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Robotic ease of Disassembly Metric (Re-DiM) for human robot cooperative disassembly: A case study for a vacuum cleaner

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Abstract

Remanufacturing, a beacon of economic and ecological alignment, hinges on disassembly's complexity. As both manual and robotic approaches face challenges, systems in which human and robots can work iteratively offer adaptable solutions, curbing the required system flexibility at acceptable capital expenditure. However, today no metrics exist to evaluate the ease of disassembly of product designs when considering a combination of manual and robotic disassembly Therefore, this study extends the existing ease of Disassembly Metric (e-DiM) for designers, policymakers, and recyclers in anticipation of the industrialization of human-robot cooperative disassembly systems. For the development of such a metric the expected limitations of robotic disassembly systems are first discussed based on prior research. Subsequently, a set of criteria are presented to define which operations can be performed successfully in a flexible system. Finally, the Robotic ease of Disassembly metric (Re-DiM) is introduced, which serves to comprehensively evaluate both manual and robotic disassembly times. To validate Re-DiM's applicability, the ease of both manual and robotic disassembly is evaluated for all critical components of a robotic vacuum cleaner. The presented case study highlights today's robotic disassembly challenges, underscoring also the relevance of novel design for robotic disassembly approaches.

Keywords: Circular economy, Re-manufacturing, Robotic disassembly, Disassembly metric, Human-Robot collaboration

1. Introduction

The European Union's circular economy ambitions presents opportunities and challenges, as outlined in the European Commission (EC)'s action plan. It aims to enhance strategies for handling End-of-First-Life (EoFL) products across sectors in which the EC envisages a crucial role for manufacturers to adopt innovative remanufacturing practices. While traditional manufacturing prioritizes financial gains over environmental impact [1], remanufacturing introduces a paradigm shift by focusing on both economic benefits and ecological preservation [2]. By maximizing resource utilization, critical raw material recovery and extending product lifecycles, remanufacturing also aligns seamlessly with the principles of a circular economy [3].

In remanufacturing, disassembly is pivotal but challenging compared to assembly due to varied product conditions, orientations, missing parts and/or product information and smaller lot sizes as products often return over a longer period of time [3, 4]. Consequently, EoFL product disassembly is commonly known to be time-consuming and labour-intensive. While manual disassembly offers high flexibility to handle complex tasks and to deal with uncertainties [5], several drawbacks are to be considered: limited scalability, concerns on safety and health risks. While robotic disassembly could alleviate these issues, it faces various challenges, such as high capital costs and limited adaptability for intricate tasks [6].

Therefore, human-robot systems offer heightened efficiency and flexibility, providing a unique way to balance labour and capital expenses, while encompassing opportunities to reduce safety and health risks in disassembly [12]. Similar to a Flexible Manufacturing System (FMS), a human-robot disassembly system has the potential to collaborate with a variety of similar products to offer a solution for a Flexible Re-Manufacturing System (Re-FMS). These systems are also known to coop better with unpredictability in task frequency,

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return volume, and variations [7]. Overall there are two distinct approaches: Co-operative, where humans and robots work independently on separate tasks towards a common goal without a shared workspace, and Collaborative, where they share tasks and workspace, either independently or jointly, often involving physical interaction [8].

In Industry 4.0 different technologies, such as digitalization, automation, and data analytics can enhance product design for a circular economy [9]. It is crucial to acknowledge that these technologies can present some economical or technical challenges, especially when they are in their early phases of development and require additional refinement and validation [10]. While rapid advancements in the field of robotic disassembly are anticipated, it is also expected that factors such as capital investment, reverse logistics costs, and their environmental impacts will impose limitations on their industrialization. Therefore, robotic disassembly process development and product design should be more interlinked. To support the design process, strategies such as Design for Disassembly (DfD) and Design for Remanufacturing (DfR) can be followed. These design methods seek to reduce, for example, the number and complexity of connectors, thus improving the accessibility of the components.

