DECISION SUPPORT FRAMEWORK USING KNOWLEDGE BASED DIGITAL TWIN FOR SUSTAINABLE PRODUCT DEVELOPMENT AND END OF LIFE

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ABSTRACT

In order to have a sustainable disassembly process, a successful decision-making based on reliable and up-to-date information should be made while taking into consideration sustainability indicators. In this context, The aim of this paper is to introduce a decision support system based on knowledge based and digital twin in order to help stakeholders to choose the most sustainable disassembly scenario .In this research, firstly, we presented the state of art of disassembly process, digital twin, knowledge based system and the merging of knowledge based system and digital twin for disassembly. Secondly, we presented the knowledge based digital twin (KBDTw) system framework for a sustainable disassembly process. Thirdly, a case study is presented about the use of KBDTw in the end-of-life of internet boxes. Finally, a conclusion and future work are conducted.

Keywords: Knowledge management, digital twin, Sustainability, Decision making, Design engineering

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1 INTRODUCTION

In the framework of sustainability and sustainable development, the disassembly process has significant potential to reduce the use and waste of raw materials, increases the utilization of resources, pollution (Liu *et al.*, 2019),(Slama *et al.*, 2020) and to increase the recycling yield and purity for precious metals, critical metals and plastics (Vanegas *et al.*, 2018a). In order to have a sustainable disassembly, the decision-making of this process should be sustainability oriented. Yet, the decision making of disassembly process should also be based on reliable and up-to-date product lifecycle information. However, due the complexity and all the uncertainties of the disassembly products (e.i. uncertain shapes, sizes, physical conditions of the materials used, etc.) (Abdullah, Popplewell and Page, 2003) and the difficulty in obtaining accurate product life cycle information once remanufacturers receive the return products (Parlikad and McFarlane, 2007). It is very important to explore new ways to make both disassembly and environmental information available to the decision makers so that they can take the necessary decisions to have the most sustainable disassembly process of end of life (EoL) products (Mouflih et al., 2022). Therefore and due to the characteristics of the knowledge based system in terms of knowledge storage and the functionalities of the digital twin (DTw) to ensure the digital continuity between the different entities in real time, the use of both of these technologies can be very helpful withing the framework of decision making of the disassembly process of EoL products. The aim of this paper is to introduce a decision support system based on knowledge based and digital twin in order to help stakeholders to choose the most sustainable disassembly scenario.

In this research, firstly, we present a state of art disassembly process, digital twin, knowledge based system and the merging knowledge based system and digital twin for disassembly. Secondly, we presented the knowledge based digital twin (KBDTw) system framework for a sustainable disassembly process. Thirdly, a use case of use of the KBDTw in the End of Life (EoL) of internet boxes is presented. Finally, a conclusion and future work are conducted.

2 STATE OF THE ART

2.1 Disassembly process

The disassembly process is a systematic approach separating a product into parts or removing its components, subsets or constructive parts (Gungor and Gupta, 1998), it is one of the most strategic processes of remanufacturing since it plays a key role in recycling of materials and components (Mok, Wu and Lee, 1999).

2.1.1 Sustainable disassembly

Sustainable disassembly requires considering simultaneously the economic, environmental and social implications associated with the disassembly of products. Most of the considered indicators in the disassembly process in the found researches are focusing mostly on economic aspects of sustainability, with low environmental and social sustainability consideration. (Kristensen and Mosgaard, 2020).

For example: (Vanegas et al., 2018b) proposed a method to assess the capability to disassemble partially or totally a product based on an indicator called "Ease of Disassembly Metric", in order to facilitate the recycling operations, reuse and repair. Also, (Das, Yedlarajiah and Narendra, 2010) created a decision making supporting index, based on time, tools, texture, access, instructions, risk and force requirements; based on "Disassembly Effort Index". And (Marconi et al., 2018) proposed a tool to evaluate efficient disassembly process for industrial products based on an indicator called "Effective Disassembly Time".

Regardless of the research conducted in order to improve the sustainability of disassembly and its decision-making. However, it is considered a very critical process due to its high degree of uncertainty caused by the unknown state of the quality and structure of products in their end of life (Gungor and Gupta, 1998). Which makes the data acquisition and availability very challenging and complicates the decision-making. One of the most promising technologies in overcoming the issues related to decision-making and the sustainable challenges of the disassembly process is the DTw.

