Journal of Industrial Ecology
https://doi.org/10.1007/s44498-026-00150-9

RESEARCH

Modelling disassembly and reassembly times (DaRT) for assessing repairability

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Received: 14 September 2025 / Accepted: 14 July 2026

Abstract
Repair plays a pivotal role in the circular economy, but evaluating repairability factors such as disassembly times can be complex and time consuming. Existing tools listing proxy times to avoid such measurements had limited libraries of activities, only relevant to ICT product fasteners, and reassembly times were neglected or assumed to be equal to disassembly times, which is not always true. This study introduces the Disassembly and Reassembly Time (DaRT) model: a simplified, time-based tool developed from over 10,000 data points on many connection types from several household products, generating proxy times for many more activities applicable to many more product types. It also compared median times for disassembly and reassembly, showing which tasks are similar enough to use the same proxy time, while highlighting occasional differences, such as part-handling steps. Validated through comparisons with independent disassembly data for vacuum cleaners, washing machines, and smart TVs, DaRT demonstrates strong correlation and minimal bias. Balancing ease of use with reliability, it outperforms simpler step-count methods and offers greater practicality than the complex eDiM. Overall, DaRT enhances repair scoring systems, guides design for repair, and fosters a more circular electronics industry, ultimately fueling more sustainable innovation.

Keywords Circular economy · Design for repair · Repair scoring systems · Disassembly time · Electronics

1 Introduction

Repair is a vital strategy in the circular economy for electronic appliances, representing an approach to waste reduction, resource efficiency, and environmental sustainability. The European Union's recent policies on the right to repair reflect this growing importance (European Commission, 2023; European Parliament, 2022; Manoochehri, et al., 2022). Various repairability scoring systems (Cordella et al., 2019; Ministère de la Transition énergétique, 2024) have been established to assess repairability and to promote better repairable products.

Ease of disassembly is an important criterion in repairability scoring systems (Barros & Dimla, 2023; Vanegas et al., 2018). As a result, the ability to determine the ease of disassembly and reassembly reliably and easily is not merely a technical concern. It's crucial for developing a robust repairability scoring system that influences policymakers, designers, and manufacturers. Currently, two distinct methods are used to assess the ease of disassembly: "proxy time methods", such as eDiM (ease of Disassembly Metric) (Vanegas et al., 2018) and iFixit Proxy time (Flipsen et al., 2019), which estimate disassembly times through modelling the required actions, and the "step method" (EN45554 Standard, 2020), which counts the number of disassembly steps. Although the step method has been widely used in various repairability scoring systems (Cordella et al., 2019; Ministère de la Transition énergétique, 2024), proxy time method (specifically eDiM) has shown to provide a better representation of ease of disassembly (Bracquené et al., 2021; Dangal et al., 2025). Compared to the step method, eDiM's time-based approach aligns better with practical repair scenarios, where time is a crucial factor for professional repair services and provides a better indication of the level of difficulty to end-users. As a result, a scoring system directly based on required time instead of number of steps can more reliably assess ease of disassembly and incentivize manufacturers to design products with reduced repair time and complexity. However, eDiM and iFixit proxy times

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Published online: 04 August 2026

only measure disassembly times, and only measure times for a limited number of fastener types, limiting their accuracy and applicability. This raises a challenge for repairability research and policy: how can time-based disassembly (and reassembly) efforts be estimated with sufficient fidelity to be meaningful, while remaining simple enough to be applied at scale across heterogeneous appliances and testing contexts?

For assessment purposes, another disadvantage of eDiM its demanding time-consuming calculations, frequent updates, and grappling with the complexity of countless tool and connector combinations (Vanegas et al., 2018; Wang et al., 2024). Furthermore, the model operations that are at the core of eDiM are currently limited to monitors, laptops and TVs. These limitations hinder the application of the eDiM approach to other product types and towards implementation in scoring systems. Related work has repeatedly highlighted the trade-off between methodological richness and operational usability in repair/disassembly metrics, particularly when methods are transferred from controlled modelling contexts into routine product testing and policy-facing scoring systems (Bracquené et al., 2021; Peeters, et al., 2018). The aim of this paper is, therefore, to explore the opportunities of a model for disassembly and reassembly based on experimental data that is easier to use and applicable towards a broader *range* of products. More specifically, this paper asks: Can an empirically derived proxy time model, grounded in observed repair practice and structured around discrete repair actions, accurately estimate disassembly and reassembly times across a diverse set of household appliances, while substantially reducing the analytical and operational burden? The scientific implication is a generalizable, data-grounded pathway for translating observed repair work into scalable repairability metrics, thereby strengthening the evidentiary basis of repair scoring and design guidance.

To achieve this, a twofold approach was followed. First, disassembly and reassembly times were determined for a large set of different household products with very different product architecture: washing machines, vacuum cleaners and smart TVs. The data for all disassembly and reassembly times were subsequently divided into suitable groups to develop a simplified time-based disassembly and reassembly assessment model. The resulting model (DaRT) was compared with eDiM to understand the extent of its similarities and differences.

To check the model's validity and applicability, a separate set of appliances (washing machines, vacuum cleaners and TVs) were dismantled by external testing bodies and DaRT times were calculated and compared with the actual disassembly times.

The structure of this paper is as follows. The Methods section details the multi-criteria selection of appliances and the empirical protocol used by professional repairers to record over 10,000 action datapoints. The Results section presents the synthesized proxy times, highlighting the similarities and critical differences between disassembly and reassembly tasks, different action groups, as well as a comparison with existing eDiM metrics. In the Validation section, the model's predictive accuracy is tested against independent data from professional labs to ensure reliability and ease of use. Finally, the Discussion and Conclusion interpret these findings, addressing the balance between model simplicity and accuracy, while outlining how DaRT can be integrated into circular economy policies to influence more sustainable products.

2 Methods

The development of the DaRT model followed a structured sequence designed to maximize both empirical accuracy and practical usability, as illustrated in Fig. 1. This logical progress ensured that the resulting proxy times were derived from professional performance data, synthesized, and independently validated for predictive accuracy.

2.1 Product selection

Washing machines, vacuum cleaners, mobile phones and smart TVs were used for this study as a result of a multi criteria analysis within the Horizon 2020 PROMPT Project (https://prompt-project.eu/results/design-for-product-repairability/). The selection is based on their ubiquity in homes, their varying complexity in mechanical and electronic design, and repair frequency.

