Robotics and Circular Economy

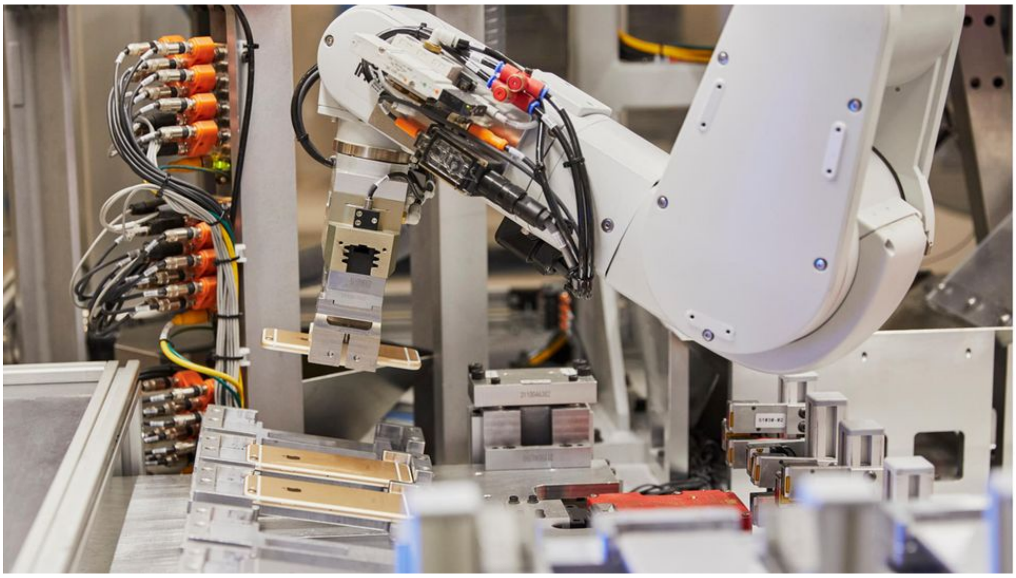

Figure 1: Source: Apple (2018)

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Preface

Everyone is currently talking about the topic of circular economy. It is primarily a question of making our planet's resources available to future generations and ensuring that the European Union's commitment to reducing CO2 emissions is achieved. Young people are pushing hard for a commitment to sustainability in production, and they are right to do so. At the same time, however, the protection of social achievements and prosperity must not be neglected. At first sight, this is a conflict of interests that cannot be solved. At second sight, the dual economy and robotics open up many new opportunities and business areas, bring independence in the supply of raw materials and enable us to develop our innovative power in new ways. In this context, I suggested and initiated the idea of a handbook as a group project for the students on the course "Industrial Robots". The feedback from the students was highly positive and the results are impressive.

IFT colleagues Philipp Eisele and Thomas Streßler handled the editorial work. The final formatting was carried out by Thomas Streßler, for which he is very much appreciated.

This publication combines the topics of robotics and the circular economy in a completely new form and presents the state of the art in both fields. The aim of the contributions is to show that robotics is a key technology for achieving the Sustainable Development Goals. Current research results demonstrate the very high potential for achieving the goals while at the same time ensuring high economic efficiency and work safety.

I would like to thank all students who have worked on the book with enthusiasm and motivation. I hope that readers will enjoy studying this publication and that the book "Robotics and Circular Economy" will provide you with a wide range of inspiration and valuable references.

Prof. Franz Haas

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Contents

1 Basics of Circular Economy

1.1 Introduction

1.1.1 Definition of Circular Economy

In today's economy, we extract materials from the earth, make products from them and then throw them away as waste - the process is linear. In contrast, a circular economy is an industrial economy that relies on the recycling of natural resources to minimize or eliminate waste.[1] It uses renewable energy sources and largely avoids pollutants.[2]

The transition from a linear to a circular economy requires a long term commitment by stakeholders from all sectors. Companies can contribute to the transition by building up competencies in circular design to implement product reuse, and recycling, and serving as trend-setters of innovative circular economy business models. To avoid waste, when the lifetime of a product ends, there should be found an alternative way to use the material to extend its lifespan. In this way, waste transforms to new resources.

As can be seen in Figure 3, an ideal waste management system would eliminate residual waste.[3] This means that as less as necessary new raw material from nature is required and an ideal circular economy is created. The circular economy distinguishes between two different types of materials: materials of biological origin that can return to the biosphere as raw materials (e.g. forest products) and technical materials that are not biodegradable (e.g. plastics and metals).[4]

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[1] cf. Bastein/Reolofs/Rietvelt/Hoogendoorn, 2013, p. 4.

[2] cf. Ellen-MacArthur-Foundation, 2023, accessed: 01.12.2023.

[3] cf. European-Parlament, 2023, accessed: 01.12.2023.

[4] cf. Ellen-MacArthur-Foundation, 2023, accessed: 01.12.2023.

Figure 2: Circular Economy and the SDGs, Source: Cork University Business School

1.1.2 Circular Economy and SDG‘s

Goals that a circular economy can contribute to include some SDG´s[5] for example end hunger (via sustainable food production), clean water, affordable and clean energy, and climate action.[6]

By 2030, the year by which we hope the SDGs have been fulfilled to a high rate, a huge percentage may all have circular jobs. If every job is circular, we can then leave the word circular out, and we go back to being innovators, project leaders and lecturers who simply do their job, but then in a circular way.[7]

1.1.3 Circular Economy and Economy

The circular economy not only offers the opportunity for sustainable production but can also reduce costs. In an analysis of EU manufacturing sectors, the Ellen MacArthur Foundation has identified potential net material cost savings of between € 265 billion and € 490 billion per year. This sum corresponds to around 23% of the current total input costs of these sectors. The greatest potential cost savings were identified in the automotive sector, followed by the machinery and equipment sector and electrical machinery.[8]

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[5] cf. School, 2021, accessed: 01.12.2023.

[6] cf. Schroeder/Anggraeni/Weber, 2018, p. 5.

[7] cf. Ellen-MacArthur-Foundation, 2023, accessed: 01.12.2023.

[8] cf. ibid., accessed: 01.12.2023.

1.2 Role of Robotics

Nowadays the importance of robotics is evident, an increase in robotic applications can be seen on many fronts of modern-day problems. With the previous explanation of circular economy, this chapter provides a quick overview regarding the areas and applications of robotics in circular economy. Technology that cooperates with robotics can provide a variety of ways to promote and support the recycling economy. Robotic systems themselves rely on a concept called "Sense, Think, Act" which enables robots to perceive the environment through the signals of sensors, data is analyzed with algorithms and actions are performed by means of actuators.[9]

There are limited possibilities for the circular economy to be improved by robots alone, but Industry 4.0 provides an excellent synergy in this respect. Rüßmann has identified nine fundamental pillars of technology advances that constitute Industry 4.0 such as Autonomous Robots, Simulation, Big Data and Analytics, Horizontal and Vertical System Integration, the Industrial Internet of Things, Cybersecurity, the Cloud, Additive Manufacturing, and Augmented Reality.[10]

With the combination of robotic systems, and Industry 4.0 many fields of circular economy can be enhanced.[11] For instance, robots can be used to automate the sorting of recyclable materials by using cameras and sensors to distinguish different waste, which can increase the efficiency of the recycling process and reduce the amount of waste that ends up in landfills.[12]

Sustainable manufacturing processes is also an area of application, where robots can be used for the automation of different stages in a manufacturing process to reduce energy consumption and carbon footprint. For example, robots may be used for assembly, disassembly or removal of products that will reduce the number of needed human workers therefore reducing the risk of an injury, while also monitoring environment conditions and water consumption in real time.[13] A study found that additive manufacturing can be used to transform waste into new products, and that the use of robotics in additive manufacturing can lead to further improvements in the circularity of the processes.[14]

Lastly, the design of circular products, components and materials is a key aspect of the circular economy, and artificial intelligence as well as robotics in general can play a key role. With the ability to identify the best way to design products based on criteria of circularity, considering both the use of raw

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[9] cf. Wang/Herath, 2022.

[10] cf. Rüßmann, 2015, accessed: 20.12.2023.

[11] cf. Bogue, 2022, p. 6-10.

[12] cf. Ellen-MacArthur-Foundation2, 2019, accessed: 20.12.2023.

[13] cf. Daneshmand, 2023, p. 2973-3000.

[14] cf. Shanmugam, 2020, p. 11.

materials in production and the object's entire life cycle while also speeding up the process and therefore hasten the arrival of the product on the market it holds huge importance today.[15] In summary, robotic automation is a key enabler for the circular economy as it promotes resource efficiency, waste reduction and product life extension. Robots play an essential role in the design of a more Sustainable Future through their support for recycling, waste management, product design and sustainable manufacturing process.

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[15] cf. Enel-Group, 2020, accessed: 21.12.2023.

1.3 Challenges

Robots can be used in various fields within the circular economy, as described in the previous chapter. However, their use is not always straightforward and is often linked to challenges which need to be addressed. Waste is often heterogeneous and so may be its disassembly or sorting. The software of the robot must first identify, which kind of waste it is working with right now, then it has to choose the right treatment accordingly. To solve this task, deep learning is often used. In order to be able to do this, first, a model must be designed and trained. For training, a lot of different data is needed to make sure, that the robot is really able to distinguish between different kinds of waste.[16] Collecting this variety of data may be very time consuming, but if the data could be shared across recycling plants or even countries, it would spread the work among many users. Of course, data sharing is nothing companies like to do and thus, it is not easy to implement.[17] After a robot identified an object and decided what to do with it, it often needs to pick it up. This is a challenge which spreads across several industries because grasping is not as easy for robots as it is for humans. We are simply not able to produce as small and effective sensors and actuators as humans possess with their nerves, skin and muscles. And of course, as always, the cost factor plays a role. Nowadays, robots are pretty good in manipulating a small variety of objects within a constant environment. The robot hand can be optimized for the small set of objects and the grasping is pretty reliable. This, however, is not possible for the unexpected and broad variety in shape, texture and material of waste. Even though a robot can be equipped with several tools to choose from, this is also not an optimal solution. Not only it is time consuming to change the tool (which may happen often because of the heterogenous waste) but it is also more expensive than a specialized robot. Flexible objects like fabric or vegetables are an even bigger challenge for robots to grab because of their varying shape. Since clothes are also permeable to air, picking them up by sucking with pneumatic vacuum pumps, like it is often done in the industry, is also no solution.[18]

A possible trade-off to reduce the problems of big data and not reliable grasping under certain conditions by still keeping the advantages of robots is a so-called cobot. A cobot works together with a human in the same working environment. Both of them do, what they do best. The robot focuses on dangerous, heavy and easy tasks, while the human is responsible for complicated ones and tasks, where the robots grasping tools reaches their limits. Normal robots are strictly separated from humans for example by a fence. Cobots cannot be isolated like

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[16] cf. Sarc, 2019, p. 476-492.

[17] cf. Morgan/Jacobs, 2020, p. 71-103.

[18] cf. Billard/Kragic, 2019, p. 364(6446).

that. In order to still be able to implement one and satisfy legislation as well as safety, there need to be some additional measures.[19]

The robot's speed and power must definitely be reduced and additional sensors are also required to monitor the humans behavior and to detect dangerous situations.[20] The safety mechanisms must be very reliable which leads to complex – and thus again expensive – robots.[21]

In the end, robots add a great value to circular economy, but the challenges, which all other industries must face too, still remain. Big data, robot manipulation of different materials and shapes as well as a safe interaction between robots and humans are and will be research topics for years. The solutions improve steadily, but in the end, each company, country and plant has to individually decide, whether they want to invest the required high sums in robotic solutions.

1.4 Opportunities

The previous chapter focused on the challenges and obstacles when integrating robotics into Circular Economy practices. There are, however, big opportunities when integrating such. These will be evaluated in this subchapter, including enhancements, when using automation and smart technologies. McKinsey evaluated certain factors for creating economic benefits with their "Digital Compass", where eight value drivers were defined. Since industry 4.0 and industry 5.0 can contribute to circular economy they can be used as a reference step towards the benefits and opportunities of using robotics in circular economy. As described above, a typical circular economy model (Figure 3) starts by converting raw materials into a product and ends in waste management and residual waste, respectively.

Therefore, one value driver that was identified by McKinsey, is the use of resources and process optimization. By applying robotics in the product lifecycle assessment, productivity can be increased, quality improved and due to traceability capabilities, the resource efficiency can be optimized. This application throughout the whole process can obtain a benefit by using less raw materials and as a result of that, emit less emissions.[22] Due to a more sustainable manufacturing process one can also achieve more sustainable consumption patterns through their customers since it is achievable to reduce the time to market with shorter product development cycles and with innovative aftersales

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[19] cf. Sarc, 2019, p. 476-492.

[20] cf. Renteria/Alvarez-de-los-Mozos, 2019.

[21] cf. Kragic, 2018.

[22] cf. Wee/Kelly/Breunig, 2015, p. 17-21.

Figure 3: Circular economy model, Source: European Parliament (2023)

services included.[23] These applications of robotics lead in a broader point of view to resource efficiency, cost reduction and sustainability.[24]

However, as mentioned above two main aspects of circular economy are not necessarily included in the identification of McKinsey. The waste management and the residual waste management define important sectors and therefore, it has to be pointed out that the application of robotics in those is an important task that has great potential for the implementation of circularity in a products lifespan. One approach of a circularity can be materials parsimony. The reduction of material composition complexity can be reduced and standardized to loop the materials back into the process. This can be done with the help of smart systems applied within the product lifecycle assessment. Materials parsimony can furthermore be combined with digital passports that provide a record of all relevant details of the product that can be used for disassembly, reuse, or recycling processes at the end of a products lifespan.[25] This information could also expand the knowledge base of consumers, which could lead to improved consumption patterns.[26]

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[23] cf. Blunck/Werthmann, 2017, p. 5-9.

[24] cf. Sarc, 2019, p. 476-492.

[25] cf. ibid., p. 476-492.

[26] cf. Bartekowa/Borkey, 2022, p. 17-26.

Besides adding information to the product, it is very important to optimize waste management towards circularity.[27] By applying digitalization and robotics in waste management, recycling rates could be increased.[28]This could be achieved by intelligent material detection, intelligent sorting systems, Radio Frequency Identification tags attached to products with municipal waste collection programs, such as pay-as-you-throw.[29] These exemplarily listed applications of smart technologies in circular economy could support the fulfillment of the European Circular Economy action plan.[30]

1.5 Risks

As mentioned in a previous chapter, robotic systems in conjunction with Industry 4.0 offer great potential for promoting the circular economy. Despite the above-mentioned benefits of using robotic systems, this subchapter describes some of the risks that can arise from their use. The increasing integration of robotics into our society raises many ethical concerns. One of the most important questions is how much autonomy robotic systems should have. Do they need to be controlled by humans or should they be able to make their own decisions? If they make their own decisions, then the question arises as to whether their actions should be held responsible by manufacturers, operators or users, or by themselves. Another ethical question is whether a robot should be considered a tool or a being with rights of its own. Danaher argues that the robot autonomy is a complex ethical issue with potential benefits and risks. It is important to weigh these carefully before making decisions about the development and use of autonomous robots.[31]

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[27] cf. Sarc, 2019, p. 476-492.

[28] cf. Bartekowa/Borkey, 2022, p. 17-26.

[29] cf. Aclima, 2017, accessed: 20.12.2023.

[30] cf. European-Comission, 2020, accessed: 01.12.2023.

[31] cf. Gordon/Gordon, 2021.