2.2 Digital twin

The concept of DTw was firstly introduced by the National Aeronautics and Space Administration (NASA)'s Apollo program in 1962 (Boschert and Rosen, 2016). Since then, numerous explanations

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and definitions of this concept have been proposed ((Haag and Anderl, 2019), (Zhang *et al.*, 2020)). It was defined as a as a virtual model that corresponds to physical entities in the real world, based on information collection and sharing, it can simulate the behaviour and performance of the entities in real time by (Grieves and Vickers, 2017). This technology is a very good solution for manufactures to improve the manufacturing process (Gaha, Durupt and Eynard, 2020).

2.2.1 Digital twin for sustainable disassembly

The DTw technology is mainly used for monitoring, diagnostics, prognostics as well as optimization ((Cai *et al.*, 2017), (Zaccaria *et al.*, 2018)). There is only few researches that addressed the use of this technology to improve sustainability. However, (Xiang et al., 2020) studied how a DTw-driven disassembly can find the efficient sequence through optimization of the disassembly model. Also, (Wang and Wang, 2019) presented a new DTw-based system to support the manufacturing/remanufacturing operations for the WEEE recovery to empower the disassembly and remanufacturing processes.

in order to provide the digital twin with detailed information regarding the product at the end of its life and help overcoming the issues regarding the uncertainties and the decision making of the disassembly process, the DTw needs to be combined with knowledge-based system.

2.3 Knowledge based system

Knowledge based system (KBS) is a system used to store the knowledge required for a specific problem solving application. It is a structured database that contains information in order to provide support and advice, and can be applied to a variety of application fields (Petroni *et al.*, 2019),(Bordegoni, Simões-Marques and Nunes, 2014)

2.3.1 Knowledge based system for sustainable disassembly

Some researchers studied the use of the knowledge-based system in order to promote a sustainable disassembly. For example: (Poschmann, Brüggemann and Goldmann, 2021) presented a cognitive robotic system is presented which is capable of integrating individual product lifecycle data to decide upon the actual degree of disassembly in regard to the most suitable EoL utilization option. (Terazono *et al.*, 2012) studied the advantages of sharing the recycling knowledge among stakeholders of the same sector. (Babbitt *et al.*, 2020) presented a comprehensive database of bill of material (BOM) data describing the mass of major materials and components contained in 95 unique consumer electronic products. Also, in order to optimize the waste management, (Lederer *et al.*, 2015) presented a method to gather knowledge from the stakeholders of dismantling sector. (Reyes-Córdoba, Sharratt and Arizmendi-Sánchez, 2008) presented a framework of a tool to present the knowledge of dismantling processes. To give robots knowledge about how to disassemble a product, (Vongbunyong, Kara and Pagnucco, 2013) have used knowledge bases for storing historical disassembly information and the robots can flexibly deal with their current disassembly tasks using the stored data.

2.4 Merging knowledge based system & digital twin for disassembly

Not many studies have investigated the use of knowledge based system and digital twin for disassembly process. (Ladj *et al.*, 2021) presented a knowledge-based Digital Shadow, as a core component and the backbone of future Digital Twin applications in manufacturing. Also, (Kostenko *et al.*, 2018) presented digital twins' applications in static and dynamic diagnostics tasks' solution and showed the usage of a knowledge based management system for static diagnostics task solution.

Despite the big potential gain that the merging of knowledge based system and digital twin technologies can offer to adopt a sustainable approach and to improve the sustainability of EoL of products specially the disassembly process, till this day no research on this specific area has been found.

3 KNOWLEDGE BASED DIGITAL TWIN FOR SUSTAINABLE DISASSEMBLY FRAMEWORK

In order to improve the sustainability of EoL products and resolve the issues due to lack of necessary lifecycle information that lead to not the optimum decision making (Parlikad and McFarlane, 2007), our proposition consists of a decision support tool based on knowledge based system and digital twin.

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Using the functionalities of data collection and sharing for monitoring, diagnostics, prognostics as well as optimization of the DTw and knowledge required for the decision-making provided by the KBS. The KBDTw system aims to help stakeholders choose the most sustainable disassembly scenario of EoL products.