Additionally, products across different price ranges and made by different companies were chosen to ensure a broad perspective. Different price points and brands reflect variations in design complexity and assembly methods. This diversity enables us to establish generalizability of the findings to a variety of product groups and market segments in the wider category of household appliances.

In total 12 washing machines (disassembly and reassembly), 12 vacuum cleaners (disassembly and reassembly), 7 TVs (prying actions only), and 35 smart phones (adhesive removal actions only) were analyzed (See Table 5 in Supplementary Information SI1 for information on all the investigated products).

2.2 Disassembly mapping and action time recording

The disassembly was done by professional repairers from iFixit (https://www.ifixit.com/en-eu/Store) and RUSZ (https://rusz.at/en/) with more than 5 years of experience. The entire disassembly and reassembly process was

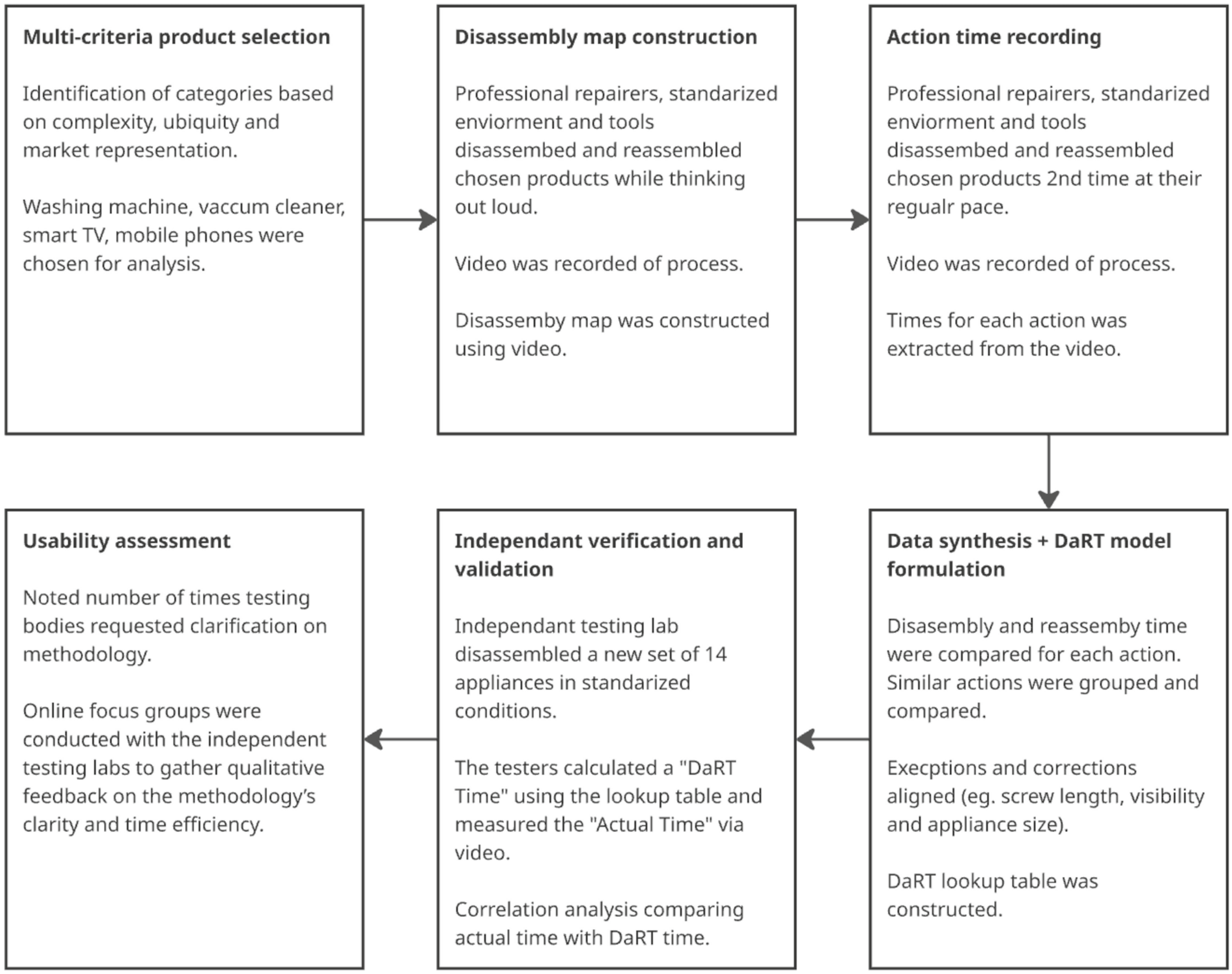

Fig. 1 Overall method flow diagram

conducted in a typical repair environment, closely replicating the conditions encountered by actual repair professionals. This included adequate lighting, sufficient space for the disassembly process, all necessary tools within the repairer's reach, and convenient access to space for placing disassembled components.

Standard tools used in the industry were employed, adding to the study's realism and relevance. Power tools were, however, omitted to maintain the simplicity of the protocol. The following protocol for disassembly and reassembly was followed for all products:

- The products were first disassembled to their individual components and then reassembled. The disassembly of a part ended when it reached permanent fixtures, such as soldering, welding, or thermal molding.
- All disassembly and reassembly actions were noted, this included: tool type, action, force used, fastener type, the visibility of fastener and the component being removed.
- During the disassembly, the actions were described aloud, mentioning and describing the target component, its location, the tool being used, and the detached/reattached fasteners.
- A disassembly map (Fazio et al., 2021) was created for each product following the procedure outlined in Dangal et al. (2025).
- The products were disassembled to their individual component and reassembled a second time by the same person.
- The entire process was video recorded from the front and top view.