Science fiction writer Isaac Asimov also recognised the ethical concerns.[32] To enable humans and robots to co-exist in a positive way, he provided the first idea for robot ethics with his Laws of Robotics, described below:[33]

- **The First Law:** A robot may not injure a human being or, through inaction, allow a human being to come to harm.
- **The Second Law:** A robot must obey the orders given by human beings except where such orders would conflict with the First Law.
- **The Third Law:** A robot must protect its own existence as long as such protection does not conflict with the First or Second Law.
- **The Fourth Law:** A robot may not harm humanity, or, by inaction, allow humanity to come to harm.

While the ethical principles for the use of robots are a good start, they do not provide concrete steps. Additional safety regulations, such as the Machinery Directive, are needed to ensure the safety of robotic systems. The ongoing development of Industry 4.0 and the increasing use of robotic systems brings with it another risk: the risk of unemployment. Experts at Oxford Economics say, that statistically speaking, every new industrial robot destroys 1.6 jobs in a factory. They also predict that by 2030, around 20 million jobs in factories around the world could be taken over by robots instead of people.[34] The risk of robots taking over a range of jobs in the future arises predominantly from their advantages: They can work without fatigue, do not need time off, can process large amounts of data quickly and are almost error free. To minimise the risk of unemployment, humans will need to use their creativity, spontaneity and unusual decision-making and thinking skills to program and monitor robotic systems. Robotic systems can then take over the repetitive and dangerous tasks that are too strenuous or risky for humans. The use of robotic systems poses not only social but also environmental risks. The high consumption of resources and energy, as well as the pollution caused by the use and disposal of robots, can have a negative impact on the environment. Widespread use also requires additional financial resources. This can intensify competition for resources, especially where socio-political objectives are a stake.[35] In conclusion, the integration of robotic systems into the workplace is a complex task that requires careful planning. Robotic systems offer opportunities and risks, but strict human control can minimise the risks and limit job losses without sacrificing the benefits.

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[32] Asimov, 1950.

[33] Asimov, 1985.

[34] cf. Lambert/Lambert, 2019.

[35] cf. Guenat, 2022.

1.6 Conclusion and Recommendations

1.6.1 Conclusion

In conclusion, circular economy shows big potential for a more sustainable future. But to use most of this potential and to make the jump from a linear to a circular economy, all the involved parties must work together. To utilize the whole potential of circular economy, the implementation and advancement of robotics is definitely needed, especially in the sense of industry 4.0, in which robotics plays in integral role. By using "Sense, Think, Act"-concepts and technologies like autonomous robots, Big Data and AI, an increase in efficiency in circular economy can be achieved.

1.6.2 Recommendations

- **Considering Effects on the environment:** Companies have to be aware of their effects on the environment and have to focus on resource efficient and environmentally friendly solutions in the sector of robotics.

- **Research and development:** A lot of investments in research and development are needed, to handle heterogeneous waste. In addition to active cooperation in data recording and data exchange between different companies and institutions, to guarantee a more efficient system in waste management.

- **Human-robotics-collaboration:** "Cobots" can be implemented to handle the challenge of more flexible and heterogeneous materials. Although a lot of safety regulations must be implemented and ensured, so that humans and robots can work safely in the same area. All in all, the integration of robotics in a circular economy is very promising, but there is a need for a careful approach, to use chances and minimize the risks. A coordinated effort of industry, regulatory authorities and research facilities is essential for the success of a sustainable change.

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2 Statistics

2.1 Introduction and Overview

In the modern days both the production of waste and the production of greenhouse gases (GHG) are at an all-time high. Although it is thought that the CO2 emissions peak in the mid-2020 the goal of a global 1.5 °C increase, which was set as a goal in 2015 with the “Paris Agreement”,[1] is far away.[2] With the current trajectory and even with further acceleration of the commitments a global temperature increase of 1.7 to 2.4°C is more likely.[3] Figure 4 shows the statistics for the above mentioned production of GHG. The Y-axis in in billion tons of CO2.

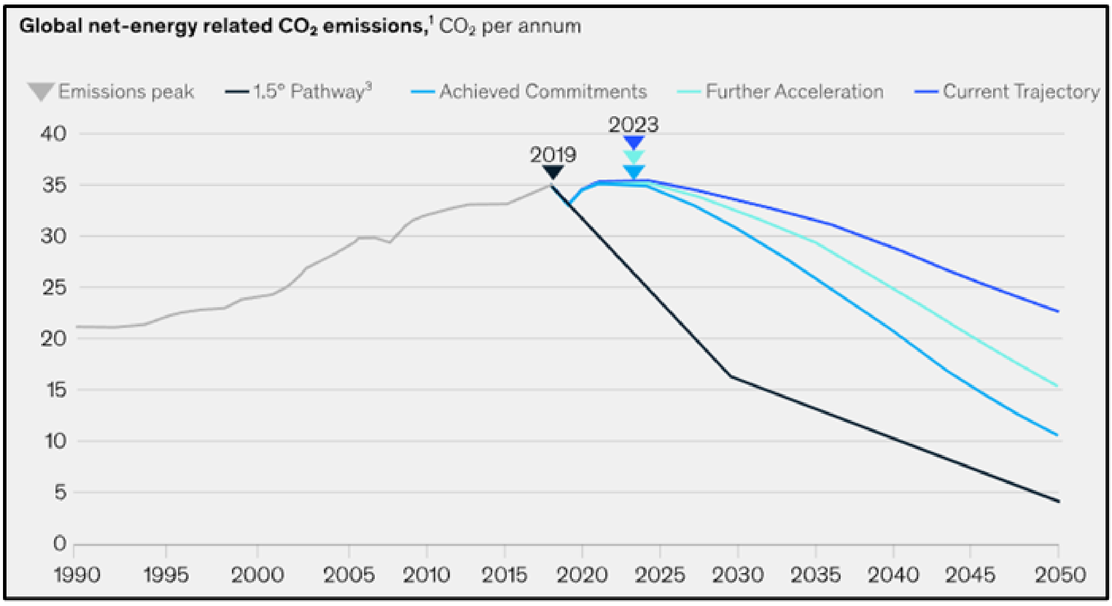

Figure 4: Global Emissions of GHG with future trajections,
Source: United Nations Environment Programme (2015)

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[1] cf. United-Nations, 2015.

[2] cf. Rolser/van-der-Meijden, 2022, accessed: 17.01.2024.

[3] cf. ibid., accessed: 17.01.2024.

Not only the emissions are a problem, but also the fact that more and more waste gets produced every year. Figure 5 shows the projected waste generation of different regions up to the year 2050.

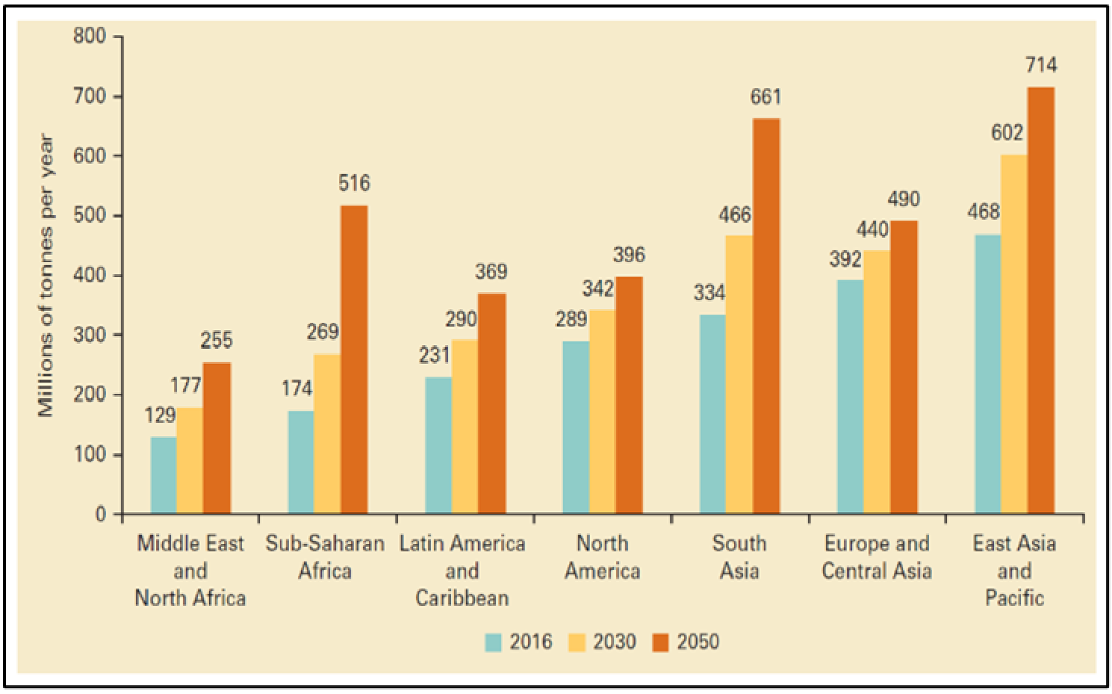

Figure 5: Projected waste generation, by region (millions of tonnes/year), Source: Kaza/Yao/Bhada-Tata/van Woerden (2018)

Overall is waste the fourth largest sector of emission accounting for around 3% of all GHG emissions.[4] To reduce emissions and waste a circular economy must be implemented. With the use of a circular economy some of the waste would be recycled and reused to produce new products this would help by decreasing the waste produced per year as well as the emissions.[5] Furthermore, the energy consumption should also be reduced because to recycle things is highly energy efficient compared to a production from scratch. A reduction in energy usage could lead to further reduction in emissions. The following sections will take a dive into the possibilities of a circular economy in the sectors of resource usage, energy, and emissions and possible usage for robotic in these circular economies. Furthermore, economic factors for the usage of robotics in these circular economies will be discussed as well as a quick overview over the different robot manufacturers and the growing implementation of robotics into circular economy.

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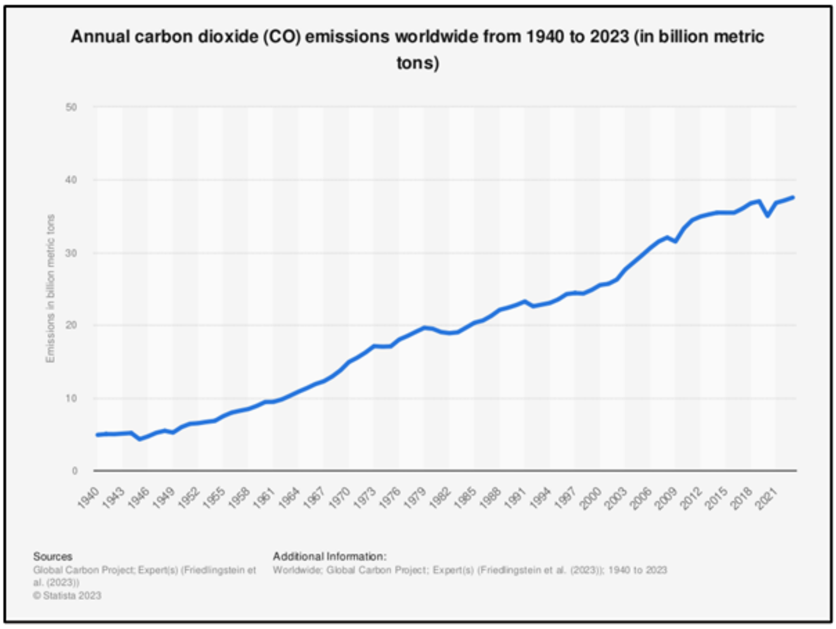
[4] cf. Eurostat, 2020, accessed: 17.01.2024.

[5] cf. ibid., accessed: 17.01.2024.

2.2 Statistics

2.2.1 Statistics relating to the environment and emissions

As shown in Figure 6, the emissions worldwide are rising a lot throughout the years. Only the Covid 19 crisis brought a brief bigger decline, which quickly turned in the opposite direction again. With an estimated total of 37,55 billion metric tons the global carbon dioxide emissions reach a record high in 2023.[6] Ancient air bubbles trapped in ice enable us to step back in time and see what Earth's atmosphere, and climate, were like in the distant past. They tell us that levels of carbon dioxide (CO2) in the atmosphere are higher than they have been at any time in the past 400 000 years.[7]



Sources
Global Carbon Project; Expert(s) (Friedlingstein et al. (2023))
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Additional Information:
Worldwide; Global Carbon Project; Expert(s) (Friedlingstein et al. (2023)); 1940 to 2023

Figure 6: Annual carbon dioxide (CO) emissions worldwide from 1940 to 2023 (in billion metric tons),Source: Tieso (2023)

To make the results in Figure 6 more tangible, the following statistics is shown in Figure 7. It shows the development of total global Greenhouse gas (GHG) emissions and the development of total GHG emissions by geographical region. Global GHG emissions sources are usually attributed to five broad sectors, characterised by the Intergovernmental Panel on Climate Change (IPCC) Working Group III (WG3) as energy systems, industry, buildings, transport, and AFOLU (agriculture, forestry, and other land uses). Together, these sectors cover aspects of energy supply (energy systems), energy demand (industry, buildings, and

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[6] cf. Tieso, 2023, accessed: 28.12.2023.

[7] cf. NASA, 2023, accessed: 28.12.2023.

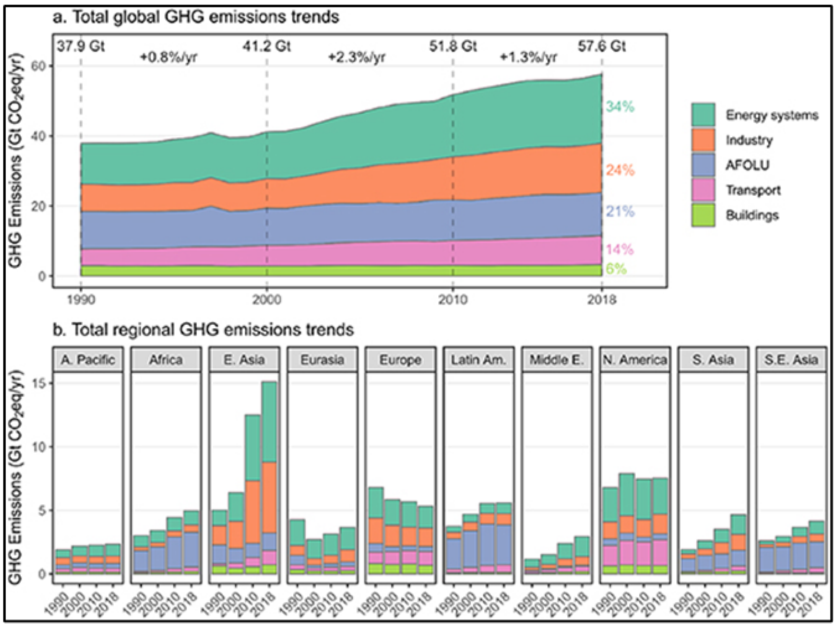

Figure 7: Global and regional GHG emission trends for all sectors, Source: Lamb (2021)

transport), non-energy related process emissions (industry), and land-based emissions and removals (AFOLU).[8] The largest share of emissions in 2018 came from the energy systems sector (34%; 20GtCO2eq), followed by industry (24%; 14 GtCO2eq), AFOLU (21%; 12 GtCO2eq), transport (14%; 8.3GtCO2eq) and the operation of buildings (6%; 3.3Gt CO2eq).[9] Figure 7 also shows that emissions in highly developed regions, such as Europe and North America, are stagnating or even falling, but are rising in Asia in particular and in other regions.