3.1 The running of the knowledge based digital twin for sustainable disassembly framework

Our approach is based on the hypothesis that products in their EoL are returned to the manufacturer for remanufacturing. In addition, the manufacturer performs all maintenance and repairing operations.
The methodology for sustainable disassembly based on knowledge based digital twin consists on seven steps as shown in Figure 1, which are identified as follow:

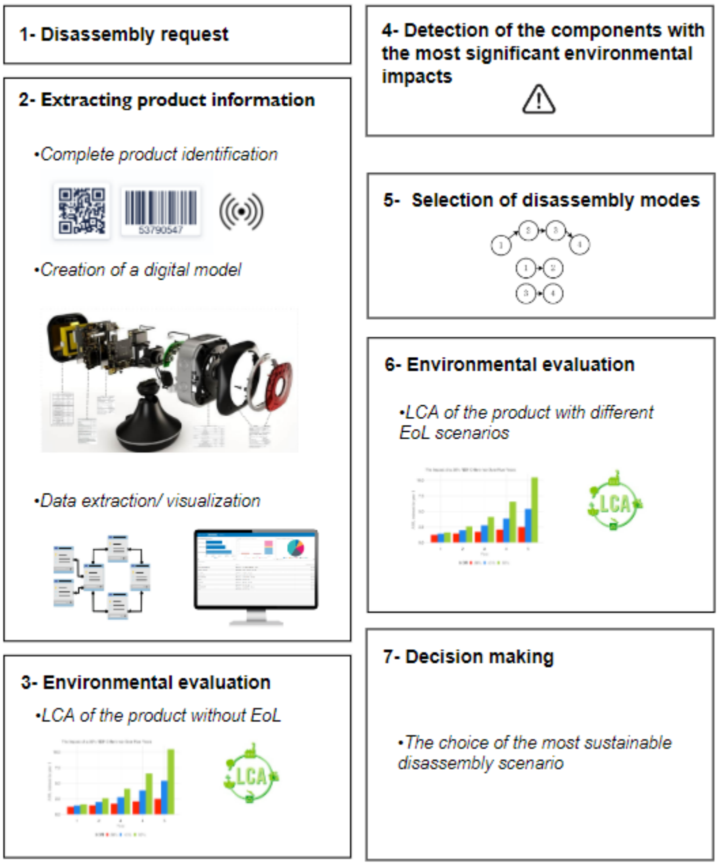

Figure 1. Proposed sustainable disassembly methodology

Step 1: After the return and cleaning of the products the disassembly step is requested either manually by an operator or automatically.
Step 2: In the extracting product information phase, the product is firstly identified by its serial number or QR code in order to extract all the data stored during its lifetime. All the information about the products use phase such as maintenance, date of its beginning of operation, changed components, etc. are stored in an independent database related to each product and constantly filed and updated during the products lifecycle by the manufacturer that is supposed to intervene in all the maintenance and repairing operations.
Once the data of the product is extracted, the digital model linked with all this data is created.
Then all the data related to the other life cycle steps of the products are extracted from the knowledge based in order to proceed the first environmental evaluation.
Step 3: Using all the data available in the system (all lifecycle products data and process data as shown in the Figure 2), the first environmental evaluation is proceeded without the EoL step in order to detect the components with the most significant environmental impact independently of the EoL scenarios.
Step 4: Based on the results of the environmental evaluation, all the components with high environmental impacts are detected.

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Step 5: The decision makers rely on the results of the previous steps in order to identify different disassembly scenarios.
Step 6: A complete environmental evaluation with all the products life steps including the different EoL scenarios previously selected.
Step 7: Based on the results of Step 5, the stakeholders can choose the most sustainable disassembly scenario.

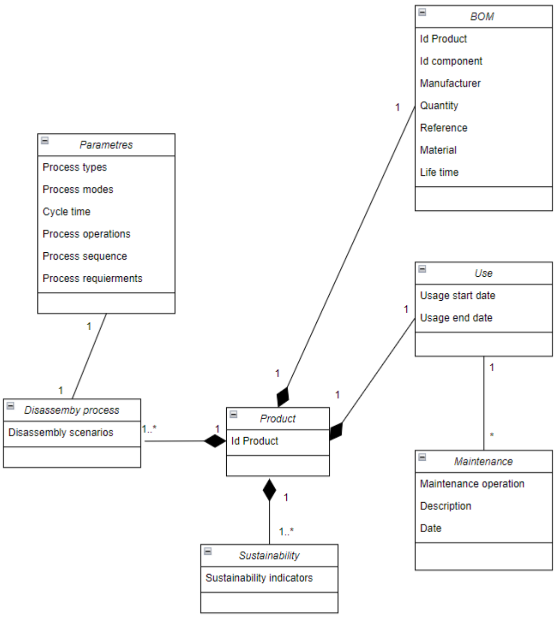

Figure 2. Class model of the knowledge based of the KBDTw

3.2 System description

The KBDTw consists of operators/ stakeholders, disassembly machines/ tools, sensors/ cameras, knowledge based, digital model and LCA tool. These components are distributed in physical world and Knowledge based digital twin which can provide in firstly data visualization (the visualization of the data about the products states and recycling rate of components), secondly it provides the environmental impact assessment simulation (which consists of LCA of the product without and with different EoL scenarios) and finally the decision support (by detecting the components with the most significant environmental impacts and most sustainable disassembly scenarios) as shown in Figure 3.

