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A BASIS FOR OPTIMIZED SELECTION OF AN END-OF-LIFE PRODUCT DISASSEMBLY SYSTEM

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Abstract. *The advancement of technology has enabled the human civilization to produce more than ever before, with the alarming consequence being the huge amount of waste generated. Therefore, the disposal of End-of-Life (EoL) products represents one of the biggest problems of the modern world. The vast majority of recycling processes would benefit from the inclusion of a disassembly stage, since a large portion of EoL products is an assembly. Disassembly has the potential to significantly improve overall waste reduction by allowing reuse, avoidance of environmental risks and hazards, and better sorting of materials. The efficient planning, creation and operation of a disassembly system requires solving of many issues related to the varieties of EoL products and their various quantities. Thus, the paper provides a basis for a method that would propose an appropriate disassembly system, based on the state of the product in real time. By monitoring the state of products, even before they enter their EoL phase, it is considered possible to have a dynamic solution suggesting the most appropriate type, number and location of disassembly systems. The method for choosing an appropriate disassembly system (preferably automatized) would improve the disassembly planning and process, by reducing the planning time, while increasing productivity.*

Key words: *End-of-Life product, Disassembly, Planning, Traceability*

1. INTRODUCTION

As the technology and life standard in human society rapidly progress, so does the consumerism culture grow. People buy more than ever before, and the projected lifecycle of a product is shorter than ever [1], resulting in the yearly increase in the production amounts. Unfortunately, the consequence is the fact that the world produces more waste than ever before [2], and the question of sustainability becomes extremely important. Manufacturers were only interested in producing as much as possible, without thinking of the problem the waste will inevitably create. Now a serious investment needs to be done to combat this alarming issue. In order to achieve a sustainable economy, a complete switch from a linear to a circular economy is needed [1]. Whilst a sustainable circular economy

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approach is becoming common [3], still more progress needs to be achieved, as the world is showing very high levels of waste generation and dependency on raw materials [4]. Many manufacturers still do not fully recognise the potential of Life Cycle Analysis (LCA) practices for the substantial improvement of their products, especially small to medium sized manufacturers [5]. According to the EU Action Plan on Critical Raw Materials [6], which aims to substantially lessen the human civilization's dependence on raw materials, recycling and re-use present the future of manufacturing. This is in accordance with the standard for ranking waste disposal options based on their environmental impact, the Lansink ladder [7]. Vast majority of recycling processes would benefit from the inclusion of a disassembly stage, since a large portion of waste is an assembly rather than a single part. Thus, disassembly is the basis for achieving this plan, as it improves the overall recycling process itself by allowing reuse, avoidance of environmental risks and hazards, and finally better sorting of materials. The advances in digitalisation are set to be integrated in the form of the European Commission's Recycling 4.0 [8], which is combining Industry 4.0 technologies with circular economy principles to advance the recycling sector. When the potential of waste (in terms of material and energy) is recognised, it is referred to as an End-of-Life product (EoL) – implying it as still a product with potential. Circular economy implies different fields [9], such as the sustainable collection of energy from waste (such as biogas, use of compost or construction building material) [10], with disassembly being one of them, and the primary focus of this research.

Before entering the specifics of disassembly, a question may be asked regarding its importance. It can be argued that disassembly is possibly even a nuisance in waste management since disassembly is an additional cost and very time consuming due to a high portion of manual work [11]. If only those arguments were taken into consideration, then it can be argued further that traditional destructive methods such as shredding [12] should be the preferred alternative. While shredding can indeed process EoL products faster and cheaper at first glance, it cannot give saved individual useful component-parts as its output: component-parts get destroyed and subsequently the materials get mixed, and needed to be sorted by various processes. In addition, shredding cannot effectively deal with processing components containing hazardous substances [12]. In contrast, disassembly results in integral component-parts which can later be reused or even recycled in a more straightforward way. As such, disassembly is the cleaner solution [6] and preferred by the LCA and circular economy approach (also in accordance with the Lansink ladder [7]).