Table 1 Actions and their details recorded during the disassembly and reassembly

Action	Details	Start moment	End moment
Grab and position tool/component/screw	Grabbing a (tool) and placing it in position for next action	Touch	Tool/component/screw positioned (PT in case of tool)
Position tool (PT)	Tool, already in hand, is positioned ready for intended operation	Prior end	Tool in position and ready for next action (is PT)
Put tool aside	Tool in hand is placed on the table	Prior end	Tool on the table + released
Open (hinge)	Rotational motion to open (e.g., door)	PT	Open action + released
Close (hinge)	Rotational motion to close (e.g., door)	PT	Close action + released
Loosen (friction fit)	Loosen friction fits (often by slowly pulling or small twists)	PT	The loosened part stops touching its housing
Pry (snap fit)	Pry using lever action	PT	Pried + released
Attach (friction fit/snap fit)	Attach two components together with friction fit or snap fit (often hand is used)	PT	Attached + released
Pull (friction fit)	Pull action (e.g., tabs)	PT	Pulled + released
Push (friction fit)	Push action (e.g., buttons)	PT	Pushed + released
Screw (wrench/screwdriver)	Screw motion often using wrench or screwdriver	PT	Screw fully tightened + released
Unscrew (wrench/screwdriver)	Unscrew motion often using wrench or screwdriver	PT	Screw fully loosened + released
Plug (hose/wires)	Plugging (e.g., wires and hoses)	Touch	Plugged + released
Unplug (hose/wires)	Unplugging (e.g., wires and hoses)	PT	Unplug + released
Detach (wires within product)	Remove cable from housing/cable guide	PT	Unrouted + released
Route (wires within product)	Attach cable to housing/cable guide	Touch	Routed + released
Pry friction-fitting/ glued circumference (per 5 cm)	Pry series of fasteners around a circumference	PT	Pried along + released
Cut	Cut (cable tie/wire) using pliers/scissors	PT	Cut + released
Heat adhesive (plate)	Using heat plate to loosen the glued surface	Part picked up	Part heated
Remove component/screw	Remove a detached part/fastener and place it on the (desk)	Prior end + PT	Removed + released on (desk)
Turn product (with both hands)	Turn product with two hands	PT	Turn + released
Tilt product	Tilt heavy parts (> 150 Newtons) to access (e.g., underneath)	PT	Tilted + released
Untilt product	Tilt back straight heavy parts (> 150 Newtons) after accessing e.g. underneath	PT	Placed back in standing position + released

The fasteners mentioned in brackets () of action column are examples and the actions are not limited to the mentioned fasteners

PT the tool in hand is in position for the action to perform, *Touch* tool or hand touches component, *Released* hand or tool stops touching affected component/fastener. *Prior end* end of the previous action

The timing and nature for each action was extracted from the second video. Table 1 lists and defines the actions timed during the disassembly and reassembly process.

2.3 Data synthesis and DaRT model formulation

A total of 10,569 datapoints of the actions mentioned in Table 1 were obtained. Only actions with more than 15 datapoints were used for statistical analysis to avoid the impact of coincidental variations. The data was visualized using a combination of histogram and box plot. Histograms provide data frequency distribution and uncover aspects like bimodality or skewness. Concurrently, the box plot provides a concise summary of the data's central tendency, variability, and potential outliers, and offers a quick overview of key statistical information.

In order to compare disassembly and reassembly times, the data was checked to see if the medians of both disassembly and reassembly of a specific reciprocal action fell within the first and third quartiles of a box plot (i.e., fell within the middle 50% of values for both). This is a measure of the degree of similarity of the median values of disassembly-reassembly pairs. Median values of one metric that fall outside the middle 50% of the other metric were considered meaningful differences.

In the same way, to explore the potential for reducing the differentiating between a large variety of tools, similar actions (like screwing with differently sized screw drivers) were grouped, and their median values were compared. Medians of actions that fall outside the interquartile range of a group were again considered meaningfully different and not belonging to the group. The median of each group was used as model timing for that group.

The median was used instead of the mean for model timings since the median is more robust against uncertainties, especially when dealing with outliers or skewed data distributions. Additionally, the use of the median mitigates the impact of non-random errors, such as systematic overestimations (Pennsylvania State University, https://online.stat.psu.edu/stat200/lesson/2/2.2/2.2.4/2.2.4.1; The Probability Analyst, https://www.theprobabilityanalyst.com/therobustmedian.html). Initially, a more advanced statistical technique, namely the Mann–Whitney test, was employed (see Supplementary Information SI2 for these results). While the majority of the results were consistent with those obtained using the current method, the Mann–Whitney test occasionally indicated statistically significant differences that were not meaningful in the context of identifying practical distinctions between actions. Therefore, we decided to determine whether the medians of different actions fall within each other's interquartile ranges, as this provides a more appropriate indicator of meaningful difference.

For comparison with eDiM timings taken from Vanegas et al (2018), type 3 connectors actions (> 20N force, D > 6 mm screws) from eDiM were considered as these connector actions provided the closest representation to the DaRT conditions.

2.4 Independent verification and validation

Validation of the DaRT model was carried out by professional testing labs, collecting their own data on disassembly and reassembly times of many parts from several products, and comparing their data to predicted DaRT times.

Four washing machines, five vacuum cleaners, and five smart TVs were evaluated as the result of a collaboration with consumer organizations within the framework of the European PROMPT project based on large variation in design features (Hann, 2022). Investigated priority parts are as follows:

- Vacuum cleaner: suction hose, dust cover, handle, cord reel, motor, on/off switch, wheels.
- Smart TVs: main board, timing control board, display assembly, internal power supply.
- Washing machine: door lock, door seal, electronics, hoses, pump, shock absorbers, tub assembly.

These priority parts were chosen due to their high failure likelihood and high functional relevance.

The following protocol was used to score criteria related to disassembly.

1. First, the disassembly and reassembly process to access all of the product's priority parts was determined.
   - o The official website was checked for a disassembly manual or instructions.
   - o If this was not available, other non-official disassembly/reassembly instructions websites such as iFixit and YouTube disassembly channels were consulted.
   - o If none of these sources provided the necessary information, the product was disassembled and reassembled in order to determine the disassembly process.
2. The device was then disassembled until each priority part was separated.
   - o Any non-standard accessories, such as display protectors or rubber bumpers, were removed before the start of the disassembly process. These accessories were not considered part of the disassembly.
   - o The disassembly of a priority part ended when it reached permanent fixtures, such as soldering, welding, or thermal molding.
   - o If multiple tools were required during a single disassembly action, the tool would only change once all fasteners requiring that specific tool have been removed.
3. The product was reassembled.
4. The product was tested again to confirm it worked correctly and disassembly had not harmed its functionality.
5. During the above steps, the entire disassembly and reassembly process was recorded in top and side-view videos.
6. During the disassembly, the actions were described aloud, mentioning and describing the target component, its location, the tool being used, and the detached/reattached fasteners.
7. Using the described information and the disassembly sequenced from the video, a disassembly map (Fazio et al., 2021) was created.
8. The proxy times for the model were calculated using the disassembly map.

