	1,4 s $A_1B_0P_3A_0$	0,4 s F_1	3,2 s	6,4 s
		Friction fit	Hand		0,0 s	1,4 s $A_1B_0P_3A_0$	0,4 s L_1	1,8 s	0,0 s	1,4 s $A_1B_0P_3A_0$	0,4 s F_1	1,8 s	3,6 s
			Spudger		1,4 s $A_1B_0G_1+A_1B_0P_1$	1,4 s $A_1B_0P_3A_0$	0,4 s L_1	3,2 s	1,4 s $A_1B_0G_1+A_1B_0P_1$	1,4 s $A_1B_0P_3A_0$	0,4 s F_1	3,2 s	6,4 s
	5N < Force < 20N	Snap fit	Hand		0,0 s	1,4 s $A_1B_0P_3A_0$	1,1 s L_3	2,5 s	0,0 s	1,4 s $A_1B_0P_3A_0$	1,1 s F_3	2,5 s	5s
			Spudger		1,4 s $A_1B_0G_1+A_1B_0P_1$	1,4 s $A_1B_0P_3A_0$	1,1 s L_3	3,9 s	1,4 s $A_1B_0G_1+A_1B_0P_1$	1,4 s $A_1B_0P_3A_0$	1,1 s F_3	3,9 s	7,8 s
		Friction fit	Hand		0,0 s	1,4 s $A_1B_0P_3A_0$	1,1 s L_3	2,5 s	0,0 s	1,4 s $A_1B_0P_3A_0$	1,1 s F_3	2,5 s	5s
			Spudger		1,4 s $A_1B_0G_1+A_1B_0P_1$	1,4 s $A_1B_0P_3A_0$	1,1 s L_3	3,9 s	1,4 s $A_1B_0G_1+A_1B_0P_1$	1,4 s $A_1B_0P_3A_0$	1,1 s F_3	3,9 s	7,8 s
	20N < Force	Snap fit	Hand		0,0 s	1,4 s $A_1B_0P_3A_0$	2,2 s L_6	4,7 s	0,0 s	1,4 s $A_1B_0P_3A_0$	2,2 s F_6	4,7 s	9,4 s
			Spudger		1,4 s $A_1B_0G_1+A_1B_0P_1$	1,4 s $A_1B_0P_3A_0$	2,2 s L_6	6,1 s	1,4 s $A_1B_0G_1+A_1B_0P_1$	1,4 s $A_1B_0P_3A_0$	2,2 s F_6	6,1 s	12,2 s
		Friction fit	Hand		0,0 s	1,4 s $A_1B_0P_3A_0$	2,2 s L_6	4,7 s	0,0 s	1,4 s $A_1B_0P_3A_0$	2,2 s F_6	4,7 s	9,4 s
			Spudger		1,4 s $A_1B_0G_1+A_1B_0P_1$	1,4 s $A_1B_0P_3A_0$	2,2 s L_6	6,1 s	1,4 s $A_1B_0G_1+A_1B_0P_1$	1,4 s $A_1B_0P_3A_0$	2,2 s F_6	6,1 s	12,2 s
Multiple motion	9 wrist turns	Screw	Screw-driver		1,4 s $A_1B_0G_1+A_1B_0P_1$	2,5 s $A_1B_0P_6A_0$	7,2 s $L_{16}+A_1B_0G_1+A_1B_0P_1$	11,1 s	1,4 s $A_1B_0G_1+A_1B_0P_1$	2,5 s $A_1B_0P_6A_0$	2,2 s F_6	11,1 s	22,2 s

