Introducing the concept of repurposing robots; to increase their useful life, reduce waste, and improve sustainability in the robotics industry

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Based on current definitions of electronic waste, the robotics industry faces a future where products created for both business and consumer markets could be required to meet regulations to manage the control of electronic products at the end of their primary life (e-waste). This paper proposes the new concept of repurposing robots; where a robot at the end of its primary life is repurposed into a new, secondary role, in a process which is generally independent of the Original Equipment Manufacturer [OEM]. By repurposing robots, future waste streams are reduced and the sustainability of the industry is increased. Outlining this new area of work, the authors highlight potential challenges to repurposing which are summarised as topics for future investigation.

1. INTRODUCTION

As electronic waste builds up across the globe, the robotics industry must take responsibility for the current and future waste streams created by the production of robots for business and consumer markets. The open-loop system of designing, producing, using and then discarding electronic products is not sustainable. An open-loop consumer culture harms not only people but the planet around us[1] and can be linked to depletion of natural resources, deforestation,[2] destruction of animal habitats, and pollution of the environment, whether through material leaching or breakdown of plastics into microplastics.[3,4]

While there are many examples of robots being used and developed for the management of other product waste within the recycling and disposal industries,[5–10] little has been written about what happens to robots and autonomous systems at the end of their useful life, when they themselves become product waste. Papers on this topic include Nguyen and Seibel[11] who present the mechanical properties of soft robotic actuators manufactured via recycling of other soft robot actuators; and Steinhilper et al.[12] which demonstrates the application of Steinhilper's remanufacturing process[13] to upcycle a handheld terminal for an industrial robot. This minimal available content reflects the relative infancy of the industry and the limited robotic products currently in circulation. However, as trends in robot number increase, the levels of research and business resource spent on the topic of sustainability must increase.

When making decisions regarding product sustainability, consumers themselves (whether businesses or individuals) are unlikely, when left to their own devices, to make a significant impact in making sustainable choices.[14] Instead, Original Equipment Manufacturers [OEMs] should aim to minimise the environmental impact of their products as part of a commitment to Responsible Innovation.[15,16] Currently, the most accessible method to do this is to recover products at the end of their life by recycling the products at a material level. However, recycling is still very environmentally wasteful, with useful systems being broken down into individual components and materials. We only have to look at the commonly used Three Rs – Reduce, Reuse, Recycle[17] to see that this hierarchy places Reuse above Recycling.

This paper firstly argues the need to create a closed-loop system for the robotics industry, based on lessons learnt from the management of other e-waste (Section 2). Secondly, it outlines the options for the management of robotic systems as waste products themselves in Section 3, including presenting the new area of investigation - repurposing. Lastly, it presents the challenges of repurposing robotic systems and areas for future work (Section 4).

2. THE GROWING PILE OF E-WASTE

2.1. *Current e-waste levels*

Products are considered Waste Electrical & Electronic [WEEE] or e-waste when they have reached the end of their useful life and are discarded in a manner where they will not be reused.[18–20] While definitions vary, Electronic & Electrical Equipment [EEE] is described, in general, as any product requiring electrical current or electromagnetic fields to meet its functional purpose.[21] E-waste covers a wide range of products, and examples include: PV panels, professional and household heating systems, washing machines, TVs, printers, photocopiers, mobile phones, toys, non-implanted medical equipment and automated dispensers.[18,22] It includes all "components, sub-assemblies and consumables which are part of the product at the time of discarding".[21] These lists do not currently include robots and autonomous systems[18,21] and so are not in the scope of current regulations.

Not only are current and historic e-waste levels already worryingly high,[18,19,22–25] but levels of e-waste are also predicted to continue to increase. Savage et al.[26] and Babu et al.[22] predict between three and five percent increase in e-waste year on year within the EU; while Sthiannopkao and Wong[19] predict an increased annual rate between five and ten percent. In 2019 alone, 53.6 million metric tons [Mt] of e-waste were produced globally and predictions by[18] expected this to rise to 74.7Mt by 2030. This is the equivalent of 7.3kgs of e-waste globally produced per capita in 2019 and 9.0kgs in 2030, though levels vary significantly by continent (see Figure 1).

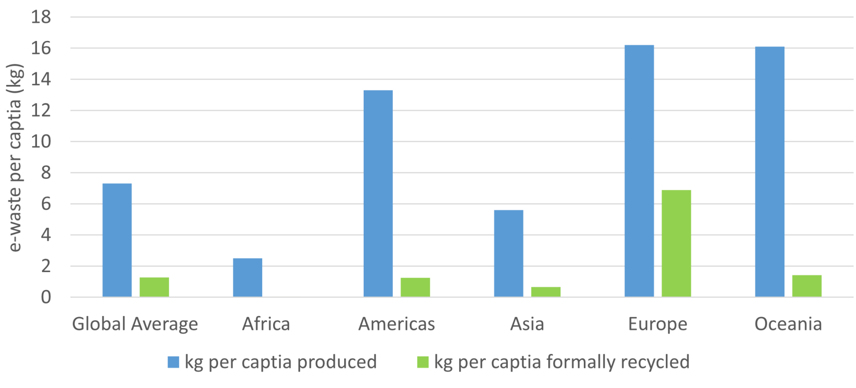

Fig. 1. Global levels of e-waste produced and recycled through formally managed waste systems in 2019[18]

2.2. *Why recycling is not good enough*

The United Nations University and collaborators present in their publication The Global E-Waste Monitor 2020[18] four different routes in which e-waste is collected and managed.