2.2.2 Statistics relating to energy consumption

As depicted in chapter 2.2.1, the global emissions are on a steady incline. This same trend also can be seen in the global energy consumption, as depicted in Figure 8. The global energy consumption has dramatically increased during the last 25 years by almost 50% from 434 to 667 exajoules.[10] While the share of renewable energy sources grew from 9,6% (42 exajoules) in 2000 to 14,3% (96 exajoules) in 2025, and is projected to reach 32,5% in 2050,[11] only relying on renewable energies to reduce the impact of the increased energy demand will not be sufficient, there also needs to be a change in the way we utilize energy.

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[8] cf. Lamb, 2021.

[9] cf. ibid.

[10] cf. Fernández, 2023, accessed: 17.01.2024.

[11] cf. ibid., accessed: 17.01.2024.

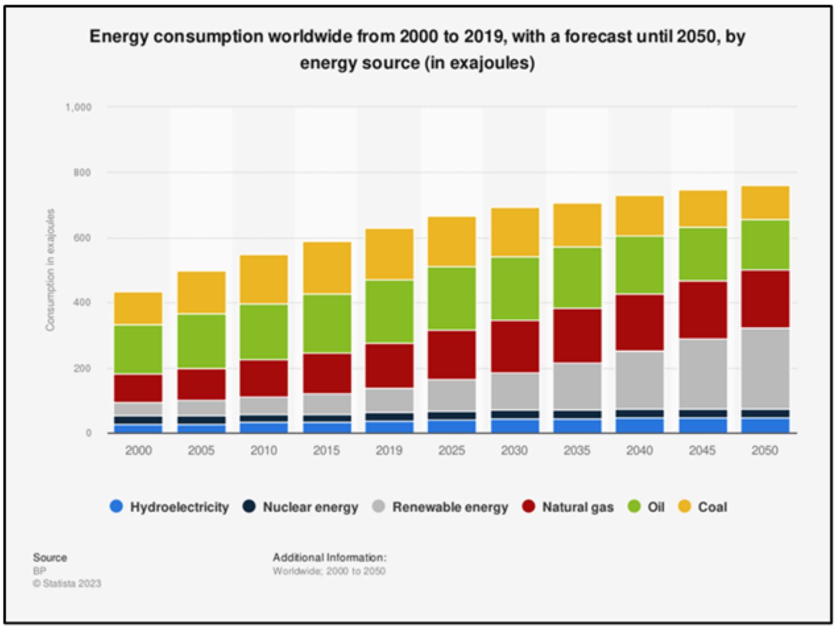

Figure 8: Energy consumption worldwide from 2000 to 2019, with a forecast until 2050, Source: Fernández (2023)

To further illustrate the big impact that the industrial sector can have by saving energy and utilizing it more effectively, we have a look at Figure 9. It depicts the primary energy consumption in the U.S., where in 2022 37,5% were used for electricity generation and a further 23% were used directly in the industrial sector.[12] Out of the total final electricity consumption worldwide in 2018, 41,9% were used by the industrial sector,[13] which brings the share of the industrial sector of the primary energy consumption to a total of 38,7%.

The biggest primary energy sources, while on the decline, are oil with 30,9% and coal with 26,7%, followed by natural gas with 23,2%.[14] The total share of these non-renewable, CO2 emitting energy sources is therefore still over 80% worldwide.

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[12] cf. Jaganmohan, 2024, accessed: 17.01.2024.

[13] cf. StatistaResearchDepartment, 2024, accessed: 17.01.2024.

[14] cf. Sönnichsen, 2023, accessed: 17.01.2024.

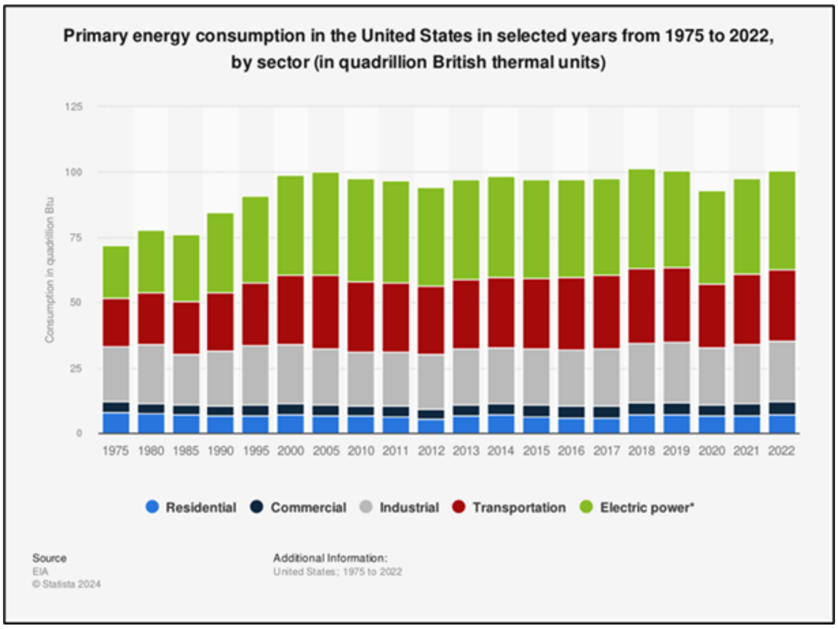

Figure 9: Primary energy consumption in the United States, Source: Jaganmohan (2024)

2.2.3 Statistics relating to resource consumption

In chapters 2.2.1 and 2.2.2, a detailed examination regarding emission consumption and energy utilization is presented. The focus now shifts to a closer examination of resource consumption. Under the theme "The world is not enough," Statista has published an article addressing global resource consumption, accessible at.[15] The evaluation of resource consumption prominently features the World Overshoot Day, determined through the ecological footprint. This milestone indicates the moment in the calendar year when humanity depletes the Earth's sustainable resources, exceeding its ecological capacity. Subsequent to this point, our existence becomes dependent on the resources earmarked for future generations, emblematic of the dissonance between human consumption and environmental sustainability. According to calculations by the Global Footprint Network the World Overshoot Day in 2023 occurred on August 2nd, this means that our resource consumption would necessitate 1.7 Earths.[16] The graphical representation in Figure 10 illustrates a shift of over a month for Earth Overshoot Day over the past two decades. Notably, recent years exhibit a stabilization in resource consumption trends.

Figure 11 below illustrates the Global Overshoot Day for various countries in 2023, highlighting Qatar and Luxembourg as early February exhausted, having

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[15] cf. Fleck, 2023, accessed: 18.01.2024.

[16] cf. Global-Footprint-Network, 2023, accessed: 18.01.2024.

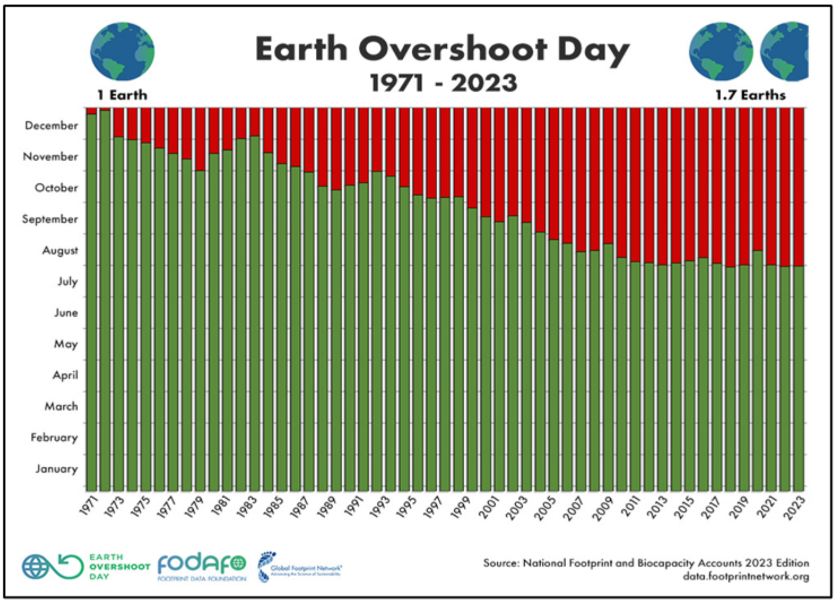

Figure 10: Statistics on the global Earth Overshoot Day from 1971 to 2023, Source: Global Footprint Network (2023)

depleted their resources for the entire year.[17] Conversely, Jamaica extends its resource sustainability until December 20. The pivotal contributors to resource consumption include fossil energy producers (coal and natural gas), automotive and aviation sectors, building energy consumption, and the intensity of animal product consumption.[18]

Ensuring the sustainable utilization of resources is imperative to preclude an ongoing burden on future generations. This imperative aligns with the broadening scope of climate and resource conservation efforts. The emphasis is not on renunciation but on a societal paradigm shift, primarily driven by the development of novel and innovative technologies, alongside the augmentation of existing ones. Within the framework of resource reduction, the circular economy emerges as a pivotal player, offering a central role in this transformative process.

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[17] cf. Geneva-Environment-Network, 2023, accessed: 18.01.2024.

[18] cf. European-Environment-Agency, 2023, accessed: 18.01.2024.

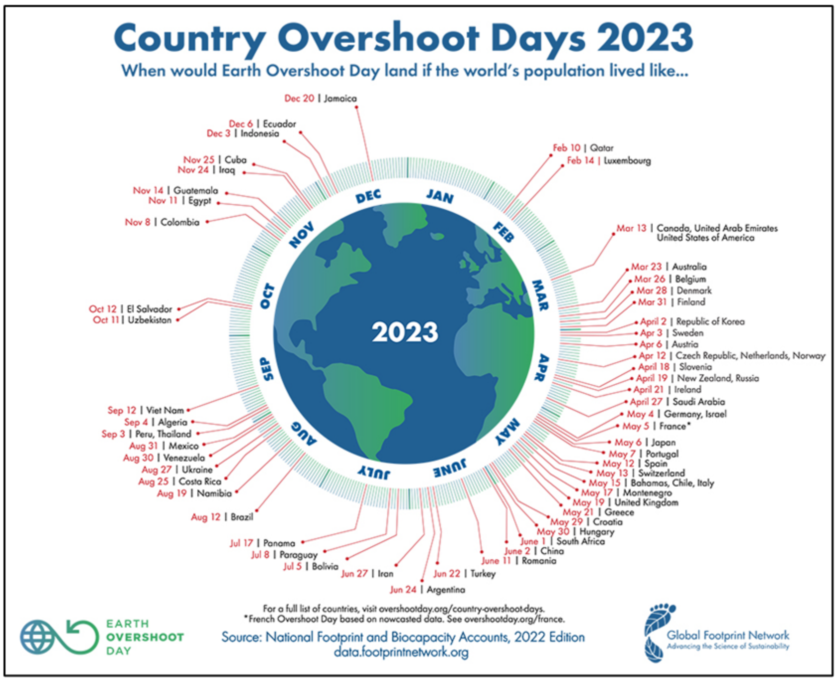

Figure 11: Earth Overshoot Day for various countries in the year 2023, Source: Geneva Environment Network (2023)

2.2.4 Economic factors

Relevant data from an economic perspective can be seen in Figure 12 below, which shows the turnover of robots in the period 2016-2028.[19] It is clear to see that this is increasing and will rise from 22.75 billion US dollars in 2016 to 45.1 billion US dollars in 2028. It can be deduced from this that robotics is playing an increasingly important role in the industry.

Figure 13 below visualizes the cost of an industrial robot, also over the period 2016-2028.[20] In Europe, for example, this increases from 1.68 thousand US dollars in 2016 to 2.1 thousand US dollars in 2028.

From the above data, it can be deduced that the role of robotics will increase in the future and that it can also be used to promote the circular economy. For example, it can be used to increase efficiency in production by using robots in recycling plants to optimize the sorting process. Robots can work quickly and precisely, which results in faster processing of recycled materials and therefore higher turnover. According to the answers generated by ChatGPT (OpenAI, 2021), cost savings can also be expected from the reuse and repair of products. For example, robots can be used to repair products in order to

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[19] cf. Thormundsson, 2023b, accessed: 18.01.2024.

[20] cf. Thormundsson, 2023a, accessed: 17.01.2024.

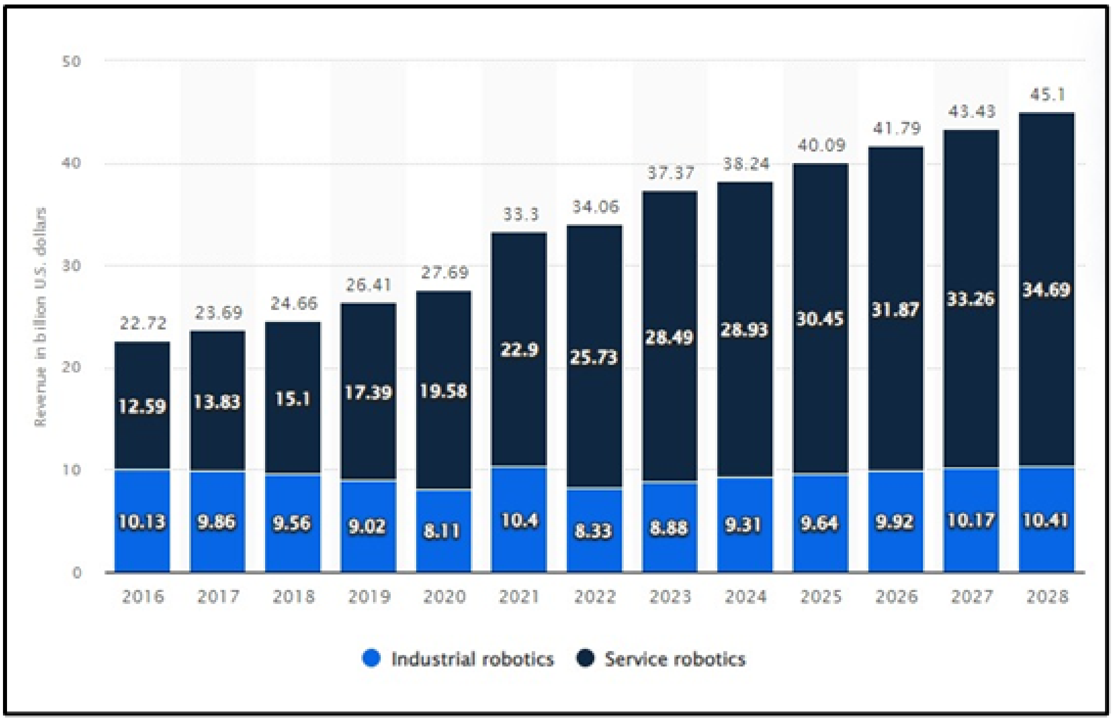

Figure 12: Revenue of robotics market worldwide from 2016 to 2028, Source: Thormundsson (2023b)