9. The product was disassembled a second time, recorded on a second video. However, this time the researcher did not speak steps out loud during disassembly.
10. The actual times needed for disassembling (and putting aside) each priority part was extracted from the second video.

2.5 Usability assessment

The DaRT assessment methodology was used by independent testing bodies (VDE Testing and Certification Institute, https://www.vde.com/tic-en/portfolio/development-testing; Müller-BBM Group, https://www.mbbm.com/mueller-bbm-group/bbm-testlab/) with the request to inform us if any part of the process was unclear or required further explanation. Over the course of the testing bodies assessing the product using DaRT methodology, we noted the number of times they requested clarifications. Additionally, at the end of the process, these testing bodies were qualitatively interviewed in online focus groups on the clarity of the process. Two focus groups with 3–4 people (one for each testing body) were held. The participants in the testing bodies were directly involved in either disassembling the appliance or conducting the entire assessment.

The following open questions were asked:

1. Did you find any aspects of the DaRT methodology unclear?
2. How does the time to use DaRT methodology compare to just disassembling the product? What part took the longest time?
3. Do you have further recommendations that could be beneficial towards overall usability of the methodology?

After each question, the group was asked for more details. Approximately 15 min were spent on each interview. Notes were taken during the interview.

Interviews were analyzed by listing everything mentioned as an unclear aspect as well as further recommendations. The similarities and differences in responses from both focus groups were examined. Any overarching themes that reflected the participants' experiences and suggestions were grouped. These themes encompassed common perceptions of the DaRT methodology's clarity, time efficiency, and usability. Although the analytical and interview process was not thorough, it offered valuable preliminary insights into the experiences of using the DaRT methodology.

3 Results

The timings of the actions distinguished during disassembly and reassembly are represented in Fig. 2, which shows the histograms and median and quartile values. This figure presents the results, distinguishing (a) tool positioning action for different tools, (b) disassembly and reassembly for turn and crank action using different tools, and (c) other disassembly and reassembly actions. Similarly, Table 2 presents: the details on observed median timings for disassembly and reassembly actions, and a comparison of the observed times to the equivalent eDiM time.

3.1 Disassembly and reassembly

By comparing the disassembly and reassembly actions from Fig. 2 and Table 2 it is evident that in most cases disassembly and reassembly timings are similar enough to be represented by a single value. For example, for "position tool" and "grab and position tool" actions, and most of the "screw" and "unscrew" actions (6/9), no significant differences between disassembly and reassembly times were observed.

On the other hand, significant differences are observed between disassembly and reassembly for removal/grab and position action for component and screw. Grabbing and placing components or screws takes significantly more time than removing and putting them away. Similarly, routing cables is more time consuming than removing them. Further, "unplug hose" takes significantly less time than "plug hose". Additional time is required to properly align screws, components, and cables during reassembly, ensuring they are correctly positioned. The extra time for attachment actions is necessary to align and position the attachment accurately. An exception to this is "tilt" and "untilt" product where "tilt" takes significantly longer than "untilt", as "tilt" generally requires more work against gravity than "untilt". However, "tilt" and "untilt" are actions observed in both disassembly and reassembly process.

When considering similar actions on washing machines and vacuum cleaners, most of the actions for washing machines and vacuum cleaners were comparable. However, times needed for "grab and position tool", "plug/unplug hose" and "turn product" were significantly longer in washing machines than in vacuum cleaners (see Table 4 in Supplementary Information SI2). The "grab and position tool" action is explained by the larger range of motion that is required from the position of the tool to the position of the fastener. Further, hoses of washing machines need to be watertight and are subjected to higher pressure in contrast to hoses of vacuum cleaners, therefore, longer time and higher force is required to do so. Similarly, turning a heavy