One of the methods available in the literature to provide feedback on the product design by measuring the effort required to disassemble a product is the ease of Disassembly Metric (e-DIM) [11]. This metric is based on calculating the disassembly time using the MOST method. By applying the e-DiM, circular economy strategies are favored, as it allows identifying the criticalities of the disassembly process on which the redesign efforts should be focused, in order to simplify the operations needed to disassemble the product. However, one of the main limitations of this method is that it focuses only on manual disassembly, which is insufficient considering that many products that are in design today are expected to return at the peak of Industry 4.0 in which robots operate in collaboration with humans also in the disassembly process [12]. The method is also not flexible enough to be extended to more complex disassembly processes, since it does not allow replicating some of the disassembly sequences that can be found in practice.

Given the constraints of e-DiM, there's a clear requirement to enhance and broaden its scope to encompass both manual and robotic disassembly. Such a metric would be invaluable for designers aiming for circular design, policymakers assessing product circularity, and recyclers in anticipation of the wide spread adaption of industry 4.0 in which disassembly tasks are orchestrated between humans and robots and during the shift towards Industry 5.0, emphasizing sustainable and human-centric production systems [13]. In this paradigm, the operator takes a central role, and the system is designed not to replace the operator but to revolve around them, prioritizing the operator's maximal comfort.

As far as the author’s knowledge extends, no metric currently integrates both manual and robotic disassembly. Hence, the presented work seeks to answer the research question: What is an effective metric in assessing human-robot cooperative ease of disassembly ? The paper first addresses the limitations of the manual disassembly metric (e-DiM) then introduces criteria for robotic disassembly and finally proposes a novel metric, Robotic ease of Disassembly Metric (Re-DiM), applicable to human-robot cooperative setting. This metric is applied to a case study involving a Bosch robotic vacuum cleaner, which is chosen due to its potential for commercialisation in a Product as a Service (PaaS) model. The study focuses on the challenges in robotic disassembly of critical parts, namely, the battery and motors. Re-DiM results and discussions reveal its efficacy in assessing human-robot co-operative disassembly, demonstrating its practical utility in real-world cases and its ability to derive design recommendations.

2. Methodology

In this section, drawing insights from prior research, a practical, cost-effective and flexible disassembly system is defined and the existing disassembly metric (e-DiM) [11] is enhanced to incorporate robotic time estimates.

Robot and toolset selection : Numerous researchers have contributed to the field of robotic disassembly in the past decade, exploring diverse areas such as Line Balancing [14], Sequence Planning [1, 2], Object Detection [15], Destructive [16] & Non-destructive Robot Disassembly [17], Information & Communication Technology [18], and Human-Robot Collaboration [4, 6]. Moreover, validation experiments using robots have encompassed a broad spectrum of products, including Mechanical Parts such as coupling [6], pumps [3] and roller chains [7], as well as Home Appliances like monitors [19], refrigerators [20] and hard disk drives [5]. Automotive Components, such as EV batteries [15, 16], turbo-chargers [4], power steering ECUs [21], and combi-meters [22]) have also been (partially) disassembled by robots. While validation trials have employed both 7-degree-of-freedom (DOF) robots, such as KUKA IIWA [4], and Cyton 1500 RM [18], predominantly 6-DOF robots are used, like ABB IRB: 120 [18], 140 [19] & 1200 [6], Techman TM14 [23], UR-5 [5, 15] & UR-10 [17], Franka Emika Panda [20], Staubli RX160 [21] and Fanuc LR 200 [16]. From prior research it is noteworthy that only a limited number of researchers have explored multi-robot disassembly scenarios [4, 15, 18, 20].

Among these works, end-effector preferences for non-destructive disassembly predominantly leaned towards the utilization of 2-finger grippers and screwdrivers. A minority of researchers incorporated alternative end-effectors such as 3-finger grippers [4] and vacuum grippers [22]. Regarding product clamping techniques, methods encompassed bolting/clamping to base tables [7], fixed/manual fixtures [3, 21], and pneumatic & motorized fixtures [4, 21]. In certain cases, particularly for heavy objects, clamping was simply not employed [17]. Throughout these experiments, robots undertook three primary tasks: un-fastening, manipulation and pick & Place. Notably, these tasks were executed across all modes of interaction, encompassing cooperative, collaborative, and no interaction scenarios.