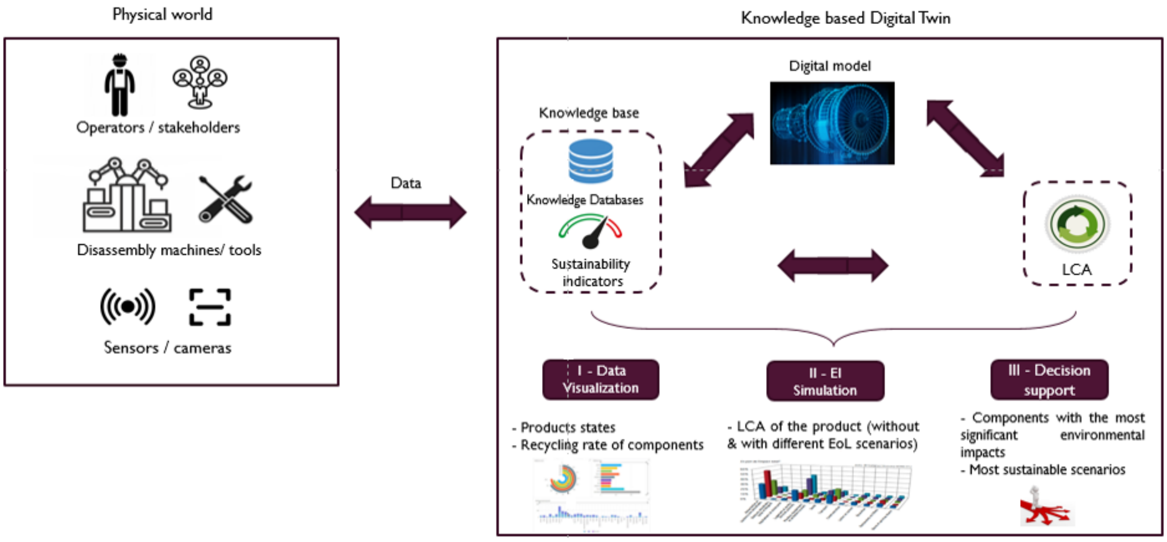

Figure 3. KBDTw framework

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As shown in the figure 3, KBDTw system has three main contributions: the data visualization, EI simulation and decision aid.

The data visualization: In the step of products' data extraction, the KBDTw system provides a complete visualization of the products information extracted from the product database and the knowledge based and the digital model.

EI simulation: The KBDTw provides the environmental impact assessment simulation, which consists of LCA of the product without and with different EoL scenarios.

Decision support: the system helps with the decision support by detecting the components with the most significant environmental impacts and most sustainable disassembly scenarios.

3.3 Case study

The case study consists of the integration of the proposed approach within the framework of the end of life of an internet box.

3.3.1 EoL of an internet box

An internet box contains plastic cover and electronic components. Its EoL is as follow (Ophéli, 2020) (Figure 4):

After receiving and unloading the boxes, they are sent to a sorting area. (sorting of accessories, different models of boxes, etc.) If the model is declared obsolete by the operator, the device is put directly into the recycling path. In the circuit of treatment of the boxes at the end of life, there are 4 particular zones: a zone of tests of functioning, a zone of repairing, a zone of levelling and a zone of reconditioning.

In the test area, the units are fully tested with a visual check of the plastic shells to detect damaged shells to a repair shop. If the test station detects a problem with at least one component of the device, it is sent to the repair area. Often, a component or shell change will solve the problem and the device is returned to the reconditioning circuit. If not, they go to a specific container that is sent to the manufacturer for repair. In the upgrading area, the devices are updated with the latest firmware version and the configuration parameters (identification number, box name, security key,...) are reset on dedicated stations. Then, the boxes are cleaned and a new label with the new information is put on. The refurbished device is installed in a new cardboard box with the necessary accessories. And finally, quality control on randomly selected devices is carried out. The boxes are then repacked and ready for reshipment.