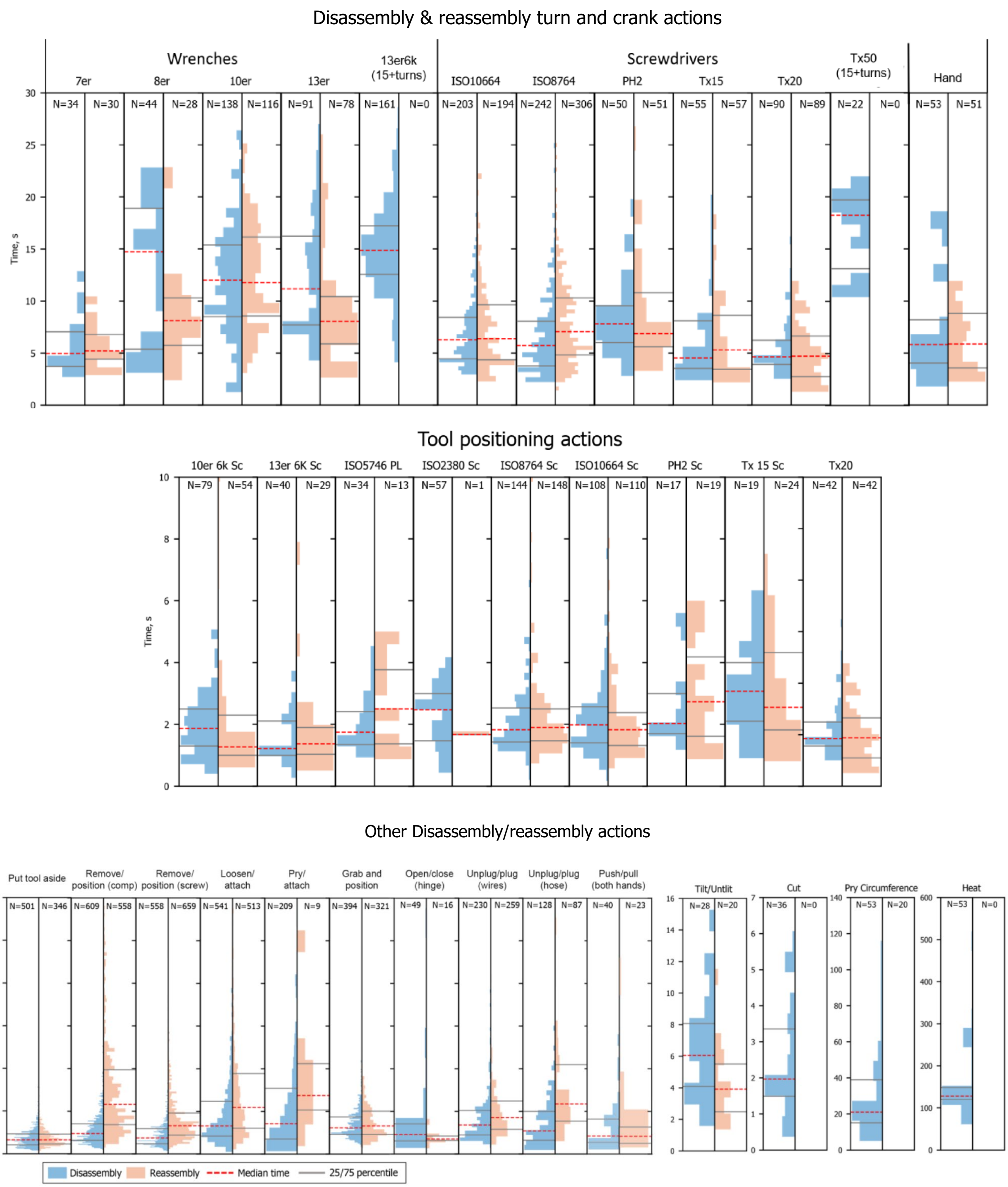

Fig. 2 Timing of disassembly and reassembly actions, distinguished by nature of activity and tool used. See Fig. 5 in Supplementary Information SI1 for further information on tool types

object like a washing machine requires significantly higher force than turning a vacuum cleaner. Actions are, therefore, distinguished between larger and smaller appliances for the forementioned three actions.

Table 2 Observed median timings for disassembly and reassembly, and its comparison to eDiM timings

Action (disassembly/reassembly)	Disass (No.)	Median time disass (s)	Reass (No.)	Median time reass (s)	Difference disass vs reass (%)	Overall median time (s)	eDiM Time (s)	% Delta DaRT (disass) vs eDiM (%)
Grab and position tool*	394	3.1	321	3.3	7.2	3.2		
Position tool*	541	1.9	444	1.8	− 3.7	1.8	1.4	30
Put tool aside*	501	1.6	346	1.6	0.0	1.6		
Open/close (hinge) *	49	2.3	16	1.8	− 24.8	2.1	2.2	4
Pry/attach (snap fit; < 20 newtons)	467	4.1	161	5.5	29.4	4.5	2.2	60
Pry (snap fit; > 20 Newton)	22	12.7	< 15					
Loosen/attach (friction fit; < 20 Newton)	541	3.3	513	5.5	49.5			
Loosen/attach (friction fit; > 20 Newton)	19	12.1	< 15					
Pull/push with both hands (friction fit) *	40	2.1	23	2.1	− 1.4	2.1	2.2	− 5
Unscrew/screw (wrench; = > 15 turns)	161	14.9	< 15					
Unscrew/screw (wrench; < 15 turns)	307	10.9	252	9.0	− 19.4	9.7		
Unscrew/screw (screwdriver; < 15 turns)	693	5.7	748	6.3	10.0	6.0	3.6	45
Unscrew/screw (screwdriver; = > 15 turns)	22	18.2	< 15					
Unplug/plug (hose)	128	2.7	87	5.9	74.0			
Unplug/plug (wires)	230	3.4	259	4.3	22.7	3.8	2.2	43
Detach/route (wires within product)	95	4.1	71	8.3	67.0			
Pry friction-fitting circumference	15	3.0	< 15					
Pry glued circumference (per 5 cm)	53	21.0	N/A					
Cut (cable ties, wires)	36	2.0	N/A				2.2	− 10
Heat adhesive (plate)	53	128	N/A				120.0	6
Remove/grab and position component	737	2.4	649	7.7	104.7		1.4	53
Remove/grab and position screw	558	1.9	659	3.3	55.3		1.4	30
Turn product	79	3.4	98	3.2	− 7.4	3.2	2.5	31
Tilt product (> 150 newtons)	28	6.1	20	3.9	− 42.9			
Overcoming low accessibility**	32	13.9					3.4	121

Disass Disassembly, *Reass* Reassembly, *empty cell* Not enough data available for evaluation

*Action used for both disassembly and reassembly

**This penalty is added to the corresponding action time and is not a stand-alone action. Actions in bold = disassembly and reassembly are significantly different. Delta DaRt vs eDiM % = (Median time disass—eDiM time)/ ((Median time disass + eDiM time)/2)) *100

Some scoring systems and eDiM distinguish between low, medium, and high force requirements for an action, using the MOST standard (Zandin, 2003) for force classification. Low force is defined as less than 5 newtons, generally corresponding to actions that can be performed using fingertip strength (e.g., prying out a button). Medium force ranges between 5 and 20 newtons and refers to actions that can be generally performed using wrist strength (e.g., prying a vacuum cleaner battery out of its slot). High force is defined as greater than 20 newtons and corresponds to actions that require arm strength (e.g., prying a motor out of its slot). However, for the products investigated, often both finger and wrist force are used in same action even if it is “low” force therefore operators could not distinguish between low and medium force and did not observe a clear difference in difficulty performing these actions. But a clear difference was distinguished between medium and high force actions. Similarly, Screws requiring more than 15 turns showed significant deviation from the rest of the data (see Fig. 2); therefore, this threshold was selected. Similar logic was applied for wrenching action.

3.2 Grouping comparable actions

Grouping comparable actions helps simplify the method, because it gives users looking up values a shorter list to choose from, but actions with significantly different timing must be distinguished. Based on the data in Fig. 2 and Table 2, the following actions have been investigated for potential grouping based on similarity of the activity carried out and the overlap of their distributions: (a) tool positioning of different tools, (b) unscrewing/screwing timings with different screwdriver and wrench types, (c) place/put away for screws, tools and components.

The “position tool” required similar timing regardless of the tool type. This observation is supported by the fact that the distribution for a single tool is much larger than the distribution of the medians of all tools. This indicates a consistency in the timing needed for positioning regardless of the tools used and implies that all positioning actions can be considered as a single group of actions. Taking the median value of this group as representative for all these actions largely simplifies the proxy timing system without introducing significant errors.