Considering current state-of-the-art in research, a single robot 6-DOF co-operative robotic disassembly cell is the most advanced system that is expected to be industrialised in the coming decennia for the EoFL treatment of a product family or category. A cooperative system is preferable to a collaborative one because the latter tends to be comparatively slower, less precise, has a limited payload capacity, and raises safety concerns, especially regarding the tooling used. The setup comprises a 6-DOF cooperative robot (minimum payload: 10 kg) and a pneumatic fixture. Consideration of more simplified

Table 1. Robotic disassembly criteria & their specifications

Criteria	Specifications
Connector conformity: Assesses if the connector complies with standard specs and enables non-destructive disassembly	- Connectors must be non-destructive, non-adhesive, removable (without damaging the product) - The fasteners must be easily available standard type screws : Cross (PH0-3), Torx (T8-45), Socket head (1/6-6), Slotted (3-8) and Pozidriv (PZ0-3).
Component Graspability: Evaluates ability to locate and lift components within robot payload limits.	Component mass ≤10kgs, and its pose (position and orientation) should be ascertainable throughout disassembly task without relying on vision system.
Task Manipulability: Gauges the gripper's ability in accessing the components and fasteners	- Clearance between disassembled component and other components should be at least 10*10 mm to prevent tool collision. - For Adhesion gripper manipulation, the component contact area ≥ 300mm2 (dia≈10mm) for suction cup positioning. - For Actuation gripper manipulation, the component grasp side length ≤ 140mm (two-finger max. stroke length)
Task Complexity: Determines the task's feasible using the available system	The manipulation task should be achievable using a single tool at the time, considering also single robot operations.

robot designs, like Cartesian robots would be constraining for most product categories.

The end effector toolkit is expected to include: (i) A screwdriver with interchangeable commonly available bits : cross, torx, socket head, slotted and pozidriv (for un-fastening task). (ii) A two-finger gripper with a minimum stroke length of 140 mm and a maximum finger width of 10 mm (for component manipulation and pick & place tasks). (iii) A vacuum gripper with two suction cups, each with a maximum diameter of 20 mm (for pick & place tasks). The system's scope encompasses small domestic appliances, such as vacuum cleaners, blenders and toasters. Different product categories like bike batteries may require specialized tools or approaches due to their distinct characteristics. Under the assumption that required manipulations can be taught, products can be readily identified, and the necessary information can be retrieved from the digital product passport, the system is designed without factoring in perception systems, feedback mechanisms, or learning algorithms, and additional measures for ensuring human safety are not being considered.

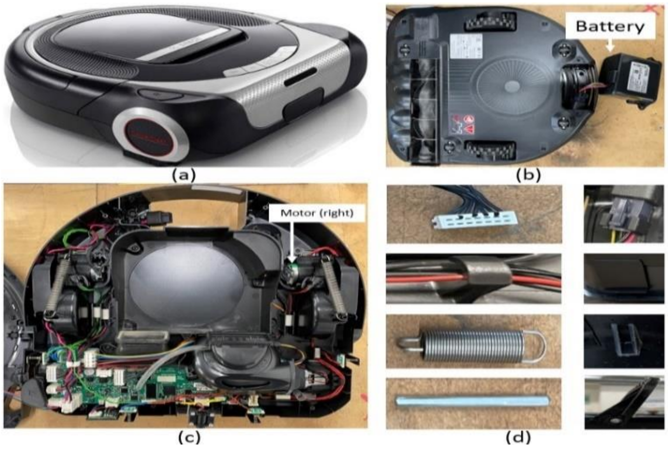

Fig 1. (a) Bosch Roxxter robotic vacuum cleaner ; Critical components - (b) Battery (c) Motor ; (d) Connectors (clockwise from top left - PCB connector, cable plug, Snap fit-1&2, hinge, metal pin, spring & hook)

Criteria for robotic disassembly: When employing standard end-effector toolsets for robotic disassembly the following product parameter define their applicability: the design of fasteners, the size and mass of components, the component orientation and positioning, complex disassembly task and the clearances between components. Based on this, four criteria are defined that must be met to facilitate the robotic disassembly of a component. Table 1 lists 4 criteria, their descriptions and specific requirements that are considered indispensable for the realization of each criterion within the proposed robotic disassembly system. While introducing the criteria, the assumption is that the exact positions of the product, components, and connectors is known before starting the disassembly. This criteria-based assessment enables a classification of the disassembly task into either exclusively feasible by human or viable by both human and robot. This categorization then dictates whether the total time required for the task is calculated either or both on the time needed by a human or robot. The criteria can also serve as a valuable resource for product designers aiming to craft environmentally conscious products that facilitate robotic disassembly.