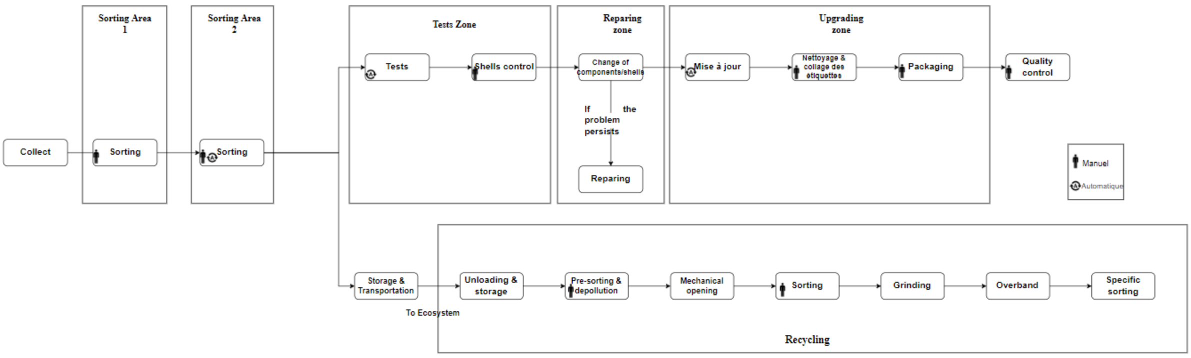

Figure 4. EoL of internet boxes

3.3.2 The use of KBDTw in the EoL of the internet boxes

The KBDTw will allow having all the necessary information in order to choose different valorisation strategies and disassembly scenarios after the second sorting area (Figure 5). Which means that instead of the obsolete boxes going directly to the recycling without favouring the use of their functional parts and components, the remanufacturer will have all the necessary data related to all the lifecycle of the internet box in order to identify the parts still reusable and if it is necessary to reuse them.

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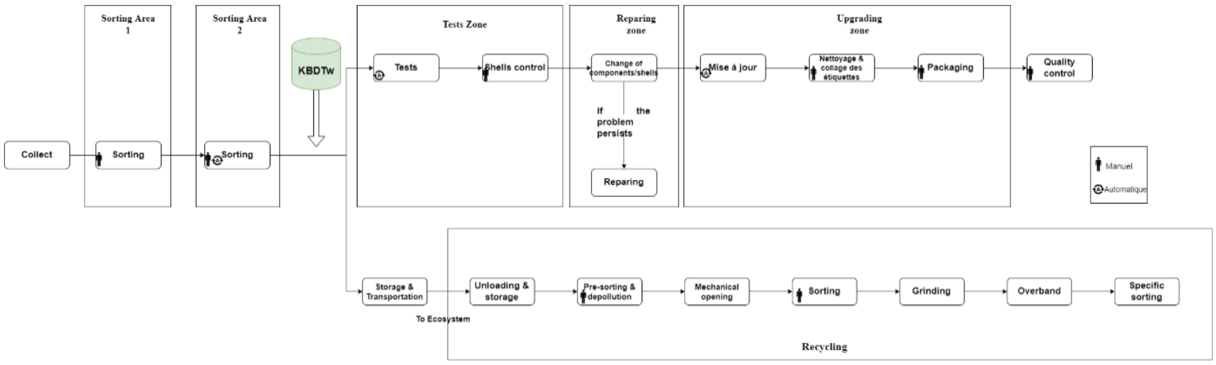

Figure 5. EoL of internet boxes with KBDTw

Following the KBDTw steps explained in the third section of the paper. The EoL of the internet box will go as follow:

After the request of the disassembly step, the internet box is firstly identified by a QR code and all the data stored during its lifetime (Table 1) is extracted.

Once the data of the product is extracted, the digital model linked with all this data is created.

Then all the data related to the other life cycle steps of the products are extracted from the knowledge based in order to proceed the first environmental evaluation.

Using all the data available in the system (e.g. components, materials, middle life data, etc.), the first environmental evaluation is proceeded without the EoL. The environmental evaluation of the results shown in the figure 7 is proceeded with a LCA software called SimaPro (Figure 6), using the databases “Ecoinvent 3” and “Methods” and “IMPACT 2002+” method. In order to conduct this environmental evaluation, only 4 steps of the internet box lifecycle were taken into consideration in this study (raw material extraction, manufacturing, distribution and the use). All technical information were extracted from different internet supplier. We also supposed that the internet box served 3 years non-stop in France with zero maintenance operation.