The timing of unscrew/screw actions was generally consistent across different screwdriver types, except for the Phillips head size 2. A comparable trend is observed with wrenches, where these actions are largely uniform across types, except for size 7. Both actions exhibited broad distributions and an almost multimodal pattern, reflecting significant variation in the required time. Further, observations of video recordings clearly showed the effect of long and short screws in disassembly time, with longer screws demanding more turns, thereby increasing the time needed to either loosen or fasten them. For simplicity and available data quality we decided to distinguish between screws shorter or longer than 15 turns. Similarly, wrench actions were grouped using the same criterion.

The time required to put away tools, screws or components also showed significant variation. Putting away tools took the least time, while putting away components took the most time. This discrepancy is due to the extra precision needed to grab and place screws or components compared to tools, which are already in hand. Placing screws and components also shows significant differences in time. Screws are placed in a single alignment slot, whereas components require alignment in various dimensions, leading to longer placement times. Therefore, removing and positioning tools, screws and components cannot be grouped.

Based on these observations and grouping, the overall histogram and box plot data of each group of actions considered for the model is re-presented in Fig. 3.

3.3 DaRT model

Based on the analysis, the Disassembly and Reassembly Timing (DaRT) model was established by integrating the median of observed timings and grouping actions as discussed. This approach ensures that the model accurately reflects typical disassembly and reassembly times while maintaining simplicity and broad applicability. Table 3 shows the groups, and their timings used in the DaRT model.

3.4 Validation of DaRT

The DaRT method for disassembly times has been evaluated by comparing actual disassembly times with DaRT proxy times for the removal of priority components in washing machines, vacuum cleaners and smart TVs by independent product testing bodies. Figure 4 compares the DaRT method’s times against the actual times to disassemble priority parts of a TV, vacuum cleaner, and washing machine. They showed an R^2 correlation of 0.98 with the observed times. The longer times (above 300 s) are dominated by washing machine components while shorter time is a mix of washing machine, vacuum cleaner and TV components. Both shorter and longer time maintain a very high correlation, 0.99 and 0.96, respectively (Dangal et al., 2025).

3.5 Usability of DaRT

Concerning the ease of use of the method, only in one instance a testing body approached us on how to deal with multiple components attached via long-soldered wires.

Regarding time requirements, participants reported that the assessment took approximately three times longer than simply disassembling the products. They indicated that most of the assessment time was spent creating the disassembly map (Fazio et al., 2021), not using Table 3’s lookup table of action times. This disassembly map needs to be produced

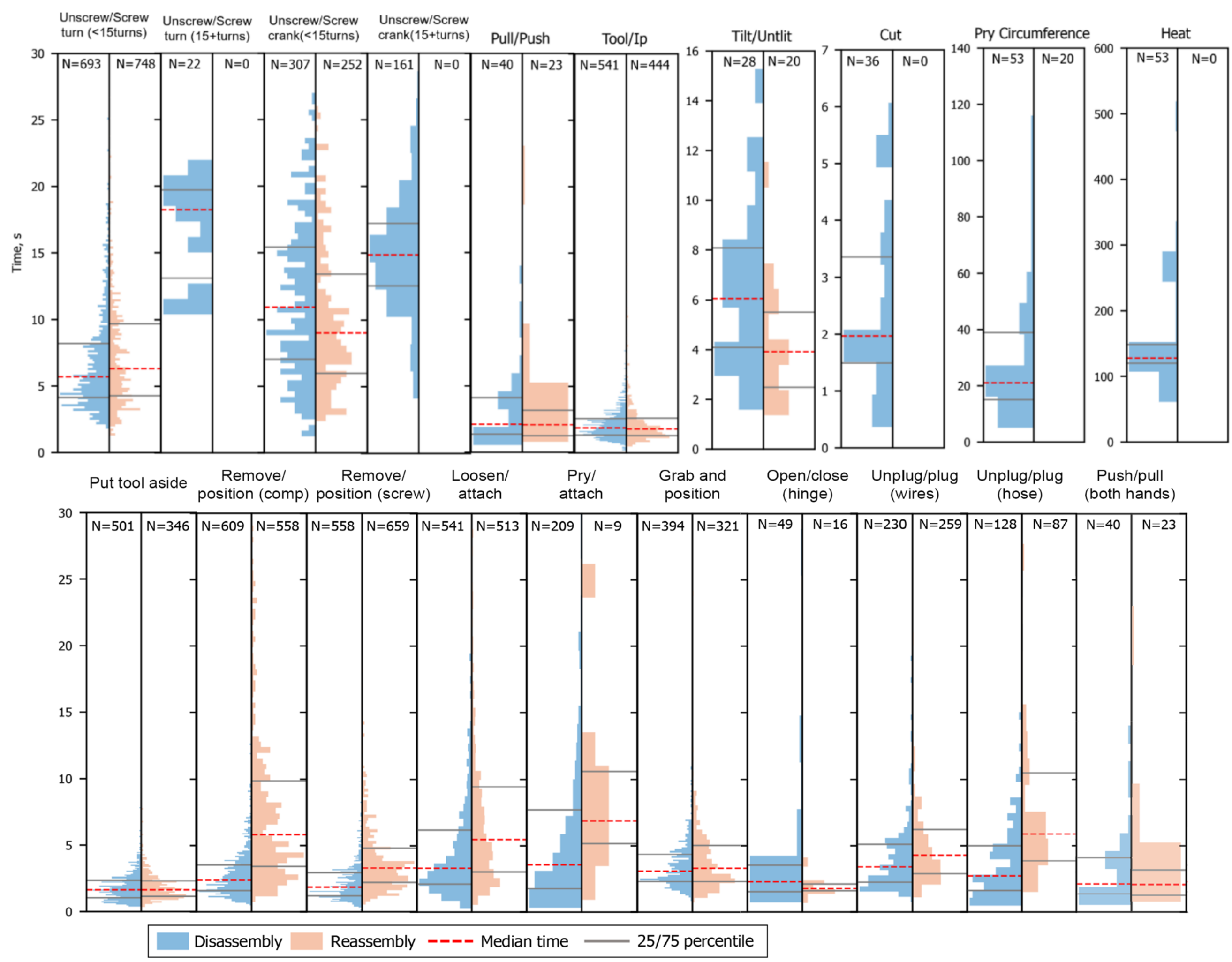

Fig. 3 Timing of groups of disassembly and reassembly actions, constituting the basis for DaRT. "Pry Circumference", "Cut" and "Heat" are irreversible and, therefore, do not contain reassembly action, "Unscrew/Screw turn (15 + turns)" and "Unscrew/Screw crank (15 + turns)" do not have sufficient data for reassembly. (n < 15). The data for Fig. 3 can be found in Supplementary Information SI2

even for using step method [33], making the ease of use of DaRT comparable to step method.