Robotic disassembly time: Building on earlier research, the breakdown of robotic disassembly time has involved various components, such as tool change, direction changes, movement, positioning, manipulation and the core disassembly

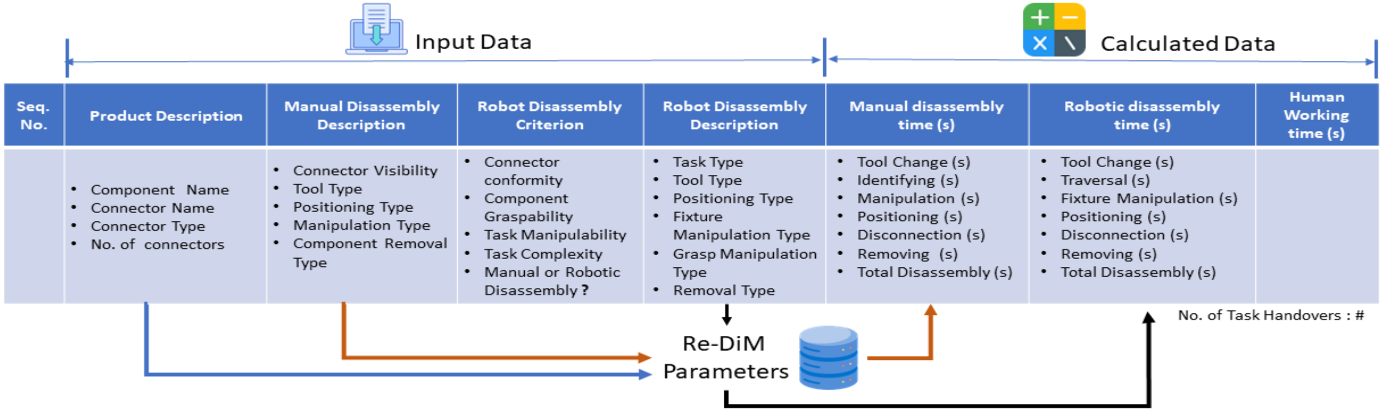

Fig 2. Re-DiM metric template for human robot collaborative disassembly

process [1, 2, 24]. Some studies have also factored additional time beyond the disassembly task, like preparation [23], waiting [4], and uncertainty periods [14], into the overall disassembly time. In light of these prior studies and the proposed robotic configuration, the robotic disassembly time is categorised into, *Tool Change:* Time needed to move from the starting position (home position) to change the tool using a tool changing system and return to the starting position. *Traversal:* Time for the end effector to move from the starting position, to approach to the initialisation position of the first the task, and to return at the end to starting position. *Fixture Manipulation:* Time required for the fixture to either clamp or re-clamp the product. *Positioning:* Time needed to move between connectors and align the tool correctly. *Disconnection:* Time required to disconnect the connector(s) from the component. *Removal:* Time needed to remove the connector and/or component from the product to a location to place the components next to the product. The cumulative sum of these six actions is systematically calculated to define the total robotic disassembly time per connector.

Re-DiM for human robot co-operative disassembly: Before the robot-related information was incorporated into the e-DiM [11], The structure of the e-DiM was modified to make it more comprehensive and usable in a generalized manner with any type of mechatronic product. To achieve this, three new columns were added to the spreadsheet, allowing specification of the type of tool positioning (e.g., light pressure, heavy pressure, etc.), operator's manipulation (e.g., turning the component with one hand, turning with two hands, disengaging wires, etc.), and component removal (e.g., no removal, light object, heavy object, etc.). e-DiM database was also expanded by creating new sequences with MOST for expanded manipulation and disassembly tasks. Just as with the e-DiM, the Re-DiM metric adopts a user-friendly spreadsheet format to ensure ease of use and seamless compatibility, without requiring any additional software installation. In addition, to facilitate the use of Re-DiM, images of different types of connectors have been included. In tandem with efforts to refine the manual e-DiM, a column is added for the allocation of disassembly tasks between human and a robotic system. As a result, the Re-DiM metric is structured across six distinct sections (see Fig 2):

(1) *Product Description [Input Data]:* This section entails inputs such as component and connector names, types, and quantities.