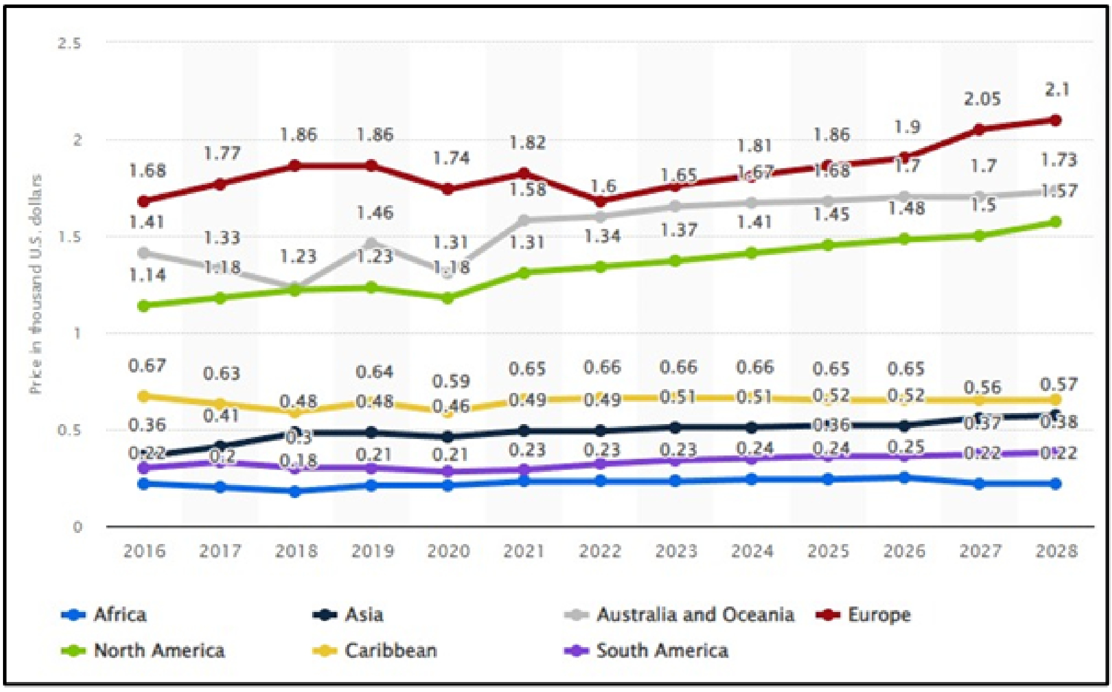

Figure 13: Price of robotics per unit worldwide from 2016 to 2028, by region, Source: Thormundsson (2023a)

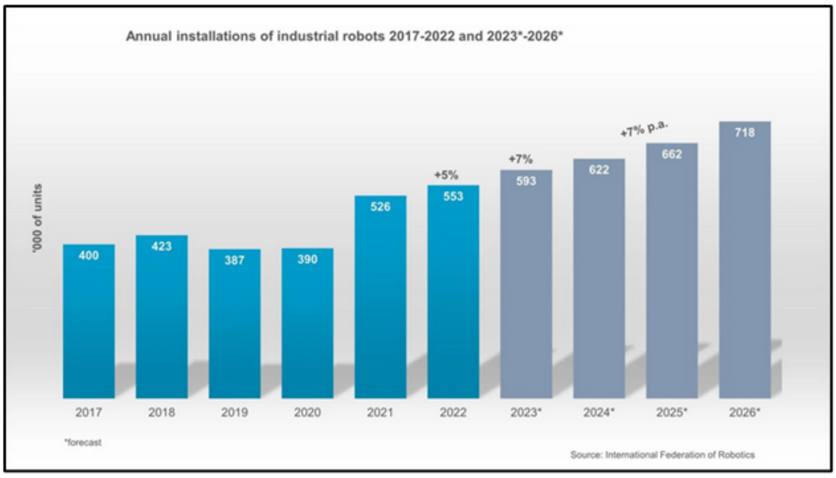

Figure 14: Annual installations of industrial robots 2017-2022 and 2023-2026, Source: IFR (2023c)

maintain or extend their own service life. Costs can be reduced by automating repair processes. In addition, products can remain in use for longer and thus reduce the demand for new products.

2.3 Robotics

2.3.1 Annual installations of industrial robots

The new World Robotics report recorded 553,052 industrial robot installations in factories around the world a growth rate of 5% in 2022, year-on-year. By region, 73% of all newly deployed robots were installed in Asia, 15% in Europe and 10% in the Americas. In 2023 the industrial robot market is expected to grow by 7% to more than 590,000 units worldwide.[21]

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[21] cf. IFR, 2023c, accessed: 18.01.2024.

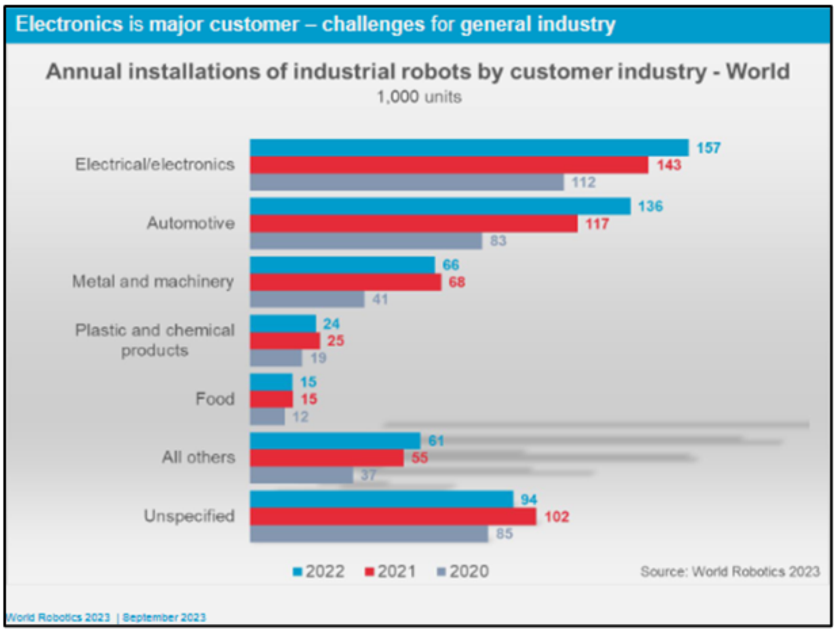

Figure 15: Annual installations of industrial robots by customer industry, Source: IFR (2023b)

2.3.2 Robotics statistics by industry

The top 5 industries for robotic adoption[22] and their numbers can be seen below:[23]

- **Electronics:** The electronics industry was the leading adopter of robots with 157,000 installations globally.

- **Automotive:** The automotive industry has been a leader in using robots for decades, but it is no longer the top industry. For applications like assembly, painting, and welding.

- **Metal and machinery:** Many companies seeing improved production times and quality control over human labour.

- **Plastic and chemicals:** Helping plastics companies to improve their productivity while also helping their sustainability efforts.

- **Food:** The food industry's adoption of robots reached an all-time high with 15,000 globally, for applications like picking, packing, and distribution.

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[22] cf. Owen-Hill, 2023, accessed: 18.01.2024.

[23] cf. IFR, 2023b, accessed: 18.01.2024.

2.3.3 Robotics companies and their approach to the circular economy and some key numbers

The leading robotics companies are listed below:[24]

- **ABB:** Zurich, Switzerland
- **Epson America Inc:** Tokyo, Japan
- **Fanuc:** Yamanashi, Japan
- **KUKA:** Augsburg, Germany
- **Kawada Robotics Group:** Nanto, Japan
- **Comau:** Turin, Italy

These companies have similar approaches in terms of circular economy applications.[25] Comparing the ABB, Locus and IRS Robotics, the main steps are reuse,[26] repair refurbish/remanufacture and repurpose.[27] As an example, the approach of ABB Robotics and some key numbers can be seen in Figure 16. Since an industrial robot has a service lifetime of up to thirty years, new tech equipment is a great opportunity to give old robots a "second life". Industrial robot manufacturers like ABB, Fanuc, KUKA, Stäubli or Yaskawa run specialized repair centres close to their customers to refurbish or upgrade used units in a resource-efficient way. This prepare-to-repair strategy for robot manufacturers and their customers also saves costs and resources. To offer long-term repair to customers is an important contribution to the circular economy.[28]

2.4 Conclusion

To reach the planned 1.5 °C global warming limit or even come close to reaching it excessive steps to a more sustainable lifestyle must be made. A circular economy would be on of these steps. Robotics can help to reduce or recycle waste in many different industries and they can also be used for tedious tasks like sorting through old metal to find the perfect alloy for re-smelting or things like this. Also, tasks that are too dangerous for humans due to their environment like disassemble nuclear reactors can be done by robots which could further increase the possibility of recyclability. Most big robotics companies already

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[24] cf. Assumnmotor, 2023, accessed: 18.01.2024.
[25] cf. Hart/Williams/O'Neil, 2023, accessed: 18.01.2024.
[26] cf. IRS-Robotics, 2023, accessed: 18.01.2024.
[27] cf. ABB, 2023, accessed: 18.01.2024.
[28] cf. IFR, 2023a, accessed: 18.01.2024.

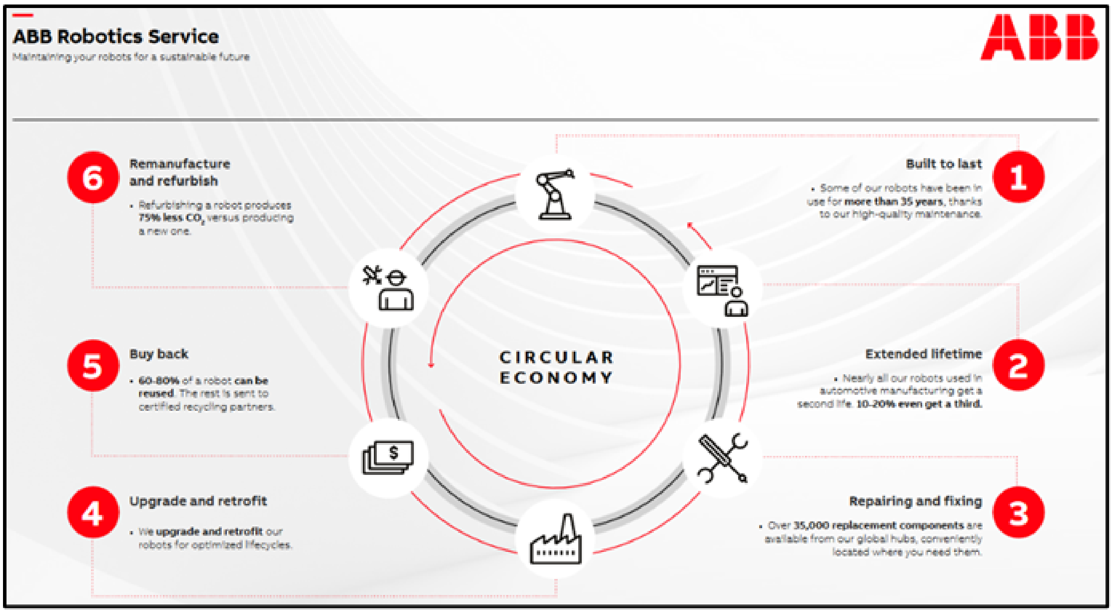

ABB Robotics Service

Maintaining your robots for a sustainable future

ABB

CIRCULAR ECONOMY

1 **Built to last**

- Some of our robots have been in use for **more than 35 years**, thanks to our high-quality maintenance.

2 **Extended lifetime**

- Nearly all our robots used in automotive manufacturing get a second life. **10-20% even get a third.**

3 **Repairing and fixing**

- Over **35,000 replacement components** are available from our global hubs, conveniently located where you need them.

4 **Upgrade and retrofit**

- We **upgrade and retrofit** our robots for optimized lifecycles.

5 **Buy back**

- **60-80%** of a robot **can be reused**. The rest is sent to certified recycling partners.

6 **Remanufacture and refurbish**

- Refurbishing a robot produces **75% less CO_2** versus producing a new one.

Figure 16: Circular economy ABB, Source: ABB (2023)

try to implement circular economy into the product line. Overall, it can be said that robotics could be a huge help enable circular economy or boost it further in different sectors. Although for clear answers further studies and research must be made.

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3 Automotive Industry

3.1 Circular Economy in the Automobile Industry

The aim of the circular economy in the automotive industry is to ensure that as many materials as possible can be reused and recycled in future vehicle generations. Nowadays, a large number of natural resources are still used in the construction of a vehicle. This dependency is to be gradually reduced so that these resources can be replaced by recycled materials. Only through this can the complete reusability of a vehicle be achieved. Achieving this goal not only has a positive impact on the CO2 balance but can also lead to higher profitability for vehicle manufacturers, as they can save costs on the acquisition of very expensive and scarce raw materials through an optimized recycling strategy.[1]

Currently, when recycling a combustion engine vehicle, intact parts are removed. For example, an old engine can be reused in a new vehicle with engine damage. The remaining materials, which are not needed, are separated into their pure types. Batteries from EVs can also be reused. Often, after their use in vehicles, they are used as stationary storage. Since they are not charged and discharged with such high power there, they still have a very long life for this use. For instance, a single 20kWh electric car battery can suffice as an energy storage for a family household.[2]

However, as can be seen from the given examples, vehicle components are either used in a used car or even repurposed in a different area. This is where the transition from a linear to a circular model comes into play. The goal of the circular economy is to reuse as many raw materials and materials from an old vehicle in a new vehicle as possible. For example, in the area of bodywork, there are indeed alternatives to the common scrap press, in which the metal parts along with plastic are pressed into a cube. However, for such alternatives, changes must already be made during production, for example, replacing the still common welding or riveting connections with laser beam soldering, where the connection can be dissolved again at a temperature of around 900°C (steel

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[1] cf. Marr, 2023, accessed: 16.01.2024.

[2] cf. ADAC, 2023, accessed: 16.01.2024.

only melts at a temperature above 1600°C), so that the old parts can be installed in a new vehicle without damage.[3]

With such ideas and techniques, the transition from the so-called 'take-make-waste' economy to a so called 'Closed Material Loop' economy is to be realized. To achieve this, it is crucial to consider carefully during the material selection process whether and how they can be recycled and restored to their initial state. In addition, attention must be paid to CO2 emissions during production, in the use of the vehicle, and during recycling, and optimized as much as possible.[4]

The 9R Framework that stands for Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, and Recycle, provides a concrete basis for planning the life cycle of a new product. This framework can also be applied to the automotive sector with minor adaptations. Figure 17 shows how the individual steps can be applied to the development of a new vehicle. The European Union has also written proposals in a press release on the legal framework conditions that should be set to promote the circular economy in the European vehicle industry. Among other things, this is intended to achieve significant CO2 savings by 2035 and also reduce dependence on raw material suppliers by processing used materials into reusable raw materials.[5]

3.2 Robotic Recycling in the Automotive Industry

Currently, most of the research into the recycling of vehicles is focused on the disassembly, recycling, and separation of the battery packs of EVs. This chapter will focus on ongoing and finished projects that investigate the recycling of the "rest of the vehicle". The disassembly and recycling of batteries will be covered in chapter 3.3.

3.2.1 Disassembly

The first step of recycling a complete car is the removal of fluids and dangerous materials, such as lubricants, batteries, antifreeze, and fuel, alongside parts of the Vehicle that can be reused as spare parts, and catalysators.[6] Due to the high variety of different cars, it is currently not common to utilize robotics in this task, and is done manually, or using heavy machinery.[7]

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[3] cf. Fraunhofer-IWU, 2023, accessed: 16.01.2024.

[4] cf. Holst/Lacy/Reers/Schmidt/Tillemann/Wolff, 2023, accessed: 16.01.2024.

[5] cf. European-Commission, 2023, accessed: 16.01.2024.

[6] cf. Umweltbundesamt, 2022, accessed: 09.01.2024.

[7] cf. ASM-Recycling, 2015, accessed: 09.01.2024.