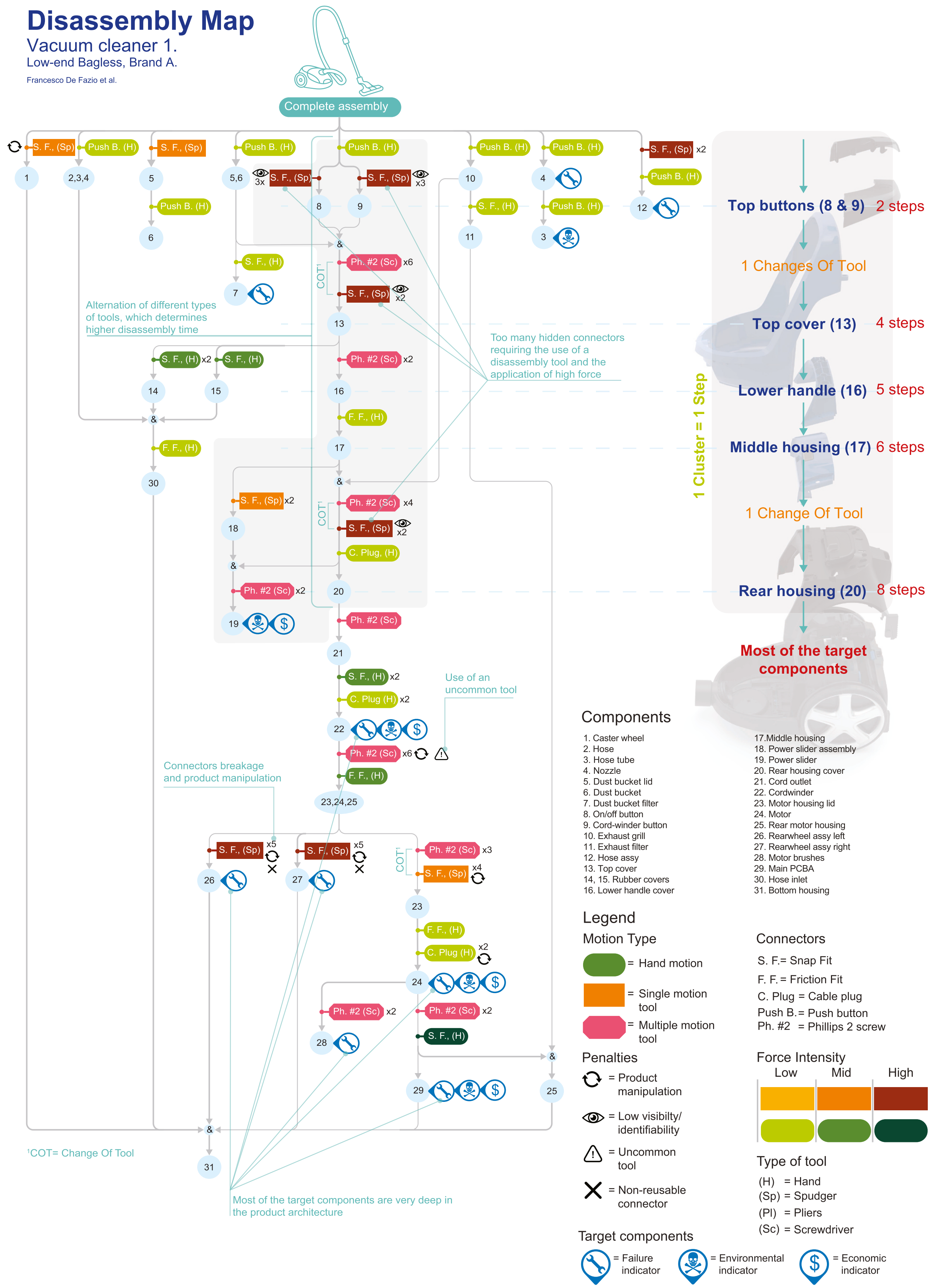

Fig. 9. Disassembly Map of the original architecture of vacuum cleaner #1.

Table 6
Penalties representation.