Disassembly is done in different ways, ranging from manual disassembly to fully automated disassembly. However, a large part of EoL products is still being treated at traditional manual recycling facilities, either locally or processed abroad in less developed countries [2, 13]. This is due to the products arriving in unpredictable conditions and varying quantities, hence why the flexibility of human workers is preferred to automation. Unfortunately, manual disassembly cannot deal with the growing quantities, thus an increase in the share of automation in disassembly is needed in order to successfully deal with the growing quantities of waste.

An ideal solution would be for manufacturers to handle their product at the end of its lifecycle [14]. Two examples come from a smartphone manufacturer, whose "robots" Liam [15] and Daisy [16] completely automatically disassemble smartphones (a large part of WEEE - Waste Electrical and Electronic Equipment). Whilst positive examples, and indeed the most wanted solutions as attempts to begin addressing automatic disassembly of WEEE, still the vast majority of the company′s products get processed in conventional ways [17, 18]. This problem is further emphasized by the fact that their disassembly line can process 1,2 million phones a year [19], while another 200 million phones have been sold in 2020 alone [20].

Manual work is dominant in disassembly [11] and it is always an option for dealing with a large variety of products, but at the same time it cannot cope with the increasing waste quantities and associated health hazards. This presents an issue, as the highest possible level of automation needs to be found for each type of product at a location. Thus, to sum up, the amount of various disassembly system options raises the need for a methodology, to guide the user towards the most appropriate disassembly system.

2. PROPOSED METHOD FOR OPTIMISED EOL PRODUCT DISASSEMBLY SYSTEM SELECTION

The uncertainties and variations found within EoL products lead to uncertainties in the disassembly process [12], which complicates the choice of a disassembly system because disassembly brings specific problems, among them:

- the variety of states an EoL product can end up in,
- securing the quantities for automatization,
- non-standard components used for maintenance, upgrading/downgrading from the original specification which complicate its automation.

The mentioned reasons, among others, inhibit automation in disassembly [21]. Disassembly is mostly being done manually, which leads to higher costs and lower productivity, and it is questionable if it is, left on its own, able to cope with the growing quantities of waste our civilization produces. Therefore, in order to fulfil the EU Action plan for recycling within sustainability and complete a conversion towards circular economy [2, 3, 6, 9], an increase of the share of automation in disassembly is necessary in order to increase productivity.

The choice of the type of disassembly (manual or automatic), and more specifically the type of system to perform it in, is the first step in disassembly system planning. Thus, the development of a method for choosing the most suitable disassembly system should present the starting point for disassembly system planning.

This is exactly the aim of the research: to develop a method for choosing the most suitable disassembly system, solving the specific problem (EoL product in question is to be disassembled, completed with the describing data) with a suitable solution in the form of an appropriate disassembly system, ranging from manual disassembly to fully automated disassembly. Enabled by product traceability, it is deemed possible to have an appropriate disassembly system suggestion, while the product is still in use, even before the EoL phase.

In order to give an appropriate disassembly system suggestion, a clear picture regarding the product (to be disassembled) needs to be given. The product is the basis of any analysis of a process and the subsequent system, as the product is being processed in a system. Even with successfully obtained large quantities, different products can suggest very different disassembly system options. Thus, the parameters which describe the (current) state of the EoL product to be disassembled present the input for the method, defined by values of those parameters of interest.

3. PARAMETERS OF THE METHOD

The key parameters of interest (and sources of data, where possible) of an EoL product (or disassembly family of EoL products) will be given in the following section. The suggestion will be made based on real-time values of the parameters. Based on these inputs, the method's output will be in the form of the suggested disassembly system. Furthermore, a dynamic characteristic of the suggestion is implied, as it can change if the parameter(s) are sufficiently changed, even while the product is still in use. The corresponding limit values are extremely product-specific for each type of EoL product, and further research will need to be done for any specific type of product. Along with the parameters, the way each of them effects the suitable suggestion will be given.