The testing bodies recommended the following improvements: (a) provide model timings for soldering and desoldering; and (b) develop timings for powered tools, as these are increasingly common.

3.6 Comparison with eDiM

The DaRT proxy times were also compared with related eDiM proxy times. As presented in the last columns of Table 2, proxy times for most of the actions closely fit to the eDiM proxy times, even though eDiM has been developed for different types of ICT equipment. The agreement between eDiM timing and the median values used in DaRT is considered to be acceptable (within 30% delta). The eDiM values for similar actions usually deviate by less than 30% from the median values and are within the observed quartiles. The eDiM proxy times in general tend more towards the lower quartile values. Further, eDiM underestimates the timing for some actions compared to DaRT, such as "pry" (snap fit; < 20 newtons), "unscrew" (screwdriver; < 15 turns), "unplug" (wires), and "overcoming low accessibility". Additionally, some actions were not described in eDiM. These include "detach/route (wires within product)", and "pry friction-fitting circumference" for adhesive removal.

Table 3 DaRT timings

Handling type	Disassembly/reassembly action	DaRT time (disassembly) [s]	DaRT time (reassembly) [s]
Tool handling	Grab and position tool	*3.2*	*3.2*
	Position tool	*1.8*	*1.8*
	Put tool aside	*1.6*	*1.6*
Reversible connection actions	Open/close (hinge)	*2.1*	*2.1*
	Loosen/attach (friction fit, < 20 newtons)	*3.3*	***5.5***
	Loosen/attach (friction fit, > 20 newtons)	*13.0*	*13.0**
	Pull/push (friction fit)	*2.1*	*2.1*
	Unscrew/screw (wrench < 15 turns)	*6.0*	*6.0*
	Unscrew/screw (screwdriver < 15 turns)	*9.7*	*9.7*
	Unscrew/screw (wrench = > 15 turns)	*21.0*	*21.0**
	Unscrew/screw (screwdriver = > 15 turns)	*18.0*	*18.0**
	Unplug/plug (hose)	*1.2*	***3.4***
	Unplug/plug (watertight hose)	*3.4*	***6.6***
	Unplug/plug (wires)	3.8	3.8
	Detach/route (wires within product)	4.1	**8.3**
	Pry/attach (snap fit, < 20 newtons)	*4.5*	***5.5***
	Pry/attach (snap fit, > 20 newtons)	*12.0*	*12.0**
	Pry friction-fitting circumference (per 5 cm)	*2.0*	*2.0**
Irreversible connection actions	Pry glued circumference (per 5 cm)	*3.0*	–
	Cut (cable ties, wires)	*6.0*	–
	Heat adhesive (plate)	*15.0*	–
Product/component handling	Remove/grab and position component	*2.4*	***7.7***
	Remove/grab and position screw	*1.9*	***3.3***
	Turn product (< 150 newtons)	*2.7*	*2.7*
	Turn (heavy appliance > 150 newtons)	*1.3*	*1.3*
	Tilt/untilt product (> 150 newtons)	*6.1*	***3.9***
Correction Time	Overcoming low accessibility	*14.0*	*14.0**
	Grab and position tool (large appliance)	*1.2*	*1.2*

"Correction Time" are values added to the other actions. * = same value as disassembly based on assumption, not from measurement. Reassembly times that are different than disassembly are indicated in bold italics. The italic data are directly taken from Table 2, based on median values of large data sets

Disass Disassembly, *Reass* Reassembly,—No data available

4 Discussion and conclusion

Based on our observations, there is no significant difference between disassembly and reassembly times for the majority of investigated actions. This is an important result as this is implicitly assumed in most of current repairability scoring systems (Cordella et al., 2019; UNEP Circularity Platform, https://buildingcircularity.org/the-french-approach-to-circular-economy-and-coherent-product-policies/), but had not been empirically demonstrated for a wide range of different products and actions. However, reassembly requires significantly more time for actions that necessitate precise positioning or alignment. Furthermore, our results show that disassembly and reassembly can generally be considered similar for actions such as "position tool" and "unscrew". The model has been validated against actual disassembly times for a range of products by independent testers, demonstrating a high degree of correlation. This substantiates its broad applicability across many product categories and suggests a low likelihood of significant biases. Therefore, the groupings proposed in this study, based on a variety of different products, largely simplify the proxy time model and improve the ease of use (Davis, 1989), scalability (Hennessy & Patterson, 2019), predictive model accuracy, and broader applicability (Box & Draper, 1987).

The grouping of actions, however, could introduce significant uncertainties and systematic biases (Cowan, 1998; Heitjan & Rubin, 1991). This is partly alleviated by the use of median values in timing models, which enhances robustness against uncertainties by minimizing the influence of outliers