Type of penalty	Penalty icon	MOST sequence	Use description
Product manipulation		A1B0G1+L3	Manipulation of moderate weight product or moving around it (max 2 steps)
Low visibility/ identifiability		T10	Hidden connector, difficult to reach with tool or to identify
Uncommon tool		–	Tool not included in the EN45554 common tool list
Non-reusable connector		–	Non-reusable connector after a first disassembly

Table 7
Target indicators representation.

Target indicator	Indicator icon	Use description
Failure indicator		It indicates the components with the highest failure rate or functional importance
Environmental indicator		It indicates the most environmentally harmful components or those with the highest embedded environmental impact
Economic indicator		It indicates the components with the highest embedded economic value

4.2. Application of the Disassembly Map method

Seven vacuum cleaners were mapped using the Disassembly Map. The map of vacuum cleaner #1 is shown in this section and further analysed, while the other six can be seen in Supplementary Material 1. Differences between architectures can be clearly observed. The length and width of the maps provides initial insights about the disassembly depth and type of disassembly dependencies between components at a glance. In SM 1, the first three maps show the entire architecture of the product (disassembly of all its parts), while the last three show only the sequences necessary to disassemble high failure components. A complete mapping is often necessary to take into account all indicators and end of life strategies. A partial mapping, focused on a specific indicator, like the failure one, allows for a less complex illustration and it can be used to guide the redesign of a product for a specific strategy (e.g. design for repair).

Analysis and redesign of a vacuum cleaner using the Disassembly Map

As an example, the Disassembly Map of vacuum cleaner #1, shown in Fig. 9, will be described in more detail. Based on the method presented in chapter 3, the main target components for repair identified for this model are the cord-winder (component 22), the motor (component 24), and the main PCBA (component 29), which can be seen at the bottom of the Disassembly Map, i.e. these require the most effort to remove. The target indicators in the Disassembly Map show that these components not only present a higher failure rate compared to the others, but they also have a high embodied environmental impact and economic value. The Map also clearly shows that six layers need to be removed before reaching them. Due to the original architecture design, these layers have to be disassembled sequentially, starting from the top buttons (components 8, 9) and working down towards the rear housing (component 20). This implies that the main target components are hard to reach and their repair will be tedious and probably not viable. Moreover, by looking at the action block colours, it becomes clear that most of the operations, twenty, require a tool, while just three can be disassembled using a hand. Furthermore, the shape of the action blocks indicates that different types of tools are required in the sequence, which results in frequent tool change. Finally, from the colour tone, the penalty icons, and the information written in the action blocks, it can be observed that ten connectors are hidden snap fits which require the use of a spudger at high force. These activities were time-consuming and seriously damaged the connectors and surrounding high-gloss surfaces.

In order to improve on the repairability, the vacuum cleaner was redesigned by applying the "clumping" methodology (Marks et al., 1993): components were clustered together based on their expected end-of-life scenario, reducing the time required to disassemble the target components. By clumping six components in one cluster (Fig. 9) the target components can now be reached in a single step instead of eight steps (Fig. 10).

This was made possible by observing in the initial Map how the deepest component of this group (the rear housing, component 20) was connected to the rest of the body using 3 screws, and one on the cord-outlet (Fig. 11). However, these screws were hidden beneath the six upper layers of plastic components. By repositioning the screws and making them reachable from the outside, all the layers on top of the inner targets were clustered together and could be removed in a single step (Fig. 10). This could be done without repositioning the components and by leaving all the other connections unchanged. Moreover, the screws were repositioned in discrete spaces, considering the cosmetic requirements defined by the Design team.

To validate the improved repairability, the redesign was assessed using eDiM. Table 8 shows a reduction in disassembly time of 60% for the cord-winder, 40% for the motor, and 38% for the PCBA. The redesign decreased the disassembly depth of these components of 7 steps. Additionally, most of the difficult disassembly sequences in the original design were incorporated into the cluster. Also six other redesign solutions followed from the Disassembly Map; these are extensively reported in (De Fazio, 2019) and summarized in the Supplementary Material 2.