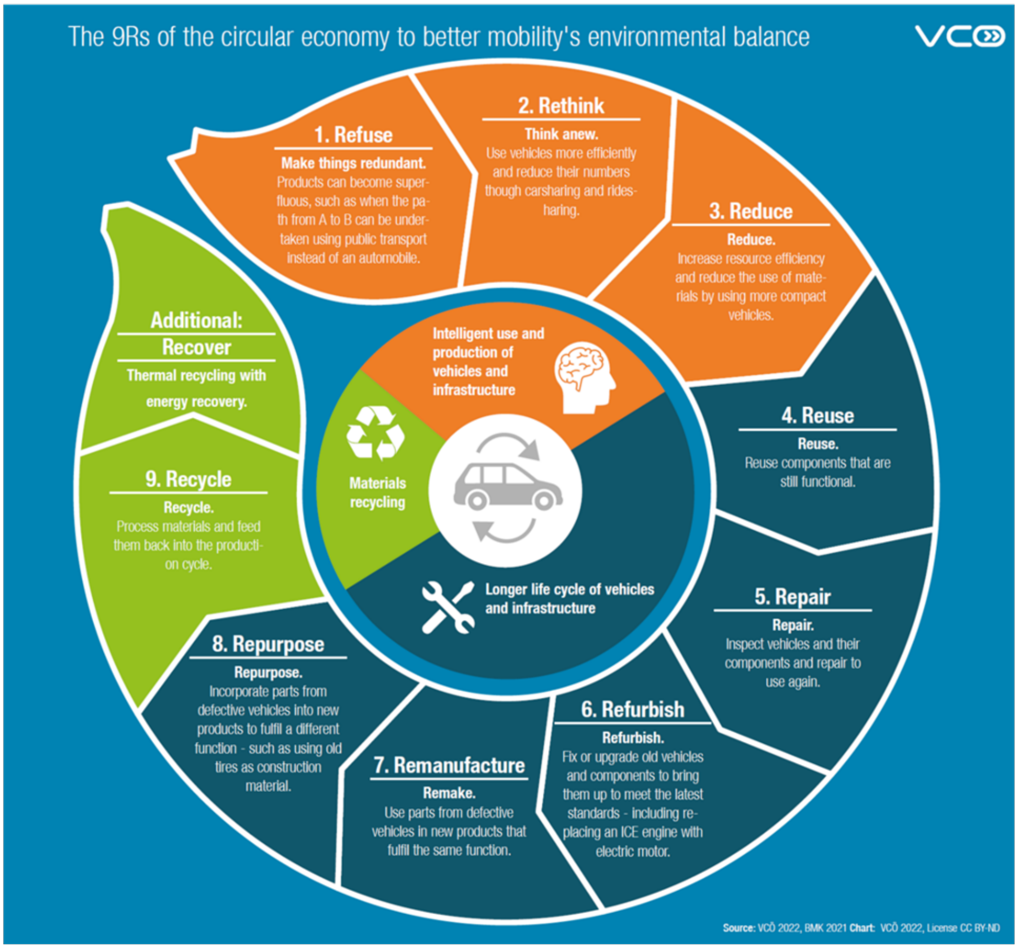

Figure 17: The 9Rs of circular economy in the automobile industry,
Source: VCOE (2022)

Current research into robotics in disassembly includes projects by the Technical University of Berlin, and the Technical University of Vienna, which see 6-axis robots or SCARA robots disassemble washing machines, displays, mobile phones and PCBs. The Technical University of Braunschweig conducted a project involving human-robot cooperation to dismantle Li-ion batteries.[8] The research project DeMoBat, among other things, looked to find a concept for a flexible disassembly system both for batteries and electric motors.[9]

Stemming from a diverse product palette, and the unknown condition a vehicle might arrive in at a disassembly line, automated disassembly requires a large

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[8] cf. Fleischer/Gerlitz/Rieß/Coutandin/Hofmann, 2021, accessed: 09.01.2024.

[9] cf. Baden-Württemberg, 2023, accessed: 09.01.2024.

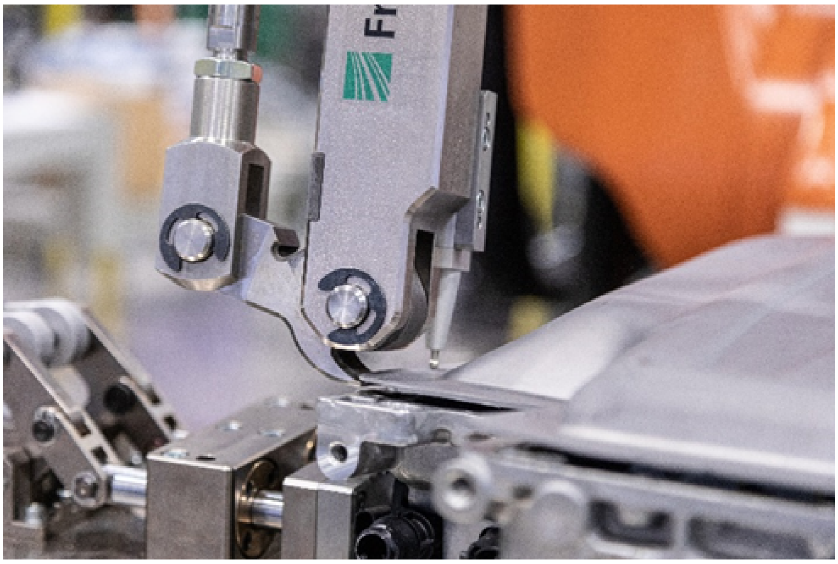

Figure 18: Flexible tool for separating glued joints, Source: Fraunhofer IPA (2023)

degree of flexibility.[10] This needs to be addressed both on a hardware and a software level. Hardware wise, robots need to be equipped with multipurpose tools or interchangeable specialized tools to hold and manipulate, and destructively or non-destructively separate parts. Software wise, a disassembly sequence could be generated with AI support, with point of interests such as screws, gripping/manipulation points, gears, or magnets.[11]

3.2.2 Separation

One of the challenges of circular economy of materials is separating the different raw materials of a car. The currently used method is to shred the vehicle into fist-sized chunks,[12] which are then separated into ferrous metals and non-ferrous materials using magnetism, as well as air currents and float-sink-tanks to separate plastics from non-ferromagnetic metals. The remaining non-metals are disposed of in an incinerator.[13] Many EVs are driven by permanent magnets, which are a valuable source of materials. They contain neodymium and cobalt, so-called rare earth elements (REEs). In theory, the easiest and most sustainable way to recycle a magnet would be to simply re-use it as is, but in practice, reclaimed existing magnets would very rarely fit a given application. One proposed solution to recover magnets from old vehicles or faulty rotos involving melting the rotor down and separating the magnet alloy from the molten metal,

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[10] cf. Fraunhofer-IPA, 2023, accessed: 10.01.2024.

[11] cf. Fleischer/Gerlitz/Rieß/Coutandin/Hofmann, 2021, accessed: 09.01.2024.

[12] cf. ASM-Recycling, 2015, accessed: 09.01.2024.

[13] cf. Umweltbundesamt, 2022, accessed: 09.01.2024.

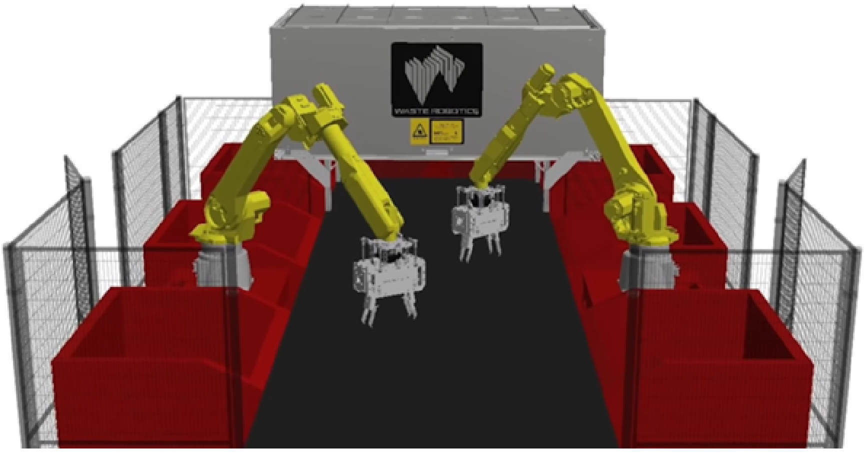

Figure 19: Recycling line for separating waste by material, Source: FANUC (2019)

rather than the currently used cost- and time intensive demagnetizing, manual disassembly, and removal.[14]

3.2.3 Recycling

One way to make recycling vehicles more economical is by raising the purity of the materials. Re-melting, purifying, and alloying the metals is necessary to make recycled metal used. The research project Car2Car aims to raise efficiency by drastically improving the purity of extracted materials.[15] Using AI based material recognition technology and laser-induced breakdown spectroscopy, the proposed system is able to separate not only glass, plastics, and metals – a highly automated process like this could separate metals by specific steel or aluminum alloy, resulting in secondary raw materials of high purity that are easy and economical to reintroduce into the production of new vehicles.[16]

3.3 Closing the Loop

3.3.1 Material selection

Optimizing the circularity of materials and components is a key element in conserving resources and minimizing environmental impacts. There are many ways for optimizing processes in recycling companies in general, but especially

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[14] cf. University, 2021, accessed: 09.01.2024.
[15] cf. FANUC, 2019, accessed: 09.01.2024.
[16] cf. BMW-Group, 2023, accessed: 09.01.2024.

in Automotive production a key important factor for improving environmental balance already lies in the design of a car. First of all, Engineers have the choice to use recycled materials for different components of the car.

Volvo: Recycled material in plastics

For example, the automobile manufacturer "Volvo" has set itself the goal to reach a rate of at least 25 percent of containing recycled material in plastics used in newly launched Volvo models until 2025. They also have launched a prototype of their SUV XC60, that contains components of the interior made of renewable fibers and plastics made from discarded fishing nets and ropes. The doormats of this prototype are made from fibers from PET plastic bottles and leftovers from clothing manufacturers. Furthermore, the seats are made of shares of PET fibers from plastic bottles, and even used car seats from old Volvo vehicles are reused as sound-absorbing material under the engine hood.[17]

Audi: Reuse of shredded material

"Audi" is currently researching about materials from shredded vehicle bodies, which are separated into material groups like steel, aluminium, and plastics. They then define which materials could be used to produce new vehicles. In a first test, steel coils for interior door parts with a secondary rate of material-loop of around twelve percent were produced.[18]

3.3.2 Use of Advanced Industrial Robots

Apart from the material selection, the use of industrial robots, also thematized in the previous chapter, is a very important step into a faster and safer recycling process for automotive applications. Currently, it is estimated that only around 20 percent of newly installed robots use sensors such as image processing or force-torque sensors to adapt programs or trajectories. With the usage of advanced sensors and Artificial Intelligence (AI), robots can recognize patterns in data and use this knowledge to solve problems. It is a big chance for the future of recycling when robots can evaluate data and derive actions from it without the intervention of an operator. For example, robots could be able to recognize different types of screws and welds and can then select the suitable procedure for separation of materials. In this way it is possible to do non-destructive disassembling of modules of a car on a grand scale in the shortest

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[17] cf. Volvo, 2018, accessed: 15.01.2024.

[18] cf. Günnel, 2023, accessed: 09.01.2024.

time possible. With the use of many different sensors, robots can also be used to sort the disassembled parts afterwards and decide what to do with them.[19]

3.3.3 Efficient “Closing the Loop”

The high costs of manual recycling are one of the main reasons why the recycling rate of car parts is rather low nowadays and not sufficient for future environmental targets. The recycling with the use of high advanced Industrial Robotics could be a big step towards the important “Closing the Loop” of materials used in Automobile Industry because it is way more cost effective and efficient than manual disassembly and sorting by hand.

3.4 Challenges

The principles of the circular economy aim to minimize waste by practises such as repair products instead of deposit them (for that the products have to be built repairable), if not repairable remanufacture it or in the last step reuse the materials of the product. In the automotive industry there are several challenges that hinder the implementation of those principles of circular economy. Some of them are listed below:

3.4.1 Regulatory complexity

The introduction of the principal Robots for Circular Economy in the automobile industry is significantly influenced by complex regulatory landscape. The different regulations and norms on national and international level makes it even harder to develop and apply uniform standards. The central challenges are to create a consistent legal framework that allows to implement a circular economy with robots. For this problem the European Commission creates the first step in this direction. They try to create a basis for a harmonised regulations that should create the transitions to sustainable practices.[20] In July 2023, a new regulation for batteries was approved by the EU with the aim to create a harmonized legislation for the sustainability and safety of batteries.

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[19] cf. Recycling-Magazin, 2022, accessed: 15.01.2024.

[20] cf. European-Commission, 2020, accessed: 15.01.2024.

3.4.2 Consumer Behaviour and Perception

Consumers often associates new products vs refurbished or remanufactured products with more quality, a higher reliability or the latest technology level. Also, preferences for specific brands or social status, as well as trends highly impacts the customer decisions. A key challenge is to raise consumer awareness and change their behaviour in relation to recycled materials and reused components. Education campaigns and knowledge transfer are important to achieve the trust of the customers of the quality and security of recycled materials. This requires multidimensional approaches that are jointly supported by industry, NGOs and government agencies.[21]

3.4.3 Technological Challenges

The step to integrate robotics to the recycling process in the automobile industry is an important step for the circular economy. But there are technological challenges. The use of robots for the precise identification, dismantling and sorting of vehicle components requires continuous innovation because the car industry is constantly bringing new vehicles onto the market and compatibility is not always given. To increase the efficiency and precision of the recycling process it is essential to do an in-depth review and further development of robot technologies.[22] A key-role here is the research and development to create customised solutions for specific requirements of the automobile industry.[23]

3.4.4 Economic considerations

A factor to consider in the transition to a circular economic model in the automobile industry are economic considerations. There is a necessary investment in new technologies, infrastructures and training of workers that will be a high financial burden for companies. Incentives in the form of subsidies and other financial incentives are needed to facilitate this transition. For this the MacArthure Foundation is a key-player by highlighting the economic and business reasons for a faster transition to a circular economic.[24]

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[21] cf. Bocken/Short/Rana/Evans, 2013, accessed: 16.01.2024.

[22] cf. Barwood/Rahimifard, 2014, accessed: 15.01.2024.

[23] cf. Li, 2016, accessed: 15.01.2024.

[24] cf. Ellen-MacArthur-Foundation, 2013, accessed: 15.01.2024.

3.4.5 Extended Producer Responsibility (EPR) Implementation

"Extended producer responsibility (EPR) is gaining considerable traction as a mechanism for increasing recycling rates and re-enforcing the value of circularity principles. This policy approach shifts costs and responsibility for managing waste from municipalities to producers. EPR has been implemented in many countries for various product categories, such as packaging, electronics, batteries, tires, and pharmaceuticals. From production to disposal, EPR aims to promote the circular economy and reduce the environmental impact of a product's life cycle."[25]

3.5 Conclusion and Recommendations

The automotive industry's transition towards a Circular Economy aims to maximize the reuse and recycling of materials in future vehicle generations. Current vehicle construction heavily relies on natural resources, and the objective is to progressively reduce this dependency by incorporating recycled materials. This leads to positive impacts to the CO2 balance and holds the potential for increased profitability by optimizing recycling strategies for expensive and critical raw materials.

1. Integration of Robotics in Disassembly:

- Advocate for widespread robotics use in disassembly to enhance efficiency.