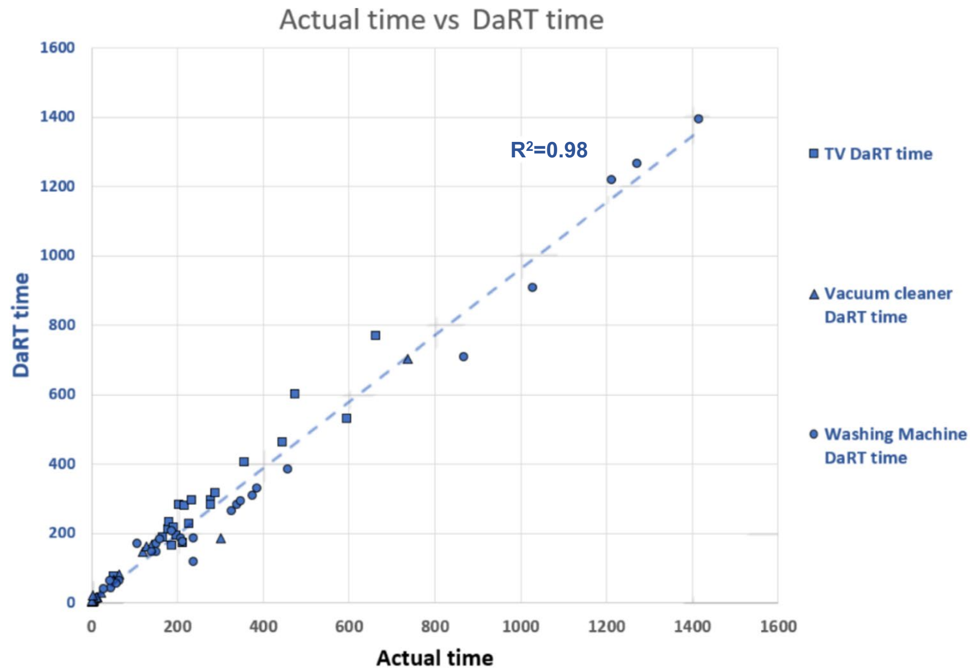

Fig. 4 DaRT disassembly timings vs actual disassembly timings for priority parts of three appliances. The data for Fig. 4 can be found in Supplementary Information SI2

and symmetrically distributed errors (The Probability Analyst, https://www.theprobabilityanalyst.com/therobustmedian.html). Additionally, having large datasets as used in this research significantly reduces biases and uncertainties since the standard error of parameter estimates decreases, allowing more precise and robust inferences. Furthermore, the influence of outliers, which can disproportionately affect smaller datasets, is diluted in larger datasets, ensuring that grouped summaries better reflect the central tendencies and true variability of the data (Cochran, 1977; Rousseeuw & Leroy, 2003).

It should be realized that the width of timing distributions is not only due to coincidental variations, but also relates to real differences in product architecture. For instance, DaRT actions such as “pry/attach” and “loosen/attach” exhibit exceptionally broad distributions. This variability arises from the nature of these actions inherently involving a range of times, due to differing levels of force, precision, and architectural differences. These variations are difficult to assess and integrating them to a finer level would complicate the assessment and be counterproductive to the aim of the new model. In this scenario, the simplicity and ease of use of the model was chosen over potential higher accuracy. This also implies that for specific products that are uniquely simple or complex, the use of the DaRT values might lead to underestimation or overestimation of the required time. However, we consider the DaRT times a reasonable compromise between useability and accuracy.

Unique actions such as removing door seals from the washing machines are not directly covered by DaRT actions. To address such unique actions, a feature termed "complex/difficult action" might be introduced, allowing users to input the approximate time required for such action. While this action does not follow a similar approach as other DaRT actions, it allows mitigation of biases towards unique actions while maintaining the simplicity of the model. This correction term serves to make proxy time comparable to actual time, but within a product category the ranking will not be dependent on it.

The DaRT proxy times in general are somewhat higher than equivalent eDiM proxy times. This can be attributed to two primary reasons. First, eDiM was developed and tested with ICT equipment (mainly laptops and monitors), making it less comparable to larger appliances. Second, eDiM was derived from the timing of MOST (Maynard operation sequence technique) (Zandin, 2003), which are standardized timings acquired from repeated motions (e.g., in assembly lines). In the context of repair, these motions are not fully repeated and additional correction term may be required to account for this, which might partly explain the larger DaRT values.

When comparing the ease of use and accuracy of DaRT with other disassembly assessment methods, such as counting the number of disassembly steps, the step method is anticipated to remain the easiest to use, as it considers only two primary parameters: tool changes and component removals. However, this simplicity comes at a significant cost to accuracy, as research indicates a low correlation between the number of steps and actual disassembly times (Dangal et al., 2025). The eDiM method, as previously discussed, is more complex, as it considers numerous tools, fasteners, and parameters, while offering accuracy comparable to the DaRT. The DaRT method, therefore, strikes a favorable balance between ease of use, versatility and accuracy.

For future work, establishing DaRT proxy times for a larger variety of product types beyond household appliances, for example furniture and cars, would be interesting. Furthermore, desoldering actions as well as reassembly timings for actions that did not have enough data could be populated with further research. Additionally, the use of power tools, which are becoming more common, could be incorporated into the model. These activities would provide a more complete model of the DaRT proxy times. Actions with exceptionally broad distributions in disassembly and reassembly timings such as loosening and prying, may require further exploration to understand how they behave with unique products. This would help determine if these actions should be categorized differently to improve accuracy, for example, based on force or newly defined actions.

The DaRT proxy time model has been established based on a large number of repair actions on a variety of domestic products. This model represents a significant step forward in assessing disassembly and reassembly times for household appliances, striking a favorable balance between accuracy and ease of use compared to existing methods like eDiM and step counting. By leveraging large datasets and simplifying the list of actions through grouping, the model achieves scalability and applicability to a broader range of products. It also shows that while disassembly and reassembly times are usually similar, there are a few cases there reassembly takes significantly longer. Its validation against actual disassembly times shows its robustness, though it reveals limitations in handling uniquely complex products.

Overall, DaRT delivers a straightforward yet effective way to assess ease of disassembly and reassembly, overcoming limitations of existing methods. Its accuracy and ease of use make it a powerful tool for building robust repairability scoring systems. These can improve environmental impact by influencing policymakers, designers, and manufacturers to create products that are easier to repair, supporting resource efficiency and sustainability goals central to the circular economy.

5 Summaries:

Supporting Information SI1: This supporting information provides additional methodological details and supporting data, including descriptions of the analyzed products and tools.

Supporting Information SI2: This supporting information provides the numerical datasets and statistical analysis results supporting the tables and figures presented in the manuscript. It includes comparative data on appliance actions, MannWhitney U test results, and disassembly time measurements provided in spreadsheet format.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s44498-026-00150-9.

Acknowledgements This work was funded by the European Commission under the Horizon 2020 Premature Obsolescence Multi stakeholder Product Testing Program (PROMPT) (Grant Agreement Number 820331). We would like to thank iFixit and RUSZ for their assistance in performing disassembly and timing actions, which were instrumental in the development of the DaRT model. We also extend our sincere thanks to VDE and BBM for their efforts in assessing products using the DaRT model, providing critical verification and validation of its application.

Author contributions S.D wrote the main manuscript. L.R and A.O supported in data analysis. J.F and R.B provided supervised and provided feedback on manuscript.

Funding Funding was provided by Horizon 2020 (820331).

Data availability Data available upon request.

Declarations

Competing Interests The authors declare no competing interests.

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