3.1 Type of EoL product

The type of EoL product parameter deals with the questions regarding the basic physical characteristics of the product (possibly even the representative product [22]). This will define the process functions and, later, the equipment needed for disassembly. For example, very different equipment is needed to disassemble a household electronic device or a vehicle (in addition to the tools to perform the disassembly, powerful equipment is needed to manipulate them). Some of the questions regarding the material type are:

- What are its size and mass?
- Is the material of the (representative) product toxic in any state, or does it contain any toxic components? Is the material contaminated or radioactive?
- Does it need a special environment to handle the health risks? If a special environment is needed for processing such products, it would guide it towards a highly specialised, low volume automatic equipment (as manual disassembly should be limited, due to the workers' health risk)
- Are the joining techniques a very specialised technology, for which automated solutions have not yet been developed?

Hazardous types of material would need to be categorised, which require regulated approach for valid reasons (e.g. for the handling of special types of hazardous or toxic material, which require specific handling and/or conform to strict regulations). For example, hazardous waste would preferably be processed without human presence [12].

3.2 Disassemblability

Disassemblability describes the difficulty of the disassembly task. Specifically for this research, the disassemblability parameter describes the difficulty of the disassembly of the EoL product in question, how feasible it is for automated disassembly. A well-designed product with disassembly in mind brings considerable benefits during recycling [23]: especially, applied fastening and joining techniques will dictate in the reversed process of disassembly whether it will be performed with or without damaging the component-parts. Additionally, a product designed with a focus on disassembly will also be more feasible for automation in disassembly, leading towards higher values of the parameter.

3.3 Traceability

Traceability describes how feasible it is to trace a product in its various life phases. Based on current trends, it is certain that traceability will be even more implemented in a wide range of products, thus it will be one of the key parameters for the selection of an appropriate disassembly system. Traceability is needed in order to gather the information regarding the status of the product among the shareholders, shown in **Error! Reference source not found.**.

Fig. 1 Shareholders involved in successful EoL product tracking

On the one hand, some products are very suitable for tracking, which are often of large dimensions and of significant value (meaning it is of interest to track). Such examples are vehicles: automobiles, trucks, motorcycles, farming equipment, etc. They are already widely tracked – the tracking by registration plate is today very well automatized by camera-based systems (e.g. in parking garages and toll booths) and through service centers and insurance. Then, devices which are connected to the network for large amounts of time (mobile phones, personal computers) are also very suitable, as well as products which require special surveillance from the authorities (eg. weapons) or special rules due to their health risks and hazards. Additionally, some products have a very long traceability period. All the mentioned products would gravitate towards higher values of the traceability factor.

On the other hand, some products are unsuitable for tracking, products which are either very cheap (limited or no real value which would justify tracking), small or unregulated (no law or regulation specifying their need for control and tracking). Currently some problems might occur. For example, recent regulations aim at banning small plastic straws and cutlery and they present a huge among of untracked products which must not end up in the environment. **Error! Reference source not found.** shows how the value of the traceability parameter will be assigned.

3.4 Geometrical continuity of the EoL product

The geometrical continuity shows how close the EoL product is to its original specification (which can be closely checked through CAD and/or scanning), needed primarily to determine the possible level of automation of the disassembly system.

EoL products which differ from the original specification (damaged or changed significantly with non-standard components) will be more complicated for automated disassembly, if not impossible. This complicates the disassembly plan, as it will deviate from the disassembly plan for the expected standard EoL products. This can be solved through its digital twin, kept up-to-date with high levels of traceability (however, this depends on the feasibility of traceability of the product, as described in section 3.3). If the principles of Big Data are implemented, then there is a possibility to determine which amount of EoL products from a batch is changed from the rest, and thus needs to be processed in a different way (leaning towards manual disassembly if sufficiently changed), leading towards higher values of the parameter.