- Invest in flexible robotic hardware and software solutions for varied disassembly requirements.

2. AI-driven Material Recognition and Sorting:

- Emphasize AI-driven material recognition to enhance material purity.

- Implement robotics with advanced sensors for efficient sorting based on material composition.

3. Collaboration for Circular Design Implementation:

- Encourage industry collaboration to implement circular design principles.

- Support initiatives like the 9R Framework, adapting it for holistic planning of vehicle life cycles.

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[25] cf. Diversys, 2023, accessed: 16.01.2024.

4. Address Regulatory Complexities:

• Collaborate with regulatory bodies to streamline and harmonize regulations related to robotics in the circular economy.

• Engage with efforts to establish consistent legal frameworks, facilitating the transition to sustainable practices.

In conclusion, the integration of robotics into Circular Economy practices within the automotive industry holds immense potential for fostering efficiency, sustainability, and cost-effectiveness. By addressing challenges through technological innovation, collaborative partnerships, and regulatory alignment, the industry can open the way for a more sustainable and efficient automotive ecosystem. These recommendations serve as a strategic roadmap, guiding the sector towards a future where vehicles are not only produced but also recycled in a manner that minimizes environmental impact and maximizes resource conservation.

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4 Battery Production

4.1 Circular Economy

Since the demand for energy storage in form of high-capacity batteries in everyday items like power tools, notebooks, tablets or electric vehicles is growing day by day, more and more batteries are needed.[1] This also means that in the future the amount of used batteries will increase.[2]

Today smaller battery-packs like the ones found in electronic devices or power tools are collected and transported to special facilities. There, the different battery-types will be sorted (e.g. lithium-ion, nickel-metal hydride). After sorting, the batteries will be broken down into its components, such as plastics and metals.[3] The metals will be reused in other batteries and the remaining residue, which cannot be recycled, will be disposed in other ways.[4]

Lithium, cobalt and nickel are one of the main materials of car batteries, which can cause environmental damage by mining in unethical and unsustainable ways.[5] Jaffe states that, battery production will also be limited if no new mines are established, or circular economy retracts materials for production.[6] Besides the positive effects on the environment, it would also be profitable, as the battery causes 50% of the car production costs, and 70% of the battery costs are caused by the materials itself.[7] Hence the importance that batteries get integrated into a well-developed product cycle.

Considering the rising demand of batteries in electric vehicles (EV), it is obvious, that recycling batteries in a circular economy will be inevitable compared to 2019, it is expected to gain 6 to 30 times more EV sales by 2030, which will lead to an excessive amount of discarded EV batteries. The number of batteries at

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[1] cf. L.Wang/X.Wang/Yang, 2020, p. 115328.

[2] cf. Wrålsen/O'Born, 2023, p. 554-565.

[3] cf. L.Wang/X.Wang/Yang, 2020, p. 115328.

[4] cf. Wrålsen/O'Born, 2023, p. 554-565.

[5] cf. Ahuja/Dawson/Lee, 2020, p. 235-250.

[6] cf. Jaffe, 2017, p. 225-228.

[7] cf. Michaelis/Rahimzei/Brückner/Rottnick, 2021.

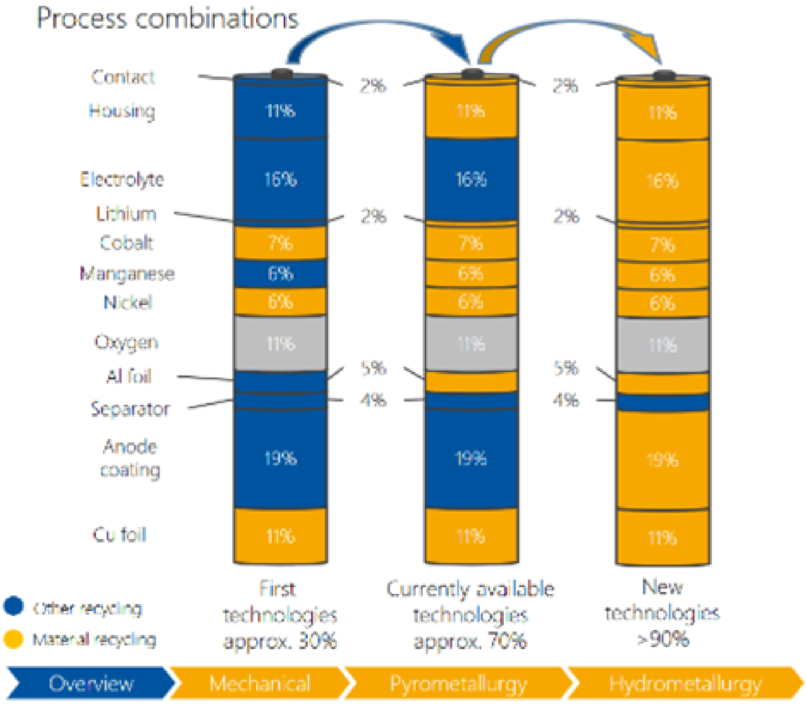

Figure 20: Process combinations in battery recycling, Source: Michaelis/Rahimzei/Brückner/Rottnick (2021)

the end of 2025 is expected to be about 3.4 million discarded end of life EV batteries with about 953 GWh of capacity.[8]

Mainly there are two options to integrate these batteries into this product lifecycle:[9]

- **A complete breakdown into individual materials:** Nowadays there are already a lot of possibilities to recycle batteries.[10] Even tough recycling technologies allow us to recycle up to 70% of a battery, it is necessary to develop new technologies to increase the quote up to 90%. This goal can be achieved by combining several different process technologies, as shown in figure.[11]
- **A second life cycle:** Giving batteries a second life is currently tested by a few different companies. Every pack which is still usable regarding capacity, will be reused. For example, to use them as storage for solar energy or wind energy or for grid infrastructure support. Batteries used as second-life batteries have the advantage of already being there and not producing any more waste.[12]

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[8] cf. Almeida/Baskar, 2022, p. 134066.
[9] cf. L.Wang/X.Wang/Yang, 2020, p. 115328.
[10] cf. Wrålsen/O'Born, 2023, p. 554-565.
[11] cf. L.Wang/X.Wang/Yang, 2020, p. 115328.
[12] cf. Wrålsen/O'Born, 2023, p. 554-565.

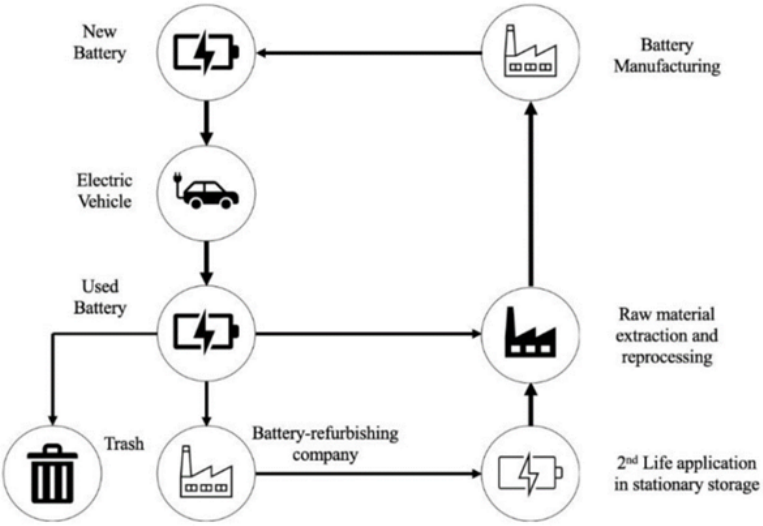

Figure 21: possible ways of treatment for used batteries, Source: Michaelis/Rahimzei/Brückner/Rottnick (2021)

4.2 Robotic Innovation

A very detailed brochure by Michaelis et al. describes both the steps in manually disassembling automotive battery packs, as well as challenges in automating the process: While automation would be required to afford disassembly at an industrial scale, lack of standardization of battery packs would be a hindrance. Some "partially automated disassembly steps by human-robot collaborations" are already in use.[13]

4.2.1 Manual Disassembly

Takahashi describes Nissan's manual disassembly process, which has the aim of extracting and evaluating battery cells. It employs nine engineers, previously including one of the designers of the Nissan Leaf. The battery cells extracted this way ("hours spent on each pack") are considered too expensive to compete with newly produced ones. Lander et al. estimated manual and robotic disassembly times and costs for several battery packs and assume that the Nissan Leaf (in its 2018 version, which also has a larger battery pack) would require about 480 minutes to disassemble manually but only 110 minutes semi-automatedly.[14] The overall cost of extracted cells is assumed to be 4.85 $/kWh.[15] Takahashi does not mention the actual cost at Nissan. Lander et al.'s assumed labor costs

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[13] cf. Michaelis/Rahimzei/Brückner/Rottnick, 2021.

[14] cf. Thompson, n.d., p. 7585-7603.

[15] cf. Takahashi, n.d.

(24.88 $/hour) could be too low or Nissan spends more person-hours on each battery pack.[16]

Additionally, there has been an advance in battery chemistries: The Nissan Leaf battery cells use an LMO or NMC cathode, the latter of which has the advantage of higher energy density, but also contains more expensive metals (nickel, cobalt). Any second life reuse for stationary storage does not need high energy density but has to compete with newly built cells of the cheaper LiFePO4 chemistry. These have the additional advantage of a longer cycle life and safety benefits.[17]

Takahashi cites a claim that other companies do not attempt second life reuse of their batteries[18] but recycle them using a hydrometallurgical process (described by Baum et al.): Mechanical comminution (crushing, milling), followed by chemical extraction of useful elements.[19] According to Michaelis et al. some laboratory scale manual disassembly does take place at other companies.[20]

4.2.2 Benefits from Disassembly

Thompson et al. point out that disassembly can either lead to a less diluted waste stream that makes hydrometallurgical recycling cheaper in terms of energy input and the amount of chemical solvents needed. Or it allows for a process called "direct recycling": the battery cell would have to be opened, the cathode and anode separated, and the cathode could be remanufactured into a new battery cell. Baum et al. describe an example where fresh Li2CO3 is added to depleted NCM powder and the result calcinated, which yields regenerated NCM powder from which a new cathode can be produced. Because of the flammable electrolyte battery cells have to be opened in an inert atmosphere.[21] While at laboratory scale a glove box can allow for manual disassembly, this is likely insufficient for industrial scale recycling (speed, safety).[22]

A prototype of a machine that could perform this task for pouch cells is presented by Li et al. A machine for cylindrical and prismatic cells would also have to remove the hard outer shell.[23]

Thompson et al. go further and argue that battery packs should also be designed in such a way that later disassembly becomes easier. For example, they mention

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[16] cf. Lander, 2023, p. 120437.

[17] cf. Harper, 2019, p. 75-86.

[18] cf. Takahashi, n.d.

[19] cf. Baum/Bird/Yu/Ma, 2022, p. 712-719.

[20] cf. Michaelis/Rahimzei/Brückner/Rottnick, 2021.

[21] cf. Thompson, n.d., p. 7585-7603.

[22] cf. Baum/Bird/Yu/Ma, 2022, p. 712-719.

[23] cf. Li, 2019, p. 4457-4464.

an ″opposite tab alignment″, where battery cathodes and anodes are arranged as many alternating layers above each other, instead of one large area cathode and anode layers that are rolled up and put into a cylindrical cell. In addition battery packs that use structural adhesives between cells are criticized, as these may have to be debonded using solvents.[24]

4.2.3 Automating the Process

Choux et al. assume that some level of automation will be required to make extracting battery cells an economical alternative to the comminution of the whole pack. An important part of disassembly is removing the electrical connections between battery modules and battery cells. Lander et al. assume welded tabs can be cut in 40 seconds by workers, a screw connection undone in 14 seconds and other parts removed by hand in 6 seconds.[25] They propose that most cost savings from automation could already be achieved by automating only some of these steps.[26]

A first step toward automation is such a collaborative/hybrid approach, where industrial robots and human workers perform tasks each is better at. Kay et al. show that a robot arm might cut welded battery tabs at twice the speed of a human and with better accuracy. This would also increase the safety of human workers, since producing a short circuit between battery terminals could lead to a thermal runaway. But humans are faster at pick and place operations – they have better dexterity and can recognize objects faster and more accurately. The article proposes human workers could remove those battery components that are not battery cells. This would have the advantage that less training would be required than for a fully manual operation.[27]

Wegener et al. demonstrate undoing screw connections. Visual object classification tries to estimate which bit to use on each screw head, and an automatic tool changer can swap out the one used by the robot arm’s electric screwdriver. They do not rely on automated task planning yet, but propose “physical demonstration”, where a human moves the robot arm to each relevant location. While such a process may be used to program assembly operations, disassembly would encounter different types of battery packs and would have to demonstrate movements for each.[28]

Choux et al. consider the development of a fully robotic approach inevitable, but this would require research on automated task planning and better image-based

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[24] cf. Thompson, n.d., p. 7585-7603.

[25] cf. Lander, 2023, p. 120437.

[26] cf. Bigorra/Tyapin, 2021, p. 387.

[27] cf. Kay/Farhad/Mahajan/Esmaeeli/Hashemi, 2022, p. 4856.

[28] cf. Wegener/Chen/Dietrich/Dröder/Kara, 2015, p. 716-721.

object recognition. The challenge is that a disassembly robot could not just execute the movements of the manufacturing robots in reverse: the movement plans that the pack manufacturer had used would not be available to another company, and the battery pack may not be in the same state as after assembly. Deformations due to an accident and damage to fasteners due to age have to be expected. Therefor they implemented an automated task planner that can propose an optimal sequence of disassembly operations. It does not require a priori knowledge of the disassembly strategy or CAD drawings provided by the manufacturer. The system can recognize screws, connectors and external electronics based on a 3D camera and the state of-the-art YOLO algorithm for object recognition. According to the discussion there is unfortunately a trade-off between computing time and detection accuracy. But the authors assume their approach can in future allow economical disassembly down to at least battery cell level.[29]

4.3 Closing the Loop

Due to the threatening impacts of the greenhouse gas driven climate change it is obvious that there is a need to reduce CO2 emissions. To achieve this and further carbon neutrality, energy storage systems in the form of Batteries are necessary. This however results in a very high demand of raw materials such as Lithium, Aluminium, Copper, etc. for the manufacturing process. With a typical lifetime of only 4-6 years the reuse and recycling of spent batteries will become more and more important.[30]

4.3.1 Strategies for improving the circularity of batteries

The 3R model, consisting of reduce, reuse and recycle as depicted in Figure 1, can be applied to reduce the environmental impact of a new Lithium-Ion battery design. Reduce means to minimize the required raw materials, the landfill amount and to increase the efficiency of the battery. Another option is the reuse of a Battery. Which increases the operational time of the battery resulting in a higher utilization of the materials used. Examples for this would be a spent vehicle battery which is reused as a backup power system in residential areas, or a laptop battery reused as an LED battery in off-grid regions. As Lithium-Ion batteries contain various valuable elements and toxic chemicals which would

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[29] cf. Kay/Farhad/Mahajan/Esmaeeli/Hashemi, 2022, p. 4856.