(2) *Manual Disassembly Description [Input Data]:* Detailing connector visibility, tools, positioning, manipulation, and component removal for manual disassembly.

(3) *Robot Disassembly Criteria [Input Data]:* This section evaluates whether each connector meets the 4 predefined robotic disassembly criteria (outlined in Section 0). Decisions are made regarding the feasibility of manual or robotic disassembly based on these assessments.

(4) *Robot Disassembly Description [Input Data]:* Expanding on the intricacies of robotic disassembly for connectors meeting the criteria, including task type, tools, positioning, fixture manipulation, grasp, and removal methods.

(5) *Manual Disassembly Time [Calculated Data]:* Calculating the total manual disassembly time using inputs from the product and manual disassembly description sections, along with Re-DiM parameters database (sum of tool change, identification, manipulation, positioning, disconnection & removal time).

(6) *Robot Disassembly Time [Calculated Data]:* Similar to manual disassembly time calculation, this section uses inputs from the product and robot disassembly description sections, along with Re-DiM parameters database, to determine the required total robot disassembly time (sum of tool change, Traversal, fixture manipulation, positioning, disconnection & removal time).

Importantly, each row of Re-DiM corresponds to a specific connector and the sequence of the connectors defines the evaluated disassembly sequence. Consequently, the sum of disassembly times for all connectors yields the overall product disassembly time for the predefined disassembly sequence. When a task can be performed by either a robot or a human during disassembly, the Re-DiM metric attributes the task to the robot and calculates the remaining tasks as human working time. Additionally, Re-DiM tracks the frequency of task handovers when products are exchanged between human and robot. In the context of circular product design, the objective is to minimize manual and robotic disassembly time, human working time, and number of task handovers.

3. Case Study for Robotic Vacuum cleaner

In this section, the proposed metric is put into action through a practical case study featuring a Bosch robotic vacuum cleaner. The objective is to demonstrate the metric's real-world relevance.

Product and disassembly system description: Bosch Roxxter robotic vacuum cleaner (shown in Fig 1) was chosen for the case study, as the offering of this product in a Product as a Service (PaaS) is investigated in the context of the ERA-MIN Scandere project, as well as the extent to which the design of this product influences the viability of such business models. After discussions with experts, two critical components were focused on : Battery and the motor. The reason for this is that the battery is expected to have a shorter lifespan that the remaining of the product (also a shorter 1-year warranty). In contrast, the motor boasts a longer life (10-year warranty) and is for this reason also considered, as it assumed possible to reuse the motor. Furthermore, both the battery and motor contain valuable raw materials.

Data collection and measurement: Manual disassembly tasks were recorded and later analyzed using MOST technique (as used in prior e-DiM [11]). The calculation of robotic disassembly time for the distance travelled was based on 50% of the maximum robot speed (determined from Staubli RX160 robot with a maximum Cartesian speed of 10.3 m/s). This assumption factors in the trapezoidal motion profile of the robot and the short distances covered during the disassembly tasks. A fixed action time of 5 seconds was assumed for activities like tool changing, clamping, de-clamping, grasping, and careful positioning. The disconnection time for screws was determined considering thread length, pitch, and a screwdriver speed of 600 rpm [24]. These parameters, like MOST, set standards for robotic disassembly time calculation, subject to future revision through experimentation.

Challenges in robotic disassembly: Battery disassembly involves two connectors: cross screws and a cable plugs.