These routes are summarised in Figure 2. Only scenario 1 presented in Figure 2 shows the correct management of e-waste. Across the globe, only 40 percent of countries have some form of legislation relating to the proper management of e-waste (scenario 1, Figure 2). However, even with legislation in place, this fails to guarantee the correct management of waste. In the EU, where recycling rates are the highest of any continent (see Figure 1) only 42.5 percent of e-waste follows this route, while 8 percent is discarded directly into municipal waste. Overall, only 17.4 percent of the world's annual production of WEEE is recycled.[18]

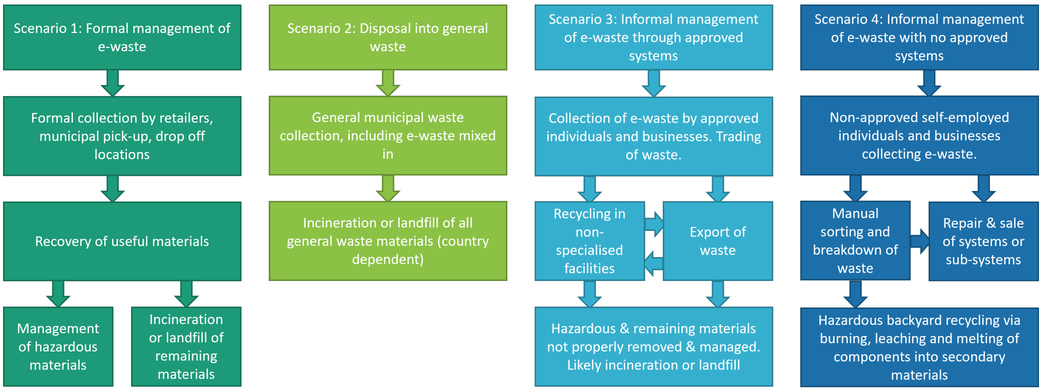

Fig. 2. A summary of the four waste management scenarios presented in The Global E-Waste Monitor 2020[18]

In scenarios 2, 3 and 4, inadequate management of WEEE results in the possibility of harmful substances coming into contact with humans and the environment. E-waste sent directly to landfill accounts for 40 percent of lead and 70 percent of heavy metals found in those locations.[22] In addition, large amounts of waste end up in developing countries via exports where approved management systems are either not in place or not overseen. Here, where one percent of the population uses waste salvaging as a source of income, people are put in direct contact with harmful substances through waste salvaging and 'backyard recycling' where waste is burnt, leached and melted into resalable materials.[18,19,22]

Knowing that so little of the e-waste intended for recycling actually makes it through controlled waste management schemes, businesses need to consider alternative end-of-life options for e-waste in order to meet future sustainability expectations and requirements.

2.3. *When robots become e-waste*

Robots and autonomous systems are not currently included in the lists of in-scope products which must meet EEE and WEEE legislation. However a robot, by definition, is a "programmed actuated mechanism with a degree of autonomy to perform locomotion, manipulation or positioning".[27] Where the power mechanism used to provide locomotion, manipulation or positioning to the system is electrical, it can be concluded that robots meet the general definitions of EEE.

At the time of publishing of the EU Directive in 2002, most robotic systems were generally limited to industrial settings where they could be classed within the 'large stationary tools' category which is exempt from the directive.[21] However, as technology develops, the use of robots is evolving from stationary manufacturing roles into service-based roles[28] which, whether used in the home or in a professional setting, could be considered to be e-waste when they cease to be required or able to perform their original function.

In addition, the rate of growth of robotic products entering the consumer and business markets will likely result in greater scrutiny of robots as waste products when they reach the end of their life. Taking only the service sector (including service robots in professional and domestic settings[29]), the International Federation of Robotics [IFR] reported a 12 percent increase in the service robot market in 2020 and also noted that 17 percent of the robot suppliers surveyed in this sector were start-ups.[30] The report observed that the majority of the start-ups, and a large number of the established businesses, had products still in the development stage that were not available for commercial use.[30] This growth in the robotics market is further supported by market analysts, Mordor Intelligence LLP, who predict the domestic robot market globally will increase from 6.8bn USD in 2021 to 21.9bn USD by 2027.[31]

Businesses and research groups working within the robotics industry, therefore, have the opportunity to anticipate the inclusion of robotic products in future e-waste definitions ahead of any potentially related legislation. In addition, opportunities for designing for a circular economy will be easier to introduce during the early stages of a product development life-cycle, rather than retrofitting to meet requirements. The book 'Designing for the Circular Economy' notes that 80 percent of a product's environmental impact is determined at the early stages of product development.[32]

The unique characteristics of a robotic system over other 'dumb' electronic products mean that, beyond the option for recycling, robots have the potential to be reused and repurposed into secondary uses which may be significantly different from their original primary function.