[30] cf. Kang, 2023, p. 108072.

damage the environment when disposed improperly, recycling is an important step towards circularity.[31]

Figure 22: 3R model (reduce, reuse, recycle), Source: Goyal/Singh/Bhatnagar (2023)

4.3.2 Recycling

The processes involved in the Recycling of Lithium-Ion batteries are sorting, dismantling and shredding. Afterwards there is the possibility to either use a hydrometallurgical or a pyrometallurgical process to extract the valuable elements. Pyrometallurgy is a well-known process in which the waste gets melted and valuable materials such as Cobalt and Nickel are extracted. The hydrometallurgical technique uses aqueous solutions to recover the necessary metals from the cathode material. Compared to the pyrometallurgical approach the hydrometallurgical process has several advantages such as a higher recovery rates of the metals, less energy expenditure and no toxic air emissions.[32]

4.3.3 Re-use

Extending the life of electric vehicle battery packs by repurposing them for residential energy storage offers environmental benefits by shifting energy

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[31] cf. Li, 2019, pp. 4457–4465.
[32] cf. Goyal/Singh/Bhatnagar, 2023, p. 119080.

usage away from peak periods. However, the environmental impact of using these batteries at home depends on the electricity's source. Even with a high proportion of renewable energy sources, using these batteries might increase emissions compared to not using them due to inefficiencies during charging and discharging. In some cases, particularly when the difference between daytime and nighttime impacts is small, this method might be less effective than doing nothing.[33] From an environmental and economic standpoint, the re-use of batteries is preferable to recycling.[34]

4.3.4 Robotics in the battery production Cycle

The disassembly of battery packs has shifted from manual handling to a collaborative process involving both humans and robots. Despite this transition, there lacks a defined approach to evaluate the effectiveness of human-robot collaborative disassembly concerning environmental impact, technical feasibility, and economic viability in dealing with spent lithium-ion batteries. The concept of humanrobot collaboration holds great promise for battery disassembly, particularly considering the intricate and uncertain nature of taking apart EV batteries.[35] Disassembling waste batteries poses challenges due to their varying degrees of deformation, diverse product structures (including architecture, shape, and material), and the presence of hazardous elements. Consequently, the future of scientific and technological advancement is likely to lean towards collaborative efforts between humans and robots during the disassembly process.[36]

4.4 Challenges

The use and recycling of more and more battery-powered devices will pose several challenges. Some of these have already been discussed in earlier chapters of this report, but the following sections cover the key issues.

4.4.1 Technological Contrains

The technological limitations differ greatly between production and recycling. Production is fully automated using robotic systems, while recycling requires a

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[33] cf. Faria, 2014, p. 169-177.
[34] cf. Goyal/Singh/Bhatnagar, 2023, p. 119080.
[35] cf. Yuan/Liu/Zhang/Pham/Li, 2023, p. 106878.
[36] cf. ibid., p. 106878.

hybrid system of machine and human due to the advanced complexity of the process.[37]

When the manual or automated process for locating the vital parts of the battery is already exhausted, the limiting factor is the working speed of the tools. It is not only important to get the job done in the shortest possible time, but also to minimize wear and tear to remain economical.[38]

The recycling rate is already quite high, for example 90% of lithium can be recovered through a combination of mechanical, thermal and chemical treatment, as well as filtration. This should be the benchmark for creating truly efficient recycling systems.[39]

4.4.2 Supply chain complexities

In terms of batteries, waste can be a valuable resource as the materials used are only mined in a few countries around the world. Therefore, a supply chain must be created that provides the global market with sustainable raw materials.[40] The storage of used batteries should be avoided at all costs due to the potential dangers to humans (thermal runaway) and the environment (electrolyte leakage). A global market should therefore be created to make recycling as cost-effective and convenient as possible.[41]

An interesting approach would be for a recycling company to specialize in a particular type of battery and purchase it on the global market. However, attention must be paid to the emissions generated during transportation. Different customers require very different battery systems. For example, a distinction must be made between a mobile application in a forklift truck and a stationary application as energy storage for solar systems. Supplying the optimum battery for each customer can be very efficient but involves a great deal of logistical effort and data traffic that should not be underestimated.[42]

4.4.3 Policies and regulatory hurdles

The EU, the USA and China enacted more and more regulations of processing procedures of waste batteries. This is related to the growing global spread of

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[37] cf. Wegener/Chen/Dietrich/Dröder/Kara, 2015, p. 716-721.

[38] cf. Kay/Farhad/Mahajan/Esmaeeli/Hashemi, 2022, p. 4856.

[39] cf. Velázquez-Martínez/Valio/Santasalo-Aarnio/Reuter/Serna-Guerrero, 2019, p. 68.

[40] cf. Harper, 2019, p. 75-86.

[41] cf. ibid., p. 75-86.

[42] cf. Almeida/Baskar, 2022, p. 134066.

electric vehicles. The focus here is on the environment, i.e. on green recycling routes. In the following, only a few regulatories are mentioned as examples.[43]

In the EU the regulatories started in 1991 with the Council Directive 91/157/EEC about the storage of batteries with the toxic materials Hg, Cd and Pb. The Council Directive 2006/66/EC define the minimum collection objective, the recycling objective and rate. It requires that the recycling processes recover at least 50% by mass. Further regulatories limit the usage of Hg and Pb in batteries or reduce the greenhouse gas emissions.[44] In the Instruction 2018/851 are some recommendations for the circular economy.[45]

In the USA, the California Cell Recycling Act was enacted in 2006. It is a collection system for batteries to recover and reuse them. The latest regulatories of 2023 are minimizing for example the emissions of fugitive lead dust. Besides the „Battery Safety Initiative for Electric Vehicles" (2023) demands that data related to electric vehicles batteries has to be collected and analyzed to understand battery defects and improve their safety.[46]

China released 2020 Industry Standards for Comprehensive Utilization of Waste LIBs in Automobiles. They demand a recovery efficiency of Li $\geq$ 85%, waste water $\geq$ 90% and Co, Ni, Mn $\geq$ 98%. Furthermore there are regulatories for a collection and recycling network and guides for Automobile LIBs recycling service (2019).

4.4.4 Environmental concerns

It is important to handle end-of-life batteries very careful because of the high hazard potential. A thermal runaway, a fire hazard or a chemical leakage are possible due to chemical chain reactions, flammable substances, short circuits or mechanical damage.[47]

Chemical recycling has the ability to eliminate hazardous substances from used batteries. But many chemicals are needed and harmful byproducts are produced like wastewater and exhaust gases, which have an impact on the environment. Hazardous substances are produced by mechanical recycling techniques, too.[48]

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[43] cf. Kang, 2023, p. 108072.

[44] cf. ibid., p. 108072.

[45] cf. Velázquez-Martínez/Valio/Santasalo-Aarnio/Reuter/Serna-Guerrero, 2019, p. 68.

[46] cf. Kang, 2023, p. 108072.

[47] cf. Michaelis/Rahimzei/Brückner/Rottnick, 2021.

[48] cf. Kang, 2023, p. 108072.

The Pyrometallurgical process produces toxic flue gases. Using this technique requires the downstream method to avoid breaking the environment requirements.[49] In addition the calcination and combustion of the batteries incur environmental and high energy costs.[50] Biorecycling has the potential for a lower energy consumption and environmentally friendly recycling of waste batteries, if it is compared with chemical or mechanical techniques. But the techniques are in the early stage of research.[51]

4.5 Conclusion

In conclusion, it is very important that the loop of batteries is closed to achieve low resource abundance, high profitable products and low CO2 production emissions and simultaneously allowing to expand our future demand of batteries in everyday products and transportation systems.[52]

A closed cycle can be achieved either by reusing the battery or by recycling the battery. With all advantages and disadvantages side by side (e.g. water consumption, lower emissions), there is a relatively low threshold for environmental benefits by giving batteries a second life. So, second life batteries should be a big aspect of the whole product life cycle. Not only from the environmental viewpoint, but also from an economic side.[53]

That is why the focus should stay on recycling, in which robots are particular in use. In collaboration with humans, robots are already capable of dismantling and processing batteries down to cell level.[54] At the current state of technology, it is possible to recover up to 90% of the lithium in lithium-ion batteries.[55] Although the technology in robotics is already very advanced, research must be continued. It has been proven that batteries contain very toxic and environmentally harmful substances. The aim should therefore be to be able to recycle batteries completely autonomously without the direct presence of humans.[56]

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[49] cf. Baum/Bird/Yu/Ma, 2022, p. 712-719.
[50] cf. Goyal/Singh/Bhatnagar, 2023, p. 119080.
[51] cf. Kang, 2023, p. 108072.
[52] cf. Michaelis/Rahimzei/Brückner/Rottnick, 2021.
[53] cf. Wrålsen/O'Born, 2023, p. 554-565.
[54] cf. Kay/Farhad/Mahajan/Esmaeeli/Hashemi, 2022, p. 4856.
[55] cf. Velázquez-Martínez/Valio/Santasalo-Aarnio/Reuter/Serna-Guerrero, 2019, p. 68.
[56] cf. Goyal/Singh/Bhatnagar, 2023, p. 119080.

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5 Non Electronic Consumer Industry

In our rapidly changing world, the idea of the circular economy, which prioritizes efficient resource use and waste reduction, is gaining traction. At the forefront of driving this transformation are robots and smart machines, revolutionizing countless aspects of our daily lives. These robots are not mere futuristic concepts; they are actively reshaping how we handle resources and waste. From revolutionizing plastic and packaging practices to streamlining waste management in construction, robots are key players in fostering sustainability.

In metal recycling, robots with artificial intelligence, like the "AIRSS" from companies such as ETIA, are driving advancements. They streamline the sorting and recycling of various metals, contributing to a more circular economy. While glass recycling faces challenges, robots and smart technology offer potential solutions, especially in efficiently handling heavy glass waste. In textiles, robots simplify recycling by identifying and sorting different clothing types, promoting a more sustainable fashion industry.

Addressing the complexity of managing leftover waste, robots with artificial intelligence play a crucial role in sorting and maximizing recycling efforts. In summary, this article highlights how robots are becoming indispensable partners, actively shaping a more sustainable and circular future across various industries.

5.1 Plastics and Packaging

In the consumer goods industry circular economy is already an important concept and robotics can have a significant impact in wider implementation, especially in the field of plastics and packaging. Production efficiency, sustainability as well as waste management can be significantly improved through the intelligent use of robotics.

5.1.1 Circular Economy in the Consumer Industry

By improving the efficiency of production processes as well as reducing waste consumer companies can use robotics to adopt circular practices. For instance, robotics can be used to redesign and improve plastic packaging in order to make it more reusable and recyclable.[1]

5.1.2 Robotic Innovations

In order to improve production efficiency and sustainability Robotics is already being widely used throughout the entire lifecycle of consumer goods. One example being recycling robots with the ability to sort and separate different plastic materials and components, improving recycling processes.[2] Another great possible use case for robotics would be developing digital passports and software to provide information about the history of a given piece of packaging and thereby simplifying waste management.[3]

5.1.3 Closing the Loop

Robotics can be a crucial part in enabling the dismantling, recycling and reintegration of consumer goods back into the production cycle. With the use of specialized recycling robots, it is possible to obtain more recyclable materials from waste streams, providing a greater volume of high-quality secondary resources.[4] Another great opportunity for the use of robotics would be to tackle challenges related to tracking and managing waste streams, ensuring that all plastic packaging can be processed accordingly.[5]

5.1.4 Challenges

The implementation of circular economy practices within the consumer industry is currently hindered by various obstacles, such as limitations in technology, complexities in supply chain management and consumer behaviour. Despite these hurdles, robotics can help address these challenges by improving production efficiency, sustainability, and waste management.[6]

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[1] cf. Foundation, 2024, accessed: 17.01.2024.
[2] cf. Laskurain-Iturbe, 2021.
[3] cf. Beuken, 2023.
[4] cf. Laskurain-Iturbe, 2021.
[5] cf. Foundation, 2024, accessed: 17.01.2024.
[6] cf. Accelerating the Circular Economy, 2024, accessed: 17.01.2024.

5.1.5 Recommendations and Conclusion

In order to implement circular economy practices in the consumer industry, particularly in the plastics and plastic packaging sector, the following suggestions can be made:

1. Incentivize and provide technical assistance for the switch to use plastic packaging that is designed for reuse and recycling, using robotics to improve production efficiency.

2. Promote the use of reusable packaging and ensure that all plastic packaging is fully reusable, recyclable, or compostable. With the aid of robotics allowing for efficient disassembly, recycling, and finally reintroduction of these materials into the production cycle.

3. Generate significant investments in robotics and automated systems that improve recycling processes, waste management and tracking.

4. Develop digital passports and software providing valuable insights into the lifecycle of packaging and waste streams. By putting these suggestions into practice, the consumer industry take the first step to move towards a more sustainable and effective sector. This will help to decrease plastic pollution and support the adoption of a circular economy for plastics, with the help of robotics.

5.2 Construction and Demolition Waste

5.2.1 Circular Economy in the Consumer Industry

A essential part of the consumer industry is the construction sector and therewith the waste that gets produced. Construction and demolition waste is a significantly part of the total waste amount. In Austria for example the parts of total waste has been 16,1% construction waste and 59,0% excavated material. From 2015 to 2019 the rates of construction waste increased up to 15% and the excavated material increased about 28%.[7]

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[7] cf. Klimaschutz Umwelt Energie Mobilität Innovation und Technologie, 2021, accessed: 19.01.2024.

5.2.2 Robotic Innovations

Probably one of the biggest chances for improving the recycling process and circular economy of construction waste is the sorting of waste by AI-based robots. The company ZenRobotics - A Terex Brand is the leading supplier of intelligent sorting robots for waste systems that can sort waste with robotic pickers up to 30kg. They are used for bulky construction waste.[8] The main parts of a system like this are basically a conveyor belt, a AI-based optical detection, robotic pickers and ejection channels. The company Lundstams in Sweden uses a system from ZenRobotics for sorting construction waste, metal waste and wood waste. The two robots in their company can handle approximately four thousand picks, the system is running 24/7 and the efficiency increase is about 20x compared to manual processing.[9]

5.2.3 Closing the Loop

Because of the big amount of the construction and demolition waste improvements would have big effects. Both, the bigger amount and the better quality of recycled materials are essential for the circular economy with focus on the construction sector.

5.2.4 Challenges

The size of companies that recycle construction waste is probably not always big enough to afford a modern robotic sorting system, respectively they do not have enough waste-flow-rate that a system like this requires. Transportation to bigger central recycling centers or modernizing of existing facilities are possibilities to improve efficiency.

5.2.5 Recomendations and Conclusion

Some recycling companies already show that the increasing of the efficiency of sorting and recycling is possible. The future aims should be to improve the technology for more flexible using, also for applications with smaller flow-rate of waste.

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[8] cf. ZenRobotics, 2023, accessed: 06.12.2023.

[9] cf. ibid., accessed: 06.12.2023.

5.3 Metal Packaging

5.3.1 Circular Economy in the Consumer Industry

A big part of the consumer industry is metal packaging. Tin cans, beverage cans, steel belts or aluminum foils are just a few examples we can find in our daily lives. But what happens to all that stuff after their time of usage is over? This is where circular economy comes into place. Getting used metal back into the economy can save a lot of energy. Reusing aluminum only needs 5 percent of the energy that would be needed for new aluminum. This is not only important to reduce costs but also to save the environment. However, to make this possible a certain responsibility of every consumer is needed because a big key for recycling is the correct separation of packaging materials.[10]

5.3.2 Robotic Innovations

Not only in the consumer industry but basically in every part of our live robotics have the potential to make our lives easy or to increase the maximum performance. This is also true for the recycling sector of the economy. The more you invest into recycling technology the more money you can save on the other side. For this reason, French designing group ETIA developed the "AIRSS". "AIRSS" is a scrap metal sorting solution using AI controlled robots. The main benefit of this system is on-line waste stream analysis with real time data collection providing information about every object on the conveyor belt. This system has to main components. On one side there is the Intelligent Robotic Sorting System with the features machine Learning, optimal vision and robot configuration. On the other side there is a robotics system with a customizable gripping device/robotic arm that uses Artificial Intelligence and Vision to automate manual sorting tasks at waste recycling plants. Each robotic arm can reach up to 60 picks per minute.[11]

5.3.3 Closing the Loop

After the separation process the ferrometals are used to produce steel again. Examples, where used ferrometals get back into the economy are steel or tinplate packaging such as cans, canisters, and closures as well as structural

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[10] cf. Klimaschutz Umwelt Energie Mobilität Innovation und Technologie, 2023, accessed: 19.01.2024.