5. Discussion

5.1. Criteria compliance

The Disassembly Map complies with all the criteria listed in section 2. It presents a standardized visualisation system, based on three main logic representations: sequence dependency, independency and multiple dependency (C.1). This allows clear communication of the disassembly depth of all components based on their location in the Map (C.2). Sequence dependent and independent operations are represented by the vertical and horizontal orientation of the graph. Although the Map representation follows strict representation logic and rules, the tool is flexible enough to represent complex and different disassembly procedures such as the representation of cluster of components and different types of disassembly interdependencies (C.3). Moreover, indicators are used to clearly highlight the most relevant components (C.4) based on their frequency of failure (relevant for repair), their economic value (relevant for design for refurbishment and part harvesting), and their embodied environmental impact (relevant for design for recycling). Disassembly time is also clearly represented in the Map. However, this is not achieved just by indicating the amount of time required by each operation, but by specifying the design features determining it (C.5). This is achieved using new standard visual elements and the action block appearance (coded using the MOST sequence models and the eDiM standard disassembly tasks). Based on the blocks' colour, shape, and colour tone it is immediately and intuitively understandable which operation determines the highest disassembly time, and therefore needs redesign. Type of tools required are also indicated in the Map, by writing their specific type in the action blocks. Additionally, the need for uncommon tools, defined based on the EN 45554:2020 (CEN-ELEC, 2020), are clearly highlighted by a specific penalty icon (C.6). Fasteners are also indicated in the action blocks, and another penalty icon is used to highlight which of these cannot be reused (C.7).