3. REPURPOSING AND THE ALTERNATIVE Rs

3.1. *Definition for repurposing a robot*

The authors propose the repurposing of a robot is defined as: **providing new utility to an existing robotic system in order to give the system a new role which is independent of the robot's original utility**. In this definition, a robot's utility is comprised of:

- Skill - the tasks which the robotic system is capable of completing, and
- Application - the context in which the robotic system is capable of functioning.

Therefore, both the skill and application of the robot must be changed in order to meet the definition of repurposing. This is supported by the British Standards Institute's general definition of repurposing, where a product or component is utilised 'in a role that it was not originally designed to perform'.[20] In order to change the skill and application of the robotic system, resources in the form of time and/or cost must be applied.

Using this definition, an example of repurposing would be to take an industrial robot that had previously been used in a production line and repurpose it into one which could be utilised in a hospital setting collecting waste. In this example, in its primary life, the robotic arm would have been required to place fixtures into a product at high speeds and high accuracy. Once its performance levels could no longer be maintained, the robot would be considered to be at the end of its primary life. By integrating the original robotic system onto a mobile base, adding vision systems and improving safety protocols, the robot could be repurposed to collect and sort waste in a hospital setting. This example meets the proposed definition of repurposing as both the skill and the application in which the robotic system have changed and it would no longer be able to meet the utility requirements of the original system. This example is further illustrated in stages A and C in Figure 3.

Repurposing in this way is unique to robotic systems in comparison to other electronic devices. A robot, by its definition (Section 2.3), can be totally reprogrammed to change its skill which, with the application of additional hardware, enables it to work in a new appli-

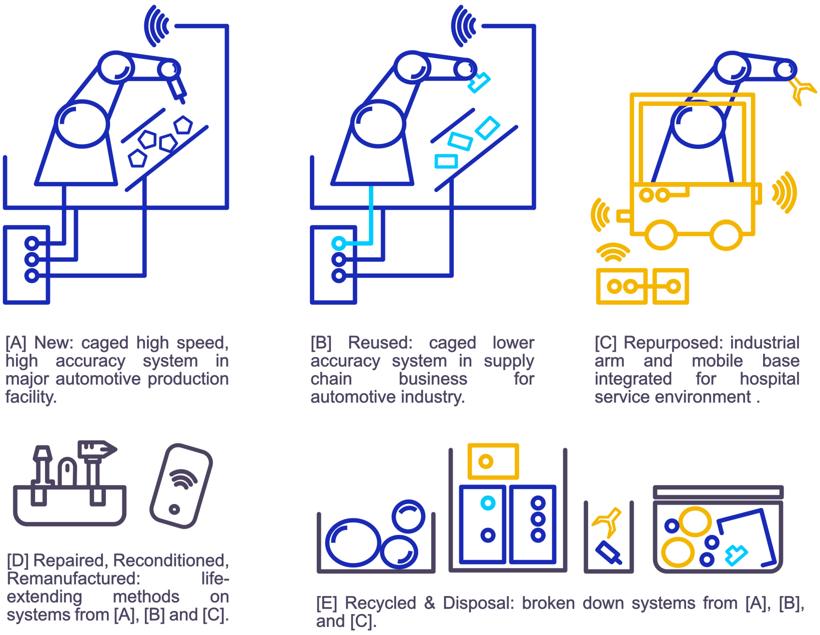

Fig. 3. Examples of repaired, reused, repurposed and recycled robotic products based on an original use as an industrial robotic arm

cation. This can be compared to the way that humans can re-skill themselves by learning new skills and taking on new tools in order to take on a role in a different sector or industry to the one they originally worked in. Many robots designed for both domestic and industrial applications should also be able to complete this transformation through repurposing. In comparison, a phone or smart washing machine might be re-programmable, but they would need to be broken down into component or sub-system level, and rebuilt into an entirely new system in order to fundamentally change their skill or application.