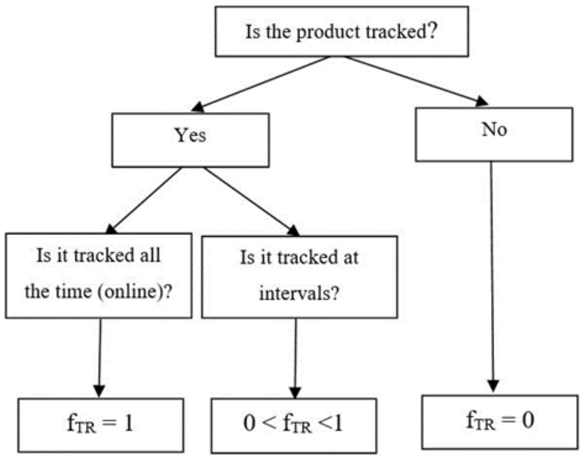

Fig. 2 The logic for assigning the value of the traceability parameter

3.5 Quantity

The available quantity of a group of EoL products is one of the key parameters for the choice of the disassembly system, as securing the quantities is the key for justifying the cost of automation. Also, it is closely connected with the area covered by the planned disassembly system, as the product must be relevant for the area.

Research needs to be done on the limit values, which are key here. For example, what is the annual number of the disassembly family of EoL products of interest sold in the region? This data can lead to defining the lower limits for automatization.

3.6 Cost of collecting

Following the question of quantities, products also vary in their cost of collecting. For some products, the collection is already very well and widely developed, organised and known. For example, the system for gathering and processing plastic and glass bottles is already well-developed and common, thus automation is well-used in those systems.

Furthermore, some products are regulated due to their importance or environmental issues, thus also collected in a specific way.

Transport is also included in the cost of collecting, and it again varies wildly between different types of EoL products. Large, bulky, heavy, and/or hazardous EoL products present a larger challenge (therefore also a larger cost) to transport and are also closely connected to the chosen means of transport. This can lead to a quantitative-based decision regarding the feasibility of, for example, having two less automatised (thus less productive) systems closer to the areas but with less transport, or a larger one with more transport?

4. Relationship Among Parameters

Depending on the values of all the previously described parameters, a unique solution (in the form of the temporary appropriate disassembly system for the EoL product in question) will be given. Still, special cases (closely connected to the type of EoL product, described in 3.1 Type of EoL product) will require a specific solution, regardless of the other factors. For example, hazardous EoL products or EoL products presenting a health-risk for humans will have to be disassembled by automation – regardless of the quantities, traceability etc. Outside these special cases, the solution will be given depending on the values of the factors for the EoL product of interest.

For example, vehicles are on the higher end of the spectrum, and their disassembly can be more effective as this information could be created and tracked well before the vehicle arrives for disassembly (as this is the case currently, data sharing must be established so the disassembler can gain data).

Low values of the parameters lead to manual disassembly, as either:

- the quantities are not sufficient, or the cost of collecting is expensive,
- the product is too complicated for automated disassembly, or differing too much from the original state,
- the product is not traced enough during its lifetime for a disassembly system suggestion to be ready and prepared, thus leading to manual disassembly as the most adaptable option to handle the product uncertainties.

It is necessary to keep the solution dynamically changeable – if some of the parameters change sufficiently enough to then offer a different solution, it needs to be up to date. This way the user can also experiment with different parameters´ values to check how "safe" inside a disassembly solution the parameters currently are. For example, it might be a risk to invest in an automated disassembly system if the solution has barely entered the field of automation, because if it drops below that the equipment will not be suitable anymore and thus not profitable as planned. This way the user can also check the surroundings of the system – what would affect the solution to move towards automation or manual disassembly. With such a dynamically changeable solution they can plan for the future.

Regarding the disassembly systems as the method's solution, they will be given as a broad group. As already mentioned before, disassembly is done in different types of disassembly systems. The biggest groups are:

- Manual disassembly system, for the widest variety of EoL products to process, and the lowest quantities.