Table 1. Example of product data extracted via QR code

Box Id	g5h77j3	
Model	Box5	
date of first use	20/01/2017	
date of the end of use	20/01/2020	
Repaired components/ parts	Name of the component/ part	Date of the operation
	None	***
Changed components/ parts	Name of the component/ part	Date of the operation
	USB port 3	03/04/2019
Other maintenance operations	Name of the component/ part	Date of the operation
	Box cleaning	03/04/2019

Based on the results of the environmental evaluation, the components with high environmental impacts in terms of global warming are the components of the PCB. The decision makers now should be able to identify different disassembly scenarios in order to promote the repair and reuse of the PCB parts.

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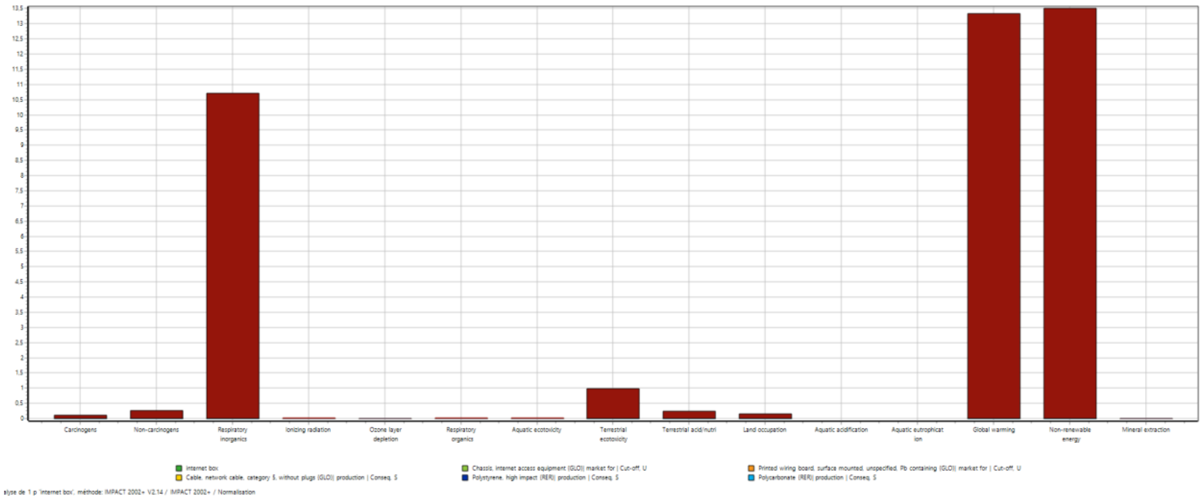

Figure 6. LCA results of an internet box without EoL step

Now that the disassembly scenarios are identified, a complete environmental evaluation with all the products life steps including the different EoL disassembly scenarios is proceeded in order to help the stakeholders to choose the most sustainable disassembly scenario and if the internet box should go directly to recycling or follow the repair and reuse of the PCB parts path.

4 CONCLUSION AND FUTURE WORK

This research work presents an introduction to a knowledge based digital twin for sustainable disassembly decision support system, which aims to help the stakeholders with the decision making in order to choose the most sustainable disassembly scenario. KBDTw should enable decision-making based on different information collected and gathered together from all the product lifecycle (using sensors, product trucking, digital twin data, etc.) and different other sources (e.g. legislation, process data, etc.) based on different sustainable indicators. At present, the research is in the initial stage, so future research directions will target all the specifications regarding the KBDTw system (e.g. its functioning, the data required, data sources, type of data, etc.).

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REFERENCES

Abdullah, T. A., Popplewell, K. and Page, C. J. (2003) “A review of the support tools for the process of assembly method selection and assembly planning”, *International Journal of Production Research. Taylor & Francis Group*, pp. 2391–2410. https://doi.org/10.1080/002075431000087265.

Babbitt, C. W. et al. (2020) “Disassembly-based bill of materials data for consumer electronic products”, *Scientific Data*, pp. 1–8. https://doi.org/10.1038/s41597-020-0573-9.

Simões-Marques, M., Nunes, I. (2022) “Application of a User-Centered Design Approach to the Definition of a Knowledge Base Development Tool”, *13th International Conference on Applied Human Factors and Ergonomics*, USA, AHFE Open Access, rancisco Rebelo and Marcelo Soares (eds) Advances in Ergonomics In Design, Usability & Special Populations: Part II . https://doi.org/10.54941/ahfe1001259.