3.2. *Alternatives to repurposing*

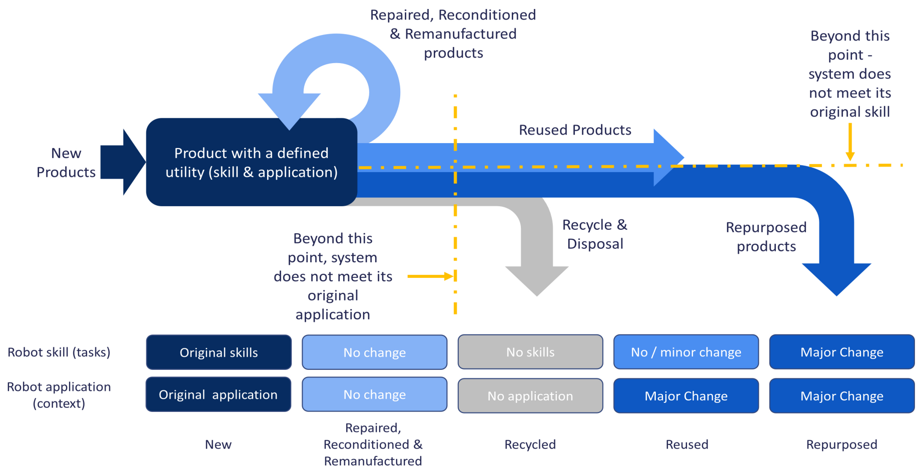

Fig. 4. A flowchart of waste management routes for robots at the end of their primary life with a comparison of skills and application.

Alongside repurposing, there are a number of alternative management routes which can be used for robotic waste at the end of its primary life; recycling and disposal, repair, remanufacturing and reconditioning, and reuse. These processes, are far better established and can be described as follows:

- Repair - where work completed by either the product owner, OEM or independent service provider returns the product to a working condition following damage or wear.[20] Following the repair, the product will meet all or most of the original utility requirements (skill and application) of the robot, though it is possible for some functionality to be lost over time. However, repairs must bring the system up to an acceptable working level, as set by the customer's requirements. Repair is illustrated by stage D in Figure 3.
- Recondition - an intermediate between repair and remanufacture where, before failure occurs, components or subsystems are repaired, returning the product to a good working condition.[20] Like repair, there may be some functionality performance loss to the original specification. Reconditioning can also be referred to as refurbishing[20] and for the purpose of this paper will be included within the concept of repair. Reconditioning is illustrated by stage D in Figure 3.
- Remanufacture - where a product is split and disassembled to component level; and components are then inspected, tested, and repaired or replaced if necessary, before reassembling.[12,13,33] In this way, the robotic product is up-cycled, with the resulting product meeting, as a minimum, the utility condition of the original product specification. During this process, it can be useful to upgrade beyond the original specification to the new accepted standard - whether this is hardware or software improvements. Remanufacture is illustrated by stage D in Figure 3.
- Reuse - where a robotic product of a given utility is placed into a new application (context). This may require minor changes to both hardware and software of the original product in order to meet the new, secondary, role. Though generally, the robot will still meet the skill functionality of the original design. A product that has been reused is capable of returning to its original application with only minor changes to its hardware or software. Reuse is illustrated by stage B in Figure 3.
- Recycle and disposal - where both working and irreparable products are disposed of either into landfill or to be recycled. During the recycling process, products are broken down into useful parts and materials for reuse at the material or component level. Products that are sent for recycling and disposal are no longer able to meet their original utility conditions following the completion of this process. Recycling and disposal are illustrated by stage E in Figure 3

Figure 4 demonstrates the flow of robotic products as they reach the end of their primary life, based on the selected waste management route. For each route the change in skill and application in comparison to the original utility is given. In addition, Figure 3 provides an example for how each management route (recycling and disposal, repair, remanufacturing and reconditioning, reuse, and repurposing) could be applied to an industrial robot arm.

It should be noted individuals and businesses may retain or store their old robotic systems at the end of their useful life. The habit of retention of old tech arises from a perception that old electronics have intrinsic value that may be realised at a later date[22] and is commonly referred to as hibernation - the difference between the total time an electronic product is owned and the total time it is used.[34,35] The United States Environmental Protection Agency calculated in 2020 that 70 percent of consumer waste electronics were stored for a period of three to five years following the end of their use.[22] Note that this figure does not currently include consumer robots. However, should robots also be hibernated in this way at the end of their primary life, their utility would be negatively affected; retaining their skill value but losing all application. At any point, the hibernated robotic system could be repaired, refurbished, remanufactured, reused, repurposed or recycled, thereby giving it a new life. For this reason, stored robotic systems are not included in their own category within the scope of the defined management routes for robots at the end of their primary life and are not included in either Figure 4 or Figure 3.

4. CHALLENGES TO REPURPOSING

Of the routes available to manage a robot at the end of its primary life, repair and reconditioning are the most accessible options for a business currently. In general, both the OEM's and independent service providers are able to carry out repair and reconditioning work making it an accessible option for nearly all robotic systems. In comparison, remanufacturing has yet to become well-established in the robotics industry. However, as more robots reach the end of their primary life, it is likely that remanufacturing will become a more commercially attractive option for those who wish to maintain value in a robot investment without the outlay for new systems. Alternatively, should a robot reach the end of its primary life and the robot owner no longer requires the system but still considers it has available utility, reuse is an already established option. Individuals are able to purchase used robotic systems through resale either directly with the owner or via brokers and auctioneers. The new owner must invest in the system in order to make minor changes to the utility of the robot, while the original owner sees a partial return on the original purchase costs. Lastly, should repair, reconditioning, remanufacturing or reuse not be possible, then it is currently only possible to recycle and/or dispose of the system through verified processes.