Table 2. Criteria assessment for vacuum cleaner robotic disassembly

Component Name	Connector Type	Task	Task Type	Robotic Disassembly Criteria										Tool for Robotic Disassembly	Robotic Disassembly Feasible?
				Connector conformity		Component Graspability		Task Manipulability				Task Complexity			
								Adhesion gripping		Actuation gripping					
				Non-destructive connector?	Fastener Type	Object Mass (kg)	Component pose fixed in space?	Contact length (mm)	Contact width (mm)	Min. stroke required (mm)	Min. clearance (mm)	One arm task?	Two finger gripper task?		
Battery	Cross screw 7mm	Un-screw the battery	Un-fastening	Yes	Cross	< 2.5	Yes	-	-	-	-	-	-	Screwdriver	Yes
	Cable plug-1	1. Pick and Place the battery	Pick &/or Place	Yes	-	< 2.5	Yes	60 - 100	40 - 60	40 - 60	< 2.5	-	-	Vacuum gripper	Yes
	Cable plug-1	2.Disconnect the cable plug	Grasping and Manipulation	Yes	-	< 2.5	No	-	-	<20	>10	Yes	No	Specialized tool	No
Sensor Cover	Snap fit-1	Disconnect the snap fit	Grasping and Manipulation	No	-	< 2.5	Yes	-	-	>150	< 2.5	No	No	Specialized tool	No
Dust collector	Hinge-1	Lift the hinge	Pick &/or Place	Yes	-	< 2.5	Yes	> 100	<20	<20	< 2.5	-	-	Specialized tool	No
Top cover	Torx screw T10	Un-screw the top cover	Un-fastening	Yes	Torx	< 2.5	Yes	-	-	-	-	-	-	Screwdriver	Yes
	Hinge-2	Lift the hinge	Pick &/or Place	Yes	-	< 2.5	Yes	> 100	<20	<20	< 2.5	-	-	Specialized tool	No
	Torx screw T10	Un-screw the top cover	Un-fastening	Yes	Torx	< 2.5	Yes	-	-	-	-	-	-	Specialized tool	No
	Snap fit-2	Disconnect the snap fit	Grasping and Manipulation	Yes	-	< 2.5	Yes	-	-	<20	2.5 - 5	Yes	No	Specialized tool	No
Suction Fan	No connector	Pick and Place the suction fan	Pick &/or Place	Yes	-	< 2.5	Yes	20 - 40	<20	60 - 100	>10	-	-	Two-finger gripper	Yes
Cylinder plug	No connector	Pick and Place the cylinder plug	Pick &/or Place	Yes	-	< 2.5	Yes	<20	<20	<20	2.5 - 5	-	-	Specialized tool	No
Wheel housing	Torx screw T10	Un-screw the wheel housing	Un-fastening	Yes	Torx	< 2.5	Yes	-	-	-	-	-	-	Screwdriver	Yes
	PCB connector	Disconnect the PCB connector	Grasping and Manipulation	Yes	-	< 2.5	Yes	-	-	<20	< 2.5	Yes	No	Specialized tool	No
	Cable Hook	Remove the cable from the book	Grasping and Manipulation	Yes	-	< 2.5	No	-	-	<20	< 2.5	Yes	No	Specialized tool	No
Motor housing	Spring hook	Remove the spring hook	Grasping and Manipulation	Yes	-	< 2.5	Yes	-	-	<20	>10	Yes	Yes	Two-finger gripper	Yes
	Metal pin	Remove the spring hook	Grasping and Manipulation	Yes	-	< 2.5	No	-	-	<20	>10	Yes	Yes	Specialized tool	No
Motor and gearbox case	Cross screw 5mm	Un-screw the motor gear box case	Un-fastening	Yes	Cross	< 2.5	Yes	-	-	-	-	-	-	Screwdriver	Yes
Motor (right)	Cross screw 4mm	Un-screw the motor	Un-fastening	Yes	Cross	< 2.5	Yes	-	-	-	-	-	-	Screwdriver	Yes

Conversely, motor disassembly entails a more extensive array of connectors: cross and torx screws, snap fits, hinges, cable and spring hooks, and metal pins. Table 2 outlines these connectors, their corresponding tasks, and the criteria for successful robotic disassembly (a single motor of the vacuum cleaner is depicted, as the sequence is analogous for all motors). This table highlights the following challenges inherent to robotically disassembling these connectors: (i) Cable plugs have variable positions during disassembly and can't be handled with two fingers alone. (ii) Snap fits, cable hooks, and PCB connectors lack the necessary clearance for gripper manipulation and, like cable plugs, prove challenging for two-finger disassembly as its designed to be disassembly using human hand. (iii) Hinges lack adequate contact area for vacuum grippers and lack clearance for two-finger manipulation. As a result, only 8 out of 18 tasks are considered feasible to executed using the proposed robotic disassembly setup.