[11] cf. ETIA-Ecotechnologies, 2023, accessed: 19.01.2024.

steel. Recycled aluminum on the other hand is used for aluminum foil, beverage cans and yogurt lids.[12]

This means the better the quality of separation is in the process, the better the quality of new materials is going to be. So, recycling really is a process that starts with responsible consumers that know how to separate their waste correctly as well as advanced technologies for separation like robots, which means there is still big potential for improvements.

5.3.4 Challenges

With the steadily increasing world population also the amount of metal waste is increasing. For that reason, one challenge is to develop machinery that is capable of handling big flows of waste in separation and all the other processes afterwards. Another challenge is to keep costs low because if the costs for recycling technologies are much higher than the money you can potentially be saving with reusing old materials there will not be much motivation to do that. Additionally, showing consumers the importance of recycling and separation is also critical.

5.3.5 Recommendations and Conclusion

As the research above shows there is still a lot of potential in the recycling industry and especially in the metal sector because it is possible to save a lot of energy. This shows the importance of using new technologies like robotics and artificial intelligence and why it is important to support research and development of new technologies as the whole world can benefit from it. Companies can save money and energy and there is less pollution for the environment as waste does not just get thrown away but is brought back into the economy repeatedly.

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[12] cf. Austria, 2023, accessed: 19.01.2024.

5.4 Glass Packaging

5.4.1 Circular Economy in the Consumer Industry

Glass is the perfect example of a Circular Economy. The recycling process can be done endlessly without losing its quality. The goal is to extend the life cycle of our products to reduce the environmental impact, by reducing the amount of manufacturing from raw materials. Glass is therefore a well-suited material for a sustainable future and will play an important role in our daily lives.[13]

5.4.2 Robotic Innovations

The recycling industry has seen some innovations in recent years. The sorting of the different glass types is done by optical, X-ray and near-infrared sensors. These sensors can quickly evaluate the chemical composition and colour of the shredded glass. Advanced technologies like artificial intelligence and machine learning algorithms help to sort and process the waste glass and make high recycling rates over 90% possible.[14]

5.4.3 Closing the Loop

The loop in a circular-economy consists of three steps: reduce, reuse and recycle.

- By reducing non-renewable materials using glass, the amount of waste can be lowered. Also, the reduction of energy consumption necessary for production can be reduced.

- Collecting and reusing the glass bottles is a core component of the Circular Economy. The bottles are collected and washed up to 50 times before getting recycled.

- The recycling of glass bottles is done by melting the old glass bottles and form new ones. It has no impact on the quality and can be done endlessly.[15]

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[13] cf. Friendsofglass, 2024, accessed: 18.01.2024.

[14] cf. Jacoby, 2021, accessed: 18.01.2024.

[15] cf. Friendsofglass, 2024, accessed: 18.01.2024.

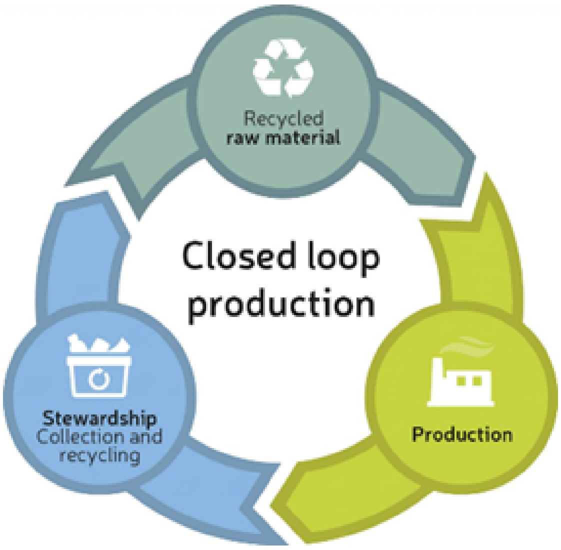

Figure 23: Closing the Loop, Source: Friendsofglass (2024)

5.4.4 Challenges

The challenge in recycling glass, therefore closing the loop in the circular-economy, is the transportation of the reused glass bottles and broken glass waste. Glass is heavy and expensive to transport. A big problem is also the fast and efficient sorting of the broken glass. To face the high volume, sorting by machines, which uses new technologies like artificial intelligence and machine learning, are required. It is very important not to mix different coloured glass to achieve high quality later in production.[16]

5.4.5 Recommendations and Conclusion

It is always better to purchase less glass, especially single-use glass items. Instead focus on reusable packaging materials when possible. Correct separation is crucial for effective recycling, there are different types of glass and they cannot be mixed. Overall glass is a sustainable packaging material, which can be used in multiple forms in our daily life. Therefore, we have to overcome the given challenges to clean up our packaging.

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[16] cf. Forest, 2019, accessed: 19.01.2024.

5.5 Textile Industry

5.5.1 Circular Economy in the Textile Industry

Textile waste constitutes a significant portion of our overall waste. According to the Environmental Agency of Austria, approximately 221,800 tons of textiles end up in waste each year in the country.[17] However, currently, less than 1% of textiles are recycled into new clothing Scaling textile recycling in Europe.[18] This wasteful practice harms the environment and, consequently, human well-being. A pivotal aspect of the circular economy for textiles is the recycling and re-usability of materials. However, automatic sorting of textiles poses a significant challenge. Here, new innovations and the use of robotic technologies can offer solutions.

5.5.2 Robotic Innovations

Historically, distinguishing and separating different textiles automatically has been challenging due to the similarity of materials. Recent innovations in robotics and automation provide opportunities to overcome these problems. For instance, the "Fibersort" system utilizes Near-Infrared (NIR) cameras to determine the fabric composition, enabling automatic differentiation between various textiles[19] Another RGB camera is then used to sort the fabrics based on their color. In a workshop addressing textile waste, Queensland University of Technology developed a pilot system where humans collaborate with robotic vision systems to optimize textile recycling.[20]

5.5.3 Closing the Loop

To enhance the re-usability and recyclability of textiles and reinforce the circular economy, a shift in the mindset of the textile industry is crucial. A significant issue currently faced is fast fashion, where numerous, low-quality, and cheap garments are produced within a short time. Instead of enticing customers with quality, the focus is on convincing them through low prices. Consequently, purchased garments often end up in the trash after a short period of use. According to Greenpeace, 30% of produced garments in industrialized countries

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[17] cf. 5Kestler, 2022, accessed: 19.01.2024.

[18] cf. Hedrich/Janmark/Langguth/Magnus/Strand, 2022, accessed: 19.01.2024.

[19] cf. Valvan, 2023, accessed: 19.01.2024.

[20] cf. Technology, 2024, accessed: 19.01.2024.

are not even sold.[21] To ensure a functioning circular economy, prioritizing quality over quantity is essential. This promotes the reusability of items and reduces the waste of resources that can no longer be utilized.

5.5.4 Challenges

There are several obstacles on the path to a functional circular economy in the textile industry. Technologically, efficiently separating and preparing textile waste for reuse remains a challenge. Systems in this industry are still in the process of maturing and are not widely adopted. Additionally, a global shift in the industry's mindset is necessary. Consumers, in particular, need to be aware that purchasing fast fashion harms the environment. A circular economy can only succeed if fashion chains prioritize quality over quantity.

5.5.5 Recommendations and Conclusion

The textile industry holds tremendous potential for the circular economy. A functional recycling system for textiles conserves resources and, consequently, saves money. Moreover, it can significantly contribute to environmental relief. Recent innovations in robotics have demonstrated the feasibility of automation in textile recycling. However, it's important to be aware that consumers themselves can significantly influence the circular economy with their purchasing decisions.

5.6 Residual waste

5.6.1 Circular economy in the consumer industry

As a significant representative of the total waste amount, which resultsfrom everyday consumer goods consumption, residual waste represents a substantial portion, the improvement of which (in terms of minimizing this share) would have extensive benefits in reducing environmental pollution. In Austria alone, approximately 1.4 million tons of residual waste are produced annually, with the majority being disposed of through thermal treatment (incineration).[22]

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[21] cf. Greenpeace., 2024, accessed: 19.01.2024.

[22] cf. Klimaschutz Umwelt Energie Mobilität Innovation und Technologie, 2021, accessed: 19.01.2024.

5.6.2 Robotic innovations

The significant or even primary challenge in residual waste lies in sorting individual components (organic waste, plastic, textiles, glass, etc.). Regarding sorting, we can discuss two fundamental functions of a robotic system – recognizing and separating individual types of materials from the total amount of the residual waste. The solutions that could fully or largely replace the human factor in recognizing different materials, and in this way lay the foundation for robot-controlled residual waste management, are undoubtedly robotic systems based on AI technology. After the successful material recognition, robotic grippers separate and sort the elements according to their composition. "AMP-Robotics" offers solutions for sorting mixed waste with an accuracy of up to 99% and up to 80 "picks" per minute.[23] The primary components of such a system include a conveyor belt for feeding the waste mass, cameras for material type recognition with integrated AI technology, and robotic arms for separation and sorting. There are also solutions without detection and recognition of material type, where residual waste is sorted based on its weight. While these solutions may not achieve the accuracy of systems with integrated AI technology, they have significantly higher sorting capacity. Such solutions are provided by the company "NIHOT".[24]

5.6.3 Closing the loop

Non-recyclable waste currently accounts for less than 40% of residual waste in Austria.[25] Due to a relatively high proportion of materials in the residual waste that can be recycled, such as plastic and metal packaging, textiles, glass, batteries, rechargeable batteries, etc., there is probably some potential for improvement in this area, the impact of which on the amount of recycled waste and therefore on the circular economy itself is indisputable.

5.6.4 Challenges

The limited capacity of waste management systems, the large amounts of waste that need to be sorted (especially in areas with high population density) and ultimately the cost of robotized systems, which are intended to increase the proportion of recycled waste in total waste amount, are obstacles to their application.

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[23] cf. AMPRobotics, 2024, accessed: 19.01.2024.

[24] cf. NIHOT, 2024, accessed: 18.01.2024.

[25] cf. Institut für Abfallwirtschaft, 2020, accessed: 19.01.2024.

5.7 Recommendations and conclusion

The combination of systems with high sorting accuracy (systems with integrated AI technology) and systems with high sorting capacity could mitigate the obstacles to the use of robotized systems. In addition to the use of robots to identify waste types, it is equally important to increase the effort of each individual person in sorting waste to the greatest extent possible. This could reduce the detection and sorting effort of the robots and simplify the integration of robotized systems into the circular economy.

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6 Elektronics

6.1 Circular Economy in Electronics

The rapid evolution of technology in the electronics industry has transformed our lifestyles, leading to a surge in electrical and electronic equipment (EEE). However, this has also resulted in a substantial increase in waste electrical and electronic equipment (WEEE).[1] Approximately 54 million tonnes of WEEE were generated globally in 2019, highlighting the urgent need for a shift towards a circular economy in electronics.[2] As the electronics industry faces increasing pressure to adopt circular practices, the influence of the European Union and changing business models become pivotal.

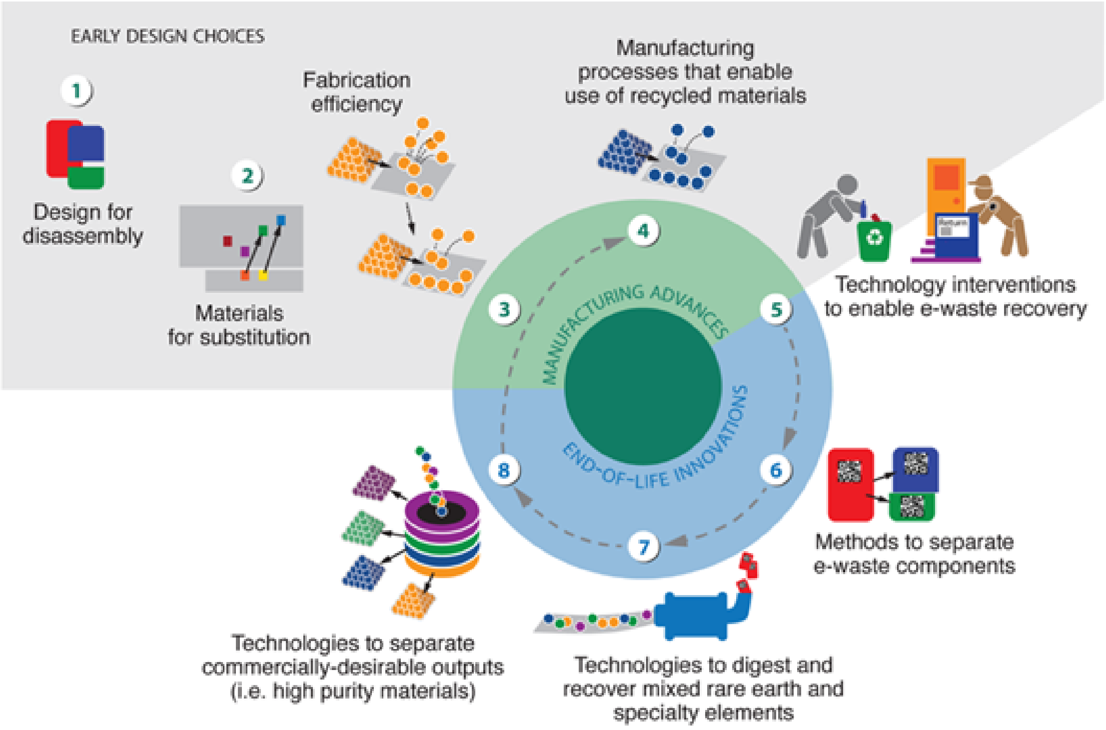

Figure 24: Vision of Circular Economy, Source: O'Connor (2016)

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[1] cf. Shittu/Williams/Shaw, 2021.

[2] cf. Forti/Baldé/Kuehr/Bel, 2020.

However, overcoming the inertia of linear product life cycle management requires a comprehensive approach. Green engineering and robotics offer innovative solutions to drive sustainability and circularity in the industry, providing a pathway to a cleaner and more efficient electronic waste management system.[3]

To embrace a circular economy, a fundamental change in product life cycle management is essential. This shift must prioritize durability, recyclability, and reduced toxicity.[4] While current recycling methods focus on mechanical processes like disassembly and shredding, they often neglect the potential residual reuse value of products. Urban mining, emphasizing material recovery from discarded electronics with residual functionality, presents an opportunity to extract maximum value before resorting to recycling. Product reuse emerges as a critical strategy in extending the usage cycle of devices with residual value.[5]

Green engineering, in tandem with robotic technology, plays a crucial role in ushering in a circular economy within the electronics industry. This dynamic combination not only fosters sustainable material supply chains but also enhances the efficiency of e-waste