As recycling and/or disposal has been demonstrated to remove all available utility within the robotic system, the resource that was placed into the system as part of its design and manufacture is lost. However, if repurposing can be made a viable and functional option for systems at the end of their primary life, it would further delay the point at which a robotic system would require being broken down into residual components or sub-systems for recycling or disposal, thereby reducing annual waste production levels and increasing product life.

Repurposing is an entirely new field of study in the area of robotics. As such, it naturally faces a number of challenges, which must be explored in order to demonstrate successfully the process and the potential of repurposing a robotic system. A number of these challenges will be addressed in future work, and are outlined in Sections 4.1 to 4.3.

4.1. *Viability*

In order to evaluate the suitability of a system for repurposing, a method must be created to show the viability of repurposing that given system; this entails presenting the ease of repurposing the system versus the expected utility received from completing the repurposing process. This evaluation would produce a repurposability metric. Figure 5 proposes an example relationship between utility (y-axis) and cost (x-axis) for repurposing a robotic system which requires interrogation in future work. Here the utility is shown as a percentage calculated against a like-new system, where the cost of a new system is also known. In scenario A (of Figure 5) the cost of repurposing is lower than the cost of a new system, and the utility of the repurposed system meets an acceptable minimum requirement. This scenario suggests that the repurposing of the proposed system should go ahead. In scenario B the required minimum utility is not met but the cost of the system is lower than the purchase of a new system. It may be possible in this scenario to review or amend requirements or find an alternative application that will make repurposing viable.

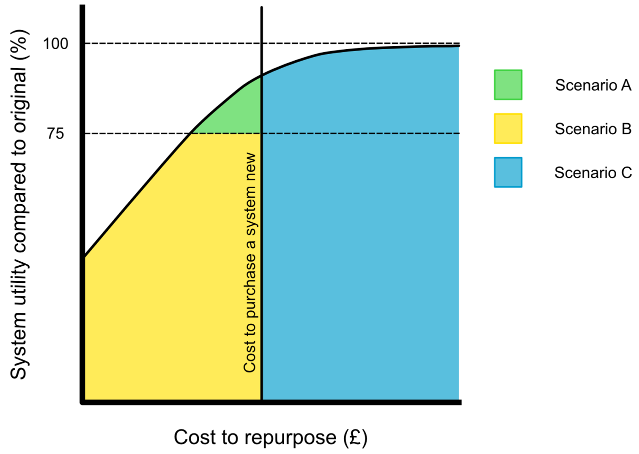

Fig. 5. A possible relationship between utility and cost of repurposing a system to be investigated in future work

In scenario C, repurposing costs are higher than those for buying a new system and it would not be economically justifiable to select repurposing. However, repurposing in scenario C could still be justified on sustainability grounds. Assuming a new robotic system and a repurposed system are able to meet the same or acceptably similar utility, the relationship between the sustainability of the system and the cost must be understood. Methods of calculating a sustainability index are required in order to understand the impact of producing a new versus a repurposed system. This should include assessing the carbon footprint to manufacture new systems versus a repurposed system. It should additionally provide an understanding of other environmental factors including, but not exclusive to; resource extraction resulting in deforestation, loss of animal habitats, and chemical leaching.

Future work required on the viability of repurposing must include an investigation into measurable indices for robot utility, cost and sustainability versus new systems. For the cost of repurposing to be calculated, technical feasibility must be understood (Section 4.2).

4.2. *Technical*

All robotic systems consist of hardware and software. The integration of these systems is generally purpose-built to enable the product to meet its desired functional requirements. As repurposing amends both the skill and application of the robotic system to meet the required new utility, it is likely that both the hardware and software will need amending in order to meet the new requirements. Integration of these amended systems will not be simple. Since this is a new concept, no examples of repurposing a robotic system exist. Therefore, a method must be developed and tested to demonstrate the process, detailing its successes and limitations. Verification of the repurposed systems must be equivalent to the verification processes for new systems, in order for the process to be accepted by customers.

In addition to this, changes in the technical capabilities of robotics, such as opportunities provided by advances in morphological computation, artificial intelligence, an increased Human-Robot-Interaction [HRI], and improvements in standardisation and modular subsystems for both hardware and software, may affect the technical possibility of repurposing a robot.

For example; improvements in HRI, which will affect both the hardware and software of robots, will have the potential to create greater levels of safety and understanding between robotic systems and human operators and the general public. These robotic systems will not only be programmed to better cope with a wider variety of human interactions,[36,37] but often will be made of more compliant materials.[38] Both these factors could make the systems more desirable for repurposing. However, by taking a robot out of its original application with the intention of repurposing, challenges will likely appear in the verification of the system to ensure it continues to react in an expected manner if its role type has changed.