5.2. Limitations

The Disassembly Map also has some limitations. Because of its

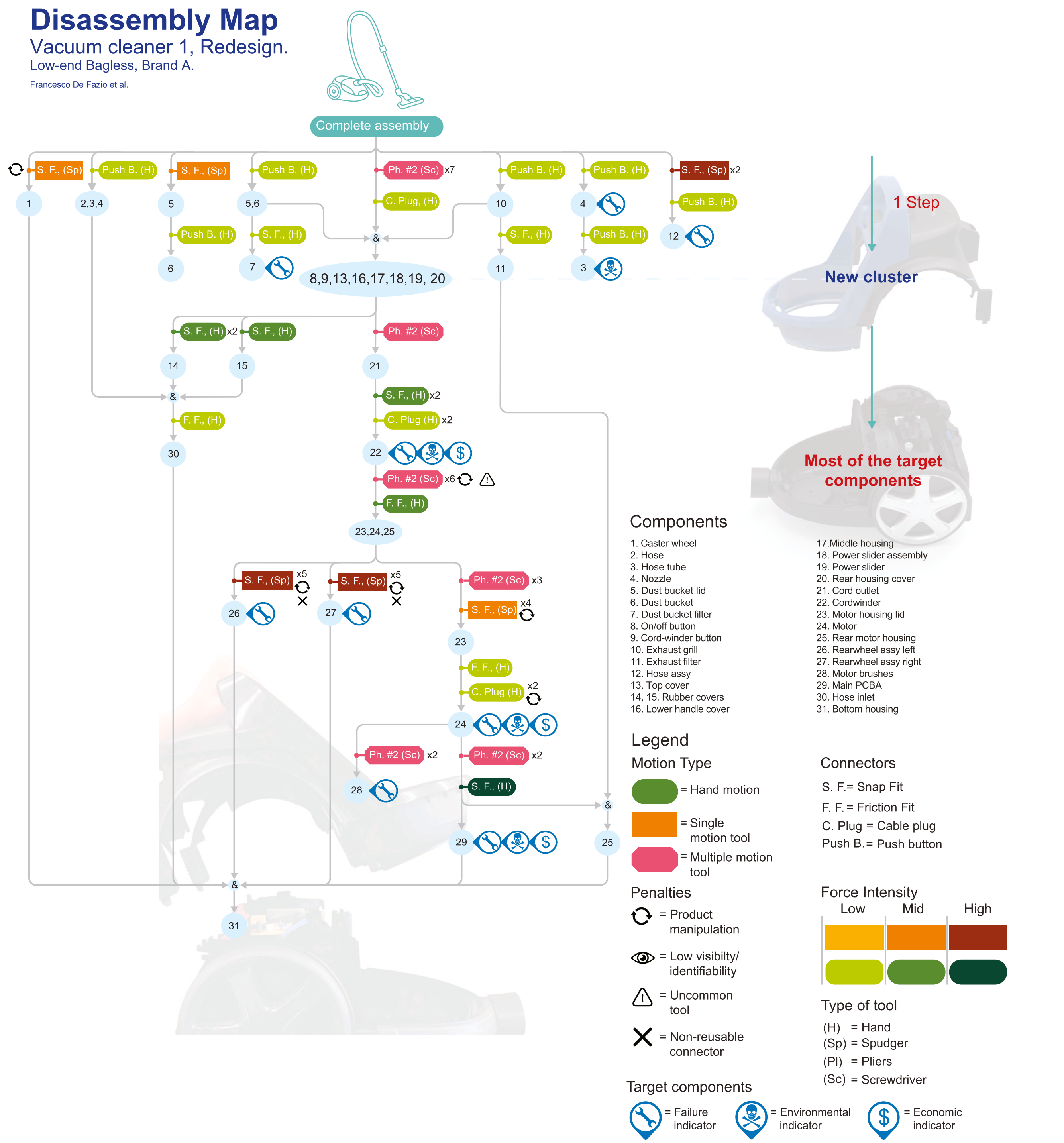

Fig. 10. Disassembly Map of the redesigned vacuum cleaner #1.

detailed nature, the tool cannot be applied when drafting a design (i.e. where the product architecture is still in its early stages). However, it can be used as an inspiration tool, by mapping and analysing a previous or a similar product. This enables designers to consider existing positive and negative design features and architecture configurations in their design process. Furthermore, the length (or 'depth') of the Disassembly Map can be used as a proxy for ease of disassembly and repair. This is however not an iron-clad rule. It is important to realize that the distances between blocks and component circles are constant but not (yet) standardized, making visual assessment of the Map not fully reliable. For instance, the Map of a product that is difficult to repair because the target components are fully integrated into other components, might still be shallow, suggesting ease of repair. Care should therefore be taken not to draw quick conclusions about ease of repair based on a superficial perusal of the Map. Moreover, it should be realised that at the moment the distance between components circles is determined by the number of action blocks, so by the number of disassembly operations, and not by the time required to dismantle them. The eDiM can be used if a more precise and quantitative assessment of disassembly time of steps is required.

Although specific rules have been formulated for the use of this tool, the representation of complex disassembly procedures and component interconnections might be still subject to personal interpretation and human error for not automized methodologies, as noted by Kwak et al.

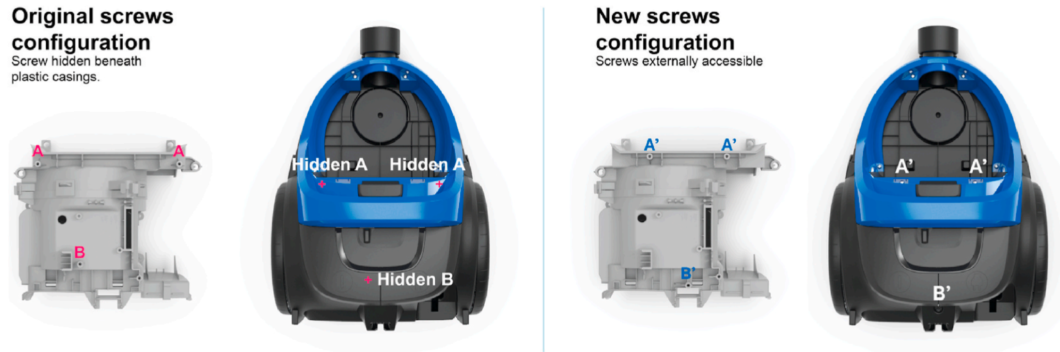

Fig. 11. Changes in the screw positioning configuration connecting the motor housing to the upper layers. The screw position has been slightly modified to allow external accessibility.