- Collaborative disassembly system, where a certain part of the disassembly task (either very simple, or difficult for a human to perform, such as manipulating a vehicle [24]) is automatised.
- Flexible automated disassembly, an automated disassembly system for a wider group of EoL products, with a degree of flexibility towards each specific EoL product.
- Single-purpose automated disassembly, for a specific EoL product (or extremely low variation), offering the highest productivity.

The subsequent steps would include, among others, the concept of a disassembly system catered for the EoL product in question.

Error! Reference source not found. shows the relation comparison between the different disassembly system options, and how they are affected by the values of the parameters for the EoL product in question.

Table 1. Comparison table of the systems and parameters

Disassembly system/parameter	*Type of EoL product*	*Disassemblability*	*Traceability*	*Geometrical continuity of the EoL product*	*Available quantity*	*Cost of collecting*
Manual disassembly	Rare, non-standard	Low disassemblability	Not traced	Damaged, non-standard	Low volume	High
Collaborative disassembly	Simple to grasp	High disassemblability	Traced at intervals	Undamaged	Medium to high volume	High
Flexible disassembly	Standard, modular build	High disassemblability	Traced at intervals	Undamaged, unchanged from original specification	Medium to high volume	Low
Automated disassembly	Simplest, also hazardous and dangerous	Very high disassemblability	High traceability	Undamaged, unchanged from original specification	High volume	Low

5. CONCLUSION

Disassembly brings specific issues which hinder its automation, which is why it is done mostly manually, leading to high processing costs and low productivity. This research aims to improve the productivity of disassembly by increasing the share of automation, by means of the choice of an appropriate disassembly system. This leads towards a method for the choice of an appropriate disassembly system for a specific product, deemed possible even during product use (before entering its EoL phase).

The result is a set basis for a program, in which the user would enter the disassembly scenario and be given a suggestion for an appropriate disassembly system. Depending on the state of the EoL product (or group of EoL products) and its accompanying data, a suitable disassembly system will be presented, even while the product is still in use. Furthermore, the user can use the method to check the surrounding of its solution, in order to prepare for any market changes, both positive and negative scenarios (e.g. how much can the quantities drop until automation is no longer feasible, or how much do they need to increase in order to justify automation – these considerations are important when investing in expensive equipment).

This method for the choice of a suitable disassembly system would greatly improve the disassembly process, enabling the human civilization to better handle the growing quantities of waste. Such improvements will shorten the preparation time and thus improve their productivity, as the disassemblers will have a ready suggestion (enabled with high-level traceability based on the real-time tracking of the product) before the EoL product even arrives to the facility, also changing the result if a large enough change has been tracked. After the choice of an appropriate disassembly system, the following steps are disassembly process planning and the design of the appropriate disassembly system.

Future research will be aimed towards identifying an example of a product family, to set the key values (as they are extremely unique towards the specific product) for an experiment. Additionally, work needs to be done towards collecting the data (from manufacturers, government agencies, disassemblers) and its integration between the shareholders (following the principles of Big Data).

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References
(Samples for Serial, Book, Proceeding, Thesis, Report - *Style Reference*)