Likewise, morphological computation - where aspects of a robot's control, perception or cognition are removed from traditional programming and instead are designed to occur naturally in the robotic body itself to mimic capabilities seen in nature[39] - may produce robotic systems that are more susceptible to being repurposed. Characteristics of robotic systems with morphological capabilities which could be advantageous in repurposing include: increased system flexibility due to high levels of sensing embedded within the robot;[40] increased dexterity for systems which are designed for self-stabilisation;[41] or an ability to control a larger ensemble of otherwise low capability robots to complete tasks that could not be met individually.[42] Note however, the robotic systems currently developed with aspects of morphological computation are often in very specialist forms that are dictated by their need to meet sensing and self-stabilising requirements. They may therefore offer limited repurposing opportunities at the end of their primary life as a result of their physical form.

As the variety in forms and functionality of robots expands, it is realistic to assume that some advancements will support repurposing, while others will hinder the process. Only once the process of repurposing is validated on currently well-understood technologies such as with industrial arms, will it be possible to assess the effects of new capabilities within the robotics industry.

4.3. *Attitudes, Incentives and Legislation*

Alongside demonstrations that it is technically possible and viable to repurpose a robot, a market must also exist for the resultant product. It has already been shown that in the consumer market, push, pull and mooring factors influence a potential consumer's decision to switch to remanufactured goods.[43] Mooring factors are determined by the consumers' pre-existing attitudes and cover social and personal values. Key pull factors influencing consumers are; incentives by governments (including legislation, tax and subsidies), and knowledge of the environmental benefits of switching to second-hand goods.[43] The key push factor that drives a consumer's decision to purchase remanufactured goods is the perception or realisation of the comparative savings that may be achieved by comparison with buying new products.[43] Investigation into the attitudes of the general public to second-hand robots compared to new robots for the consumer market will be considered in future work through participant surveys.

It is unlikely that consumer action alone will result in a significant impact in making sustainable choices.[14] Instead, product researchers, designers, engineers and manufacturers should take responsibility during the design phase to implement methods which minimise the environmental impact of their products as part of a commitment to Responsible Innovation.[15] Repurposing will be better achieved if product OEMs themselves take steps to enable the repurposing process of their robotic products. However, it can be expected that the concept of repurposing robots will have a similar reception to that which the smartphone industry gave the Right to Repair Movement. The Right to Repair movement is the global campaign to see improved consumer rights relating to the repair of electronic goods such as mobile phones and washing machines.[44] In general, large technology companies have not been supportive of the introduction of Right to Repair laws and legislation, with vocal opposition coming from Apple, Microsoft, Tesla, Amazon and many others.[45,46] Typical concerns raised by technology companies include; the security of devices being compromised by opening up to independent repairs, sensitive diagnosis information being made available to competitors, the safety of products if incorrectly repaired, and future infringements of copyright laws as a result of opened access.[45,47–50]

Countering this, the Right to Repair movement accuses technology companies of deliberately designed obsolescence in their products which, along with inaccessible repairs, has fuelled the high levels of e-waste around the world[51] as shown in Section 2.

Despite their original opposition to the effects of Right to Repair in the electronics industry, changes to laws and regulations (in development and published) in the US, UK and EU have persuaded technology firms to reconsider their stance on repairing consumer products. Examples include Apple Inc who, in November 2021, launched the Self Service Repair option which makes parts, tools and manuals available to individual customers and independent repair shops[52,53] despite their earlier resistance to the concept. Assuming robotics business concerns about repurposing will be similar to the initial reactions to Right to Repair, lessons can be learnt from the progression of the Right to Repair movement.

Understanding the concerns, constraints and benefits to robotic businesses of repurposing will be important to enabling uptake of the concept, should technical and viability studies prove successful. For this reason, a qualitative research study will be carried out which will interview robotics industry experts to understand the perception of robots as e-waste, repair accessibility and attitudes to the concept of repurposing. Interviews will include both businesses which develop or produce robotic systems, and those which use robotic systems. Data gathered from these studies will be used to address challenges for repurposing in relation to the topics of safety, security, sustainability and legislation.

5. CONCLUSIONS

What happens to robots when they have finished their primary use is a topic which, to date, has not been given substantial consideration within the industry. Robots may be utilised in the management of other product waste, but they themselves are rarely thought of as a waste product. Although robots are not currently included in the definition lists of e-waste for regulations in the EU, they do meet the general definition. With the numbers of robots increasing in both work and domestic settings, and with a greater global focus on the sustainability of all industries, those who are involved in researching, developing and producing robotic products must expect greater scrutiny of how those systems are disposed of at the end of their primary life.

This paper has argued that recycling should be the last resort when it comes to the management of robotic e-waste due to the examples set by other electronic products which are subject to poor recycling rates and poor waste management practices in the recycling methods. Instead, the concept of repurposing has been proposed as a method to delay the time before which a robotic product is discarded for recycling and disposal. When carried out, the repurposing of a robotic system will increase the useful life of the product and contribute to a circular economy. The authors have defined repurposing as providing new utility to an existing robotic system in order to give the system a new role that is independent of the robot's original utility, with utility being a combination of skills and application of the robot. As an entirely new field of study, this paper has outlined the major challenges and opportunities for repurposing which will be investigated by the authors in future work.