Table 8
Results comparison between the original and the redesigned architecture. The parts considered are the target components for repairability.

Results comparison. Original vs Redesign												
Part	Steps (n.)		Tool change (n.)		Connections (n.)		eDiM (s)		% of total eDiM		% of total connectors	
	Original	Redesign	Original	Redesign	Original	Redesign	Original	Redesign	Original	Redesign	Original	Redesign
Nozzles	1	1	0	0	1	1	6	6	0,7	0,7	1,2	1,2
Hose	1	1	0	0	3	3	21	21	2,3	2,3	3,5	3,5
Filter	2	2	0	0	2	2	13	13	1,4	1,4	2,3	2,3
Cord-winder	12	5	7	2	31	15	396	160	43,3	17,5	36	17,4
Wheel	14	7	8	4	43	27	539	306	59	33,2	50	31,4
Motor	16	9	9	5	48	32	576	341	63,1	37,3	55,8	37,2
PCBA	17	10	10	6	51	35	616	380	67,3	41,6	59,3	40,7
Motor brushes	17	10	10	6	50	34	607	369	66,4	40,4	58,1	39,5

(2009). Finally, the method has only been tested extensively on one specific product group (vacuum cleaners). The application of this method to different types of products might require a more extensive or different representation of disassembly tool, connector, and penalty attributes, sharing limitations similar to those of the eDiM method (Vanegas et al., 2016).

5.3. Recommendations for further research

This first iteration of the Disassembly Map method was developed by application to a single product group. Therefore, a further iteration to generalise the representation of action blocks may be required for a wider applicability. Furthermore, in order to facilitate a more objective assessment of the disassembly effort, the vertical length of the Map may be standardized to reflect the level of difficulty of each disassembly operation, instead of only reflecting the number of action blocks.

6. Conclusion

The research objective of this paper was to create and test a new method for assisting designers to assess the ease of disassembly and repair of household products. The Disassembly Map is a product architecture mapping method created to facilitate design for disassembly, which is essential when designing for serviceability and repairability. It is an analysis and modelling tool which encourages designers to assess the impact that different design solutions and disassembly processes have on disassembly and repair. This is achieved by creating an accurate representation of all steps required to completely dismantle a product. The novel feature of this method is the combined representation of all essential design features for product disassembly, suggested by the most recent research and standards (CENELEC, 2020; Cordella et al., 2019), in one single visualization tool. It also introduces new standard visual elements and attributes to more easily and intuitively communicate parameters related to the calculation of disassembly time based on the MOST system (Zandin, 2002). By visualizing the effort to disassemble target components, by showing the most difficult disassembly operations, and by highlighting the disassembly position of target components, it guides product redesign, for instance by clustering components.

The Map adds to the body of knowledge on product architecture mapping by providing a rich visual representation which can be easily and almost intuitively understood. The Disassembly Map has shown to be an intuitive and effective tool to guide design for repair. The systemic and standardized logic of the Disassembly Map makes it applicable for a wide target audience: product designers and architects, engineers, design consultants, but also for design researchers who can use this method to assess and compare different product architectures with respect to disassembly and repair.

CRediT authorship contribution statement

Francesco De Fazio: Investigation, Methodology, Validation, Writing – original draft. **Conny Bakker:** Supervision, Writing – review & editing. **Bas Flipsen:** Supervision, Writing – review & editing. **Ruud Balkenende:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.128552.

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