1. Rocca, R., Rosa P., Sassanelli, C., Fumagalli L., Terzi, S., 2020, *Integrating Virtual Reality and Digital Twin in Circular Economy Practices: A Laboratory Application Case*, Sustainability, 12(6), DOI: 10.3390/su12062286
2. Brooks, A. L., Wang, S., Jambreck, J. R., 2018, *The Chinese import ban and its impact on global plastic waste trade*, Science Advances, 4(6), DOI: 10.1126/sciadv.aat0131
3. Taffuri, A., Sciullo, A., Diemer, A., Nedelciu, C. E., 2021, *Integrating Circular Bioeconomy and Urban Dynamics to Define an Innovative Management of Bio-Waste: The Study Case of Turin*, Sustainability, 13(11), DOI: 10.3390/su13116224
4. Aleksandrova, I., Gubernatorov, A., 2020, *Tools for Implementing the Financing Mechanism for the Waste Processing Industry*, 13th International Conference "Management of large-scale system development", Moscow, (MLSD), DOI: 10.1109/MLSD49919.2020.9247835
5. Glisovic S., Stojiljkovic, E., Stojiljkovic, P., 2018, *The state of play in disseminating LCM practices in the Western Balkan region: the attitude of Serbian SMEs*, International Journal of Life Cycle Assessment, 23(7), p. 1396-1409, DOI: 10.1007/s11367-015-0894-7
6. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0474 (last access: 16.10.2023)
7. Willems, B., Dewulf, W., Duflou, J. R., 2006, *Can large-scale disassembly be profitable? A linear programming approach to quantifying the turning point to make disassembly economically viable*, International Journal of Production Research, 44(6), p. 1125–1146, DOI: 10.1080/00207540500354168
8. Blömeke, S., Rickert, J., Mennenga, M., Thiede, S., Spengler, T. S., Herrmann, C., 2020, *Recycling 4.0 – Mapping smart manufacturing solutions to remanufacturing and recycling operations*, Procedia CIRP 90, 90, p. 600-605, DOI: 10.1016/j.procir.2020.02.045
9. McDougall, F. R., White, P. R., Franke, M., Hindle, P., 2001, *Integrated Solid Waste Management: a Life Cycle Inventory*, Blackwell Science.
10. Chandrappa, R., Das, D. B., 2012, *Solid Waste Management*, Springer-Verlag, Berlin
11. Das, S. K., Naik, S., 2002, *Process planning for product disassembly*, International Journal of Production Research, 40(6), p. 1335-1355, DOI: 10.1080/00207540110102142
12. Vongbunyong, S., Chen, W. H., 2015, *Disassembly Automation: Automated Systems with Cognitive Abilities*, Springer.
13. Chen, W. H., Foo, G., Kara, S., Pagnucco, M., 2019, *Application of a multi-head tool for robotic disassembly*, Procedia CIRP 90, West Lafayette.
14. https://www.apple.com/me/recycling/ (last access: 12.07.2021)
15. https://mashable.com/2016/03/21/apple-liam-recycling-robot/?europe=true (last access: 12.07.2021)

16. https://www.apple.com/newsroom/2018/04/apple-adds-earth-day-donations-to-trade-in-and-recycling-program/ (last access: 15.04.2023)
17. https://www.vox.com/2017/11/8/16621512/where-does-my-smartphone-iphone-8-x-go-recycling-afterlife-toxic-waste-environment (last access: 19.04.2023)
18. Poschmann, H., Brueggemann, H., Goldmann, D., 2020, *Disassembly 4.0: A Review on Using Robotics in Disassembly Tasks as a Way of Automation*, Chemie Ingenieur Technik, 92(4), p. 341-359, DOI: 10.1002/cite.201900107
19. https://www.recyclingtoday.com/article/smartphone-recycling-refurbishment-attitudes-changing/ (last access: 19.04.2023)
20. https://www.forbes.com/sites/dwightsilverman/2021/02/22/apple-back-on-top-iphone-is-the-bestselling-smartphone-globally-in-q4-2020/?sh=4bd3bbe64ca7 (last access: 19.04.2023)
21. Foo, G., Kara, S., Pagnucco, M., 2022, *Challenges of robotic disassembly in practice*, Procedia CIRP 105, p. 513–518, DOI: 10.1016/j.procir.2022.02.085
22. Kunica, Z., 2016, Projektiranje proizvodnih sustava. Sveučilište u Zagrebu, Fakultet strojarstva i brodogradnje
23. Frizziero, L., Liverani, A., Caligiana, G., Donnici, G., Chinaglia, L., 2019, *Design for Disassembly (DfD) and Augmented Reality (AR): Case Study Applied to a Gearbox. Machines*, 7(2), DOI: 10.3390/machines7020029
24. https://www.indra.fr/en/home (last access: 12.04.2023)