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References

1. S. Carlisle and P. Hanlon, *Health Promotion International* **22**, 261(Sept. 2007).
2. P. Dauvergne and J. Lister, *Organization Environment* **23**, 132(Jun. 2010).
3. M. Smith and D. C. Love, *Current environmental health reports* **5**, 375(Sept. 2018).
4. Z. Huang, Y. Weng, Q. Shen, Y. Zhao and Y. Jin, *Science of The Total Environment* **785**, p. 147365(Sept. 2021).
5. C. Spelhaug, Amp robotics installs its first recycling robots in the united kingdom and ireland with recyco AMP Robotics Corp. News [online] www.amprobotics.com/news-articles/amp-robotics-installs-its-first-recycling-robots-in-the-united-kingdom-and-ireland-with-recyco (accessed Aug. 15, 2022), (2021).
6. E. Slow, Viridor invests in max-ai sorting robot letsrecycle.com [online] `www.letsrecycle.com/news/viridor-max-sorting-robot/` (accessed Aug. 15 2022)(Aug., 2018).
7. S. Faibish, H. Bacakoglu and A. Goldenberg, *Proceedings - IEEE International Conference on Robotics and Automation* **1**, 9 (1997).
8. L. Chin, J. Lipton, M. C. Yuen, R. Kramer-Bottiglio and D. Rus, *RoboSoft 2019 - 2019 IEEE International Conference on Soft Robotics* , 102(May 2019).
9. J. Li, M. Barwood and S. Rahimifard, *2014 IEEE International Electric Vehicle Conference, IEVC 2014* (Mar. 2015).
10. M. Bounouar, R. Bearee, A. Siadat, N. Klement and T. H. Benchekroun, *2020 1st International Conference on Innovative Research in Applied Science, Engineering and Technology, IRASET 2020* (Apr. 2020).
11. A. Nguyen and A. Seibel, *2022 IEEE 5th International Conference on Soft Robotics, RoboSoft 2022* , 571(Apr. 2022).
12. R. Steinhilper, J. Kleylein-Feuerstein and C. Kussmann, *2016 Electronics Goes Green* (Jan. 2017).
13. R. Steinhilper, *Remanufacturing: the ultimate form of recycling* (Fraunhofer IRB Verlag, 1998).
14. A. Lubowiecki-Vikuk, A. Dabrowska and A. Machnik, *Sustainable Production and Consumption* **25**, 91(Jan. 2021).
15. UKRI, Responsible innovation UK Research and Innovation [online] `www.ukri.org/about-us/policies-standards-and-data/good-research-resource-hub/responsible-innovation/` (accessed May 9, 2022)(Oct., 2021).
16. A. Winfield and K. Winkle, *ICRES 2020: 5th International Conference on Robot Ethics and Standards* , 28(Sept. 2020).
17. Our waste, our resources: A strategy for england HM Government via gov.uk [online] `assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/765914/resources-waste-strategy-dec-2018.pdf` (accessed Sept. 9, 2022), (2018).
18. V. Forti, C. Baldé, R. Kuehr and G. Bel, The global e-waste monitor 2020: Quantities, flows and the circular economy potential United Nations University / United Nations Institute for Training and Research – co-hosted SCYCLE Programme, International Telecommunication Union International Solid Waste Association, Bonn/Geneva/Rotterdam., (2020).
19. S. Sthiannopkao, M. H. Wong, R. Naidu and M. Wong, **463-464**, 1147(Aug. 2012).
20. Design for manufacture, assembly, disassembly and end-of-life processing (made) part 2: Terms and definitions BS 8887-2:2009, British Standards Institute, (2009).
21. Directive 2002/96/ec of the european parliament and of the council of 27 january 2003 on waste electrical and electronic equipment (weee) EUR-Lex (access to European Union Law) [online] `https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex\%3A32002L0096` (accessed May 6, 2022).
22. B. R. Babu, A. K. Parande and C. A. Basha, *Waste Management and Research* **25**, 307(Aug. 2007).
23. B. C. Zoeteman, H. R. Krikke and J. Venselaar, *The International Journal of Advanced Manufacturing Technology 2009 47:5* **47**, 415(Oct. 2009).
24. R. Widmer, H. Oswald-Krapf, D. Sinha-Khetriwal, M. Schnellmann and H. Böni, *Environmental Impact Assessment Review* **25**, 436(Jul. 2005).
25. ENVIROS, Potential markets for waste electronic and electrical equipment (weee) Funded by the UK Environment Agency(Jun., 2002).
26. M. Savage, J. Lindblom and L. Delgado, Implementation of waste electric and electronic equipment directive in the eu 25 - publications office of the eu Institute for Prospective Technological Studies [online] `https://op.europa.eu/en/publication-detail/-/publication/`