Boschert, S. and Rosen, R. (2016) “Digital twin-the simulation aspect", Mechatronic Futures: Challenges and Solutions for Mechatronic Systems and Their Designers, Springer, Cham, pp. 59–74. https://doi.org/10.1007/978-3-319-32156-1_5.

Cai, Y. et al. (2017) “Sensor Data and Information Fusion to Construct Digital-twins Virtual Machine Tools for Cyber-physical Manufacturing”, *Procedia Manufacturing*. Elsevier B.V., pp. 1031–1042. https://doi.org/10.1016/j.promfg.2017.07.094.

Das, S. K., Yedlarajiah, P. and Narendra, R. (2000) “An approach for estimating the end-of-life product disassembly effort and cost”, *International Journal of Production Research*, Vol. 38 No. 3, pp. 657–673. https://doi.org/10.1080/002075400189356.

https://doi.org/10.1017/pds.2023.116 Published online by Cambridge University Press

Gaha, R., Durupt, A. and Eynard, B. (2020) “Towards the implementation of the Digital Twin in CMM inspection process: Opportunities, challenges and proposals”, *Procedia Manufacturing*, pp. 216–221. https://doi.org/10.1016/j.promfg.2021.07.033.

Grieves, M. and Vickers, J. (2017) “Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems”, *Transdisciplinary Perspectives on Complex Systems: New Findings and Approaches*, Springer, pp. 85–113. https://doi.org/10.1007/978-3-319-38756-7_4.

Gungor, A. and Gupta, S. M. (1998) “Disassembly Sequence Planning for Products with Defective Parts in Product Recovery”, *Computers and Industrial Engineering*, Vol. 35 No. 1–2, pp. 161–164. https://doi.org/10.1016/S0360-8352(98)00047-3.

Haag, S. and Anderl, R. (2019) “Automated Generation of as-manufactured geometric representations for digital twins using STE”, *Procedia CIRP*, pp. 1082–1087. https://doi.org/10.1016/J.PROCIR.2019.04.305.

Kostenko, D., Kudryashov, N., Maystrishin, M., Onufriev, V., Potekhin, V. and Vasilev, A. (2018) “Digital twin applications: Diagnostics, optimisation and prediction”, A*nnals of DAAAM and Proceedings of the International DAAAM Symposium*, pp. 0574–0581. https://doi.org/10.2507/29th.daaam.proceedings.083.

Kristensen, H. S. and Mosgaard, M. A. (2020) cA review of micro level indicators for a circular economy – moving away from the three dimensions of sustainability? ”, *Journal of Cleaner Production*, Vol. 10. https://doi.org/10.1016/J.JCLEPRO.2019.118531.

Ladj, A., Wang, Z., Meski, O., Belkadi, F., Ritou, M. and Da Cunha, C. (2021) “A knowledge-based Digital Shadow for machining industry in a Digital Twin perspective”, *Journal of Manufacturing Systems*, Vol. 58, Part B, pp. 168–179. https://doi.org/10.1016/j.jmsy.2020.07.018.

Lederer, J., Ongatai, A., Odeda, D., Rashid H., Otim S. and Nabaasa, M. (2015) “The generation of stakeholder’s knowledge for solid waste management planning through action research: A case study from Busia, Uganda”, *Habitat International*, Vol. 50, pp. 99–109. https://doi.org/10.1016/j.habitatint.2015.08.015.

Liu, Q., Liu, Z., Xu, W., Tang, Q., Zhou, Z., and Truong Pham, D. (2019) “Human-robot collaboration in disassembly for sustainable manufacturing”, *International Journal of Production Research*, Vol. 57 No. 12, pp. 4027–4044. https://doi.org/10.1080/00207543.2019.1578906.

Marconi, M., Germani, M., Mandolini M., and Favi, C., (2018) “Applying data mining technique to disassembly sequence planning: a method to assess effective disassembly time of industrial products”, *International Journal of Production Research*, Vol. 57 No. 2, pp. 599–623. https://doi.org/10.1080/00207543.2018.1472404.

Mok, S. M., Wu, C. H. and Lee, D. T. (1999) “A hierarchical workcell model for intelligent assembly and disassembly”, *Proceedings - 1999 IEEE International Symposium on Computational Intelligence in Robotics and Automation, CIRA* 1999, pp. 125–130. https://doi.org/10.1109/cira.1999.809989.