Robotic Disassembly Metric (Re-DiM): As in Fig. 1, The filled in Re-DiM is represented as a 36-column table encompassing product, manual and robotic disassembly descriptions, criteria for robotic disassembly, and calculated manual and robotic disassembly times. Time calculations utilize the Re-DiM parameter database containing the MOST sequence for manual disassembly, coupled with associated disassembly times. Additionally, robotic disassembly time parameters for each task are included in the database (As presented in section 0). According to Re-DiM results, the total manual disassembly time for the battery and motor was 195 seconds. Among the 8 robotic tasks, the disassembly time amounted to 145 seconds, while the human working time for the remaining task was 87 seconds. Notably, this necessitated 10 task handovers between human and robot.

Discussion: The Re-DiM metric results reveals that only a small number of components within current commercially available vacuum cleaner can be robotically disassembled with standard tools without human intervention. Beyond screws, many connectors pose significant challenges as the design is not adapted to the limitations of robotic disassembly. These findings underscore the importance of circular product and connector design while adhering to the criteria for robotic disassembly. Even for the few components amenable to robotic disassembly, manual disassembly often proves to be faster. For instance, disassembling the Torx screw on the vacuum cleaner's top cover showcased manual disassembly to be 12 seconds swifter than robotic disassembly. This discrepancy stem from the extra time required for robotic alignment of the Torx screwdriver, which is unnecessary when using a cross screw. Therefore, Re-DiM can illuminate areas for enhanced product design by addressing time-intensive processes.

Re-DiM's disassembly time data can serve as valuable input for policymakers when formulating regulations for products that feature rapid disassembly times. While certain standards for evaluating ease of disassembly are still under development, it's essential to recognize that the introduction of robotic disassembly does not necessarily require altering existing legislative frameworks. Instead, it presents an opportunity for potential amendments, particularly for products like electric vehicle (EV) batteries, where the potential for significant advancements in disassembly efficiency exists. Furthermore, recyclers equipped with both robotic and manual disassembly capabilities can leverage Re-DiM to strategically allocate tasks and/or to define to either fully disassemble products by operators.

While Re-DiM offers benefits, various limitations have been identified. For example, it does not account for motorized tools often used in manual disassembly. It also overlooks challenges like object positioning and accessing for clamping and removal after disconnection as well as the necessary feedback for assessing the current state and expected time required. Partial robot-assisted tasks are also omitted. For example, a robot could perform the initial battery placement step before cable plug disassembly. Furthermore, including robot direction change time requires better comprehension of robot paths. Moreover, a method to identifying and quantifying the extent to which tasks are hazardous and fatiguing is currently missing. Time involved in switching products between human and robot, along with related preparation, is not addressed.

4. Conclusion

The Robotic ease of Disassembly Metric (Re-DiM) was introduced to address the need for a comprehensive metric applicable to both human and robot disassembly. A flexible disassembly system was proposed, which aligned with prior research, robotic disassembly criteria, and the calculation of disassembly times. To demonstrate its utility, Re-DiM was employed for evaluating the ease of disassembling the battery and motor of a robotic vacuum cleaner. Re-DiM offers valuable insights and advantages by optimizing disassembly processes, informing product design improvements, assisting policymakers in shaping favorable regulations, and enabling efficient task allocation between manual and robotic disassembly methods for recyclers. Exploring Re-DiM's potential to influence product and process design is believed to be a promising avenue for further research. Future endeavours involve extending the criteria's applicability to diverse products, revisiting the set of standards for robotic disassembly time calculations, incorporating product condition monitoring, and integrating disassembly time estimation and robot control data into digital product passports.

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