9e42f67b-2c1a-4cfa-9a27-3955e0a50856 (accessed May 6, 2022)(Aug., 2007).
27. Robotics — vocabulary ISO 8373:2021(en), International Organization for Standardization [online] www.iso.org/obp/ui/#iso:std:iso:8373:ed-3:v1:en (accessed Aug. 25, 2022), (2021).
28. V. Graefe and R. Bischoff, *ICEMI 2009 - Proceedings of 9th International Conference on Electronic Measurement and Instruments* , 3418 (2009).
29. IFR, Chapter 1: Definitions and classifications of service robots https://ifr.org/img/worldrobotics/Definitions_WR_Service_Robots_2021.pdf.
30. IFR, Executive summary world robotics 2021-service robots International Federation of Robotics [online] ifr.org/img/worldrobotics/Executive_Summary_WR_Industrial_Robots_2021.pdf (accessed Feb. 14, 2022), (2021).
31. Household robots market - growth, trends, covid-19 impact, and forecasts (2022 - 2027) ReportLinker [online] www.reportlinker.com/p06241302 (accessed Jan. 27 2023)(Feb., 2022).
32. M. Charter (ed.), *Designing for the Circular Economy* (Routledge, 2019).
33. N. Nasr, *Remanufacturing in the circular economy : operations, engineering and logistics* (John Wiley Sons, Inc. ;, 2019).
34. S. Murakami, T. Tasaki, I. Diago and S. Hashimoto, *Journal of Industrial Ecology* **14**, 598 (2010).
35. G. T. Wilson, G. Smalley, J. R. Suckling, D. Lilley, J. Lee and R. Mawle, *Waste Management* **60**, 521(2 2017).
36. A. Hong, N. Lunscher, T. Hu, Y. Tsuboi, X. Zhang, S. F. dos Reis Alves, G. Nejat and B. Benhabib, *IEEE Transactions on Cybernetics* **51**, 5954(Dec. 2021).
37. A. Gaschler, S. Jentzsch, M. Giuliani, K. Huth, J. D. Ruiter and A. Knoll, *IEEE International Conference on Intelligent Robots and Systems* , 2128 (2012).
38. A. Ueno, V. Hlavac, I. Mizuuchi and M. Hoffmann, *29th IEEE International Conference on Robot and Human Interactive Communication, RO-MAN 2020* , 14(Aug. 2020).
39. V. C. Müller and M. Hoffmann, *Artificial Life* **23**, 1(Feb. 2017).
40. E. Judd, G. Soter, J. Rossiter and H. Hauscr, *RoboSoft 2019 - 2019 IEEE International Conference on Soft Robotics* , 558(May 2019).
41. R. Terajima, K. Inoue, S. Yonekura, K. Nakajima and Y. Kuniyoshi, *IEEE Robotics and Automation Letters* **7**, 1597(Apr. 2022).
42. R. Warkentin, W. Savoie and D. I. Goldman, *Proceedings - 2nd IEEE International Conference on Robotic Computing, IRC 2018* , 224(Apr. 2018).
43. B. Hazen, D. Mollenkopf and Y. Wang, *Business Strategy and the Environment* **26**, 451(May 2017).
44. N. Šajn, Right to repair briefing European Parliamentary Research Service(Jan., 2022).
45. R. Mittal, Right to repair movement around the world ipleaders [online] blog.ipleaders.in/right-repair-movement-around-world/ (accessed May 5, 2022), (2021).
46. J. Vipra and S. Rao, 'right to repair', the legislation india needs to save money, minimize e-waste The Federal [online] thefederal.com/analysis/upgrades-electronic-device/ (accessed May 9, 2022), (2021).
47. C. Godwin, Right to repair movement gains power in us and europe BBC News [online] www.bbc.co.uk/news/technology-57744091 (accessed May 5, 2022)(Jul., 2021).
48. P. Arora, Does india need a 'right to repair' legislation? The Daily Guardian [online] thedailyguardian.com/does-india-need-a-right-to-repair-legislation/t (accessed May 9, 2022), (2021).
49. M. Bergen, Microsoft and apple wage war on gadget right-to-repair laws Bloomberg [online] www.bloomberg.com/news/articles/2021-05-20/microsoft-and-apple-wage-war-on-gadget-right-to-repair-laws (accessed May 9, 2022), (2021).
50. L. Dormehl, Tech companies kill right to repair MUO (Make Use of) [online] www.makeuseof.com/tech-companies-kill-right-to-repair/ (accessed May 9, 2022), (2021).
51. Nixing the fix: An ftc report to congress on repair restrictions Federal Trade Commission [online] www.ftc.gov/system/files/documents/reports/nixing-fix-ftc-report-congress-repair-restrictions/nixing_the_fix_report_final_5521_630pm-508_002.pdf (accessed May 09, 2022(May, 2021).
52. Apple announces self service repair - press release Apple Inc. Newsroom [online] www.apple.com/newsroom/2021/11/apple-announces-self-service-repair/ (accessed May 9, 2022), (2021).
53. D. Schneider, Did apple really embrace right to repair Business of Apps [online] spectrum.ieee.org/right-to-repair-apple (accessed May 9, 2022), (2021).