Mouflih, C., Gaha, R., Durupt, A. and Eynard, B. (2022) “Sustainable end of life for mechanical product: Literature review on sustainability indicators and dismantling processes”, *in Proceedings Congrès Français de Mécanique* 2022.

Ophéli, J. (2020) A Montauban, Orange reconditionne son matériel (Livebox, Décodeur TV,...). Available at: https://selectra.info/telecom/actualites/acteurs/orange-reconditionne-materiels (Accessed: 29 July 2022).

Parlikad, A. K. and McFarlane, D. (2007) “RFID-based product information in end-of-life decision making”, *Control Engineering Practice*, Vol. 15 No. 11, pp. 1348–1363. https://doi.org/10.1016/j.conengprac.2006.08.008.

Petroni, F., Rocktäschel, T., Riedel, S., Lewis, P., Bakhtin, A., Wu, Y. and Miller, A. (2019) “Language models as knowledge bases?”, *Proceedings of the 2019 Conference on Empirical Methods in Natural Language Processing and the 9th International Joint Conference on Natural Language Processing (EMNLP-IJCNLP)*, pp. 2463–2473. https://doi.org/10.18653/v1/d19-1250.

Poschmann, H., Brüggemann, H. and Goldmann, D. (2021) “Fostering End-of-Life Utilization by Information-driven Robotic Disassembly”, *Procedia CIRP*, Elsevier, pp. 282–287. https://doi.org/10.1016/j.procir.2021.01.104.

Reyes-Córdoba, A. P., Sharratt, P. N. and Arizmendi-Sánchez, J. A. (2008) “Contribution of knowledge management for the implementation of waste minimisation measures into process industries”, *Process Safety and Environmental Protection*, Vol. 86 No. 5, pp. 375–388. https://doi.org/10.1016/j.psep.2008.02.002.

Slama, I., Ben-Ammar, O., Dolgui, A. and Masmoudi, F. (2020) “Approches d’optimisation pour un problème de planification de désassemblage sous incertitude des délais de désassemblage”, *Génie industriel et productique*, Vol. 3. https://doi.org/10.21494/ISTE.OP.2020.0578.

Terazono, A., Oguchi, M., Yoshida, A., Takigami, H., Agusa, T., Balles-teros, F.C. and Fujimori, T. (2012) “E-waste recycling in Asia: Process classification, environmental effect and knowledge sharing”, Proceeding 2012 Electronics Goes Green 2012+}, pp. 1-6.

Vanegas, P., Peeters, J., Cattrysse, D., Tecchio, P., Ardente, F., Mathieux, F., Dewulf, W. and Duflou, J. R. (2018) “Ease of disassembly of products to support circular economy strategies”, *Resources, Conservation and Recycling*, Vol. 135, pp. 323–334. https://doi.org/10.1016/j.resconrec.2017.06.022.

Vongbunyong, S., Kara, S. and Pagnucco, M. (2013) “Basic behaviour control of the vision-based cognitive robotic disassembly automation”, *Assembly Automation*, Vol. 33 No. 1, pp. 38–56. https://doi.org/10.1108/01445151311294694.

Wang, X. V. and Wang, L. (2019) “Digital twin-based WEEE recycling, recovery and remanufacturing in the background of Industry 4.0”, *International Journal of Production Research*, Vol. 57 No. 12, pp. 3892–3902. https://doi.org/10.1080/00207543.2018.1497819.

Wiendahl, H. P., Seliger, G.,Perlewitz, H.- and Bürkner, S. (1999) “A general approach to disassembly planning and control”, *Production Planning and Control*, Vol. 10 No. 8, pp. 718–726. https://doi.org/10.1080/095372899232542.

Xiang, F., Huang, Y., Zhang, Z. and Zuo, Y. (2020) “Digital twin driven energy-aware green design”, *Digital Twin Driven Smart Design*, Elsevier, pp. 165–184. https://doi.org/10.1016/b978-0-12-818918-4.00006-3.

Zaccaria, V., Stenfelt, M., Aslanidou, I., and Kyprianidis, (2018) “Fleet monitoring and diagnostics framework based on digital twin of aero-engines”, *Proceedings of the ASME Turbo Expo*, Vol. 6. https://doi.org/10.1115/GT2018-76414.

Zhang, M., Sui, F., Liu, A., & Tao, F. and Nee, A. (2020) “Digital twin driven smart product design framework”, *Digital Twin Driven Smart Design*. *Academic Press*, pp. 3–32. https://doi.org/10.1016/b978-0-12-818918-4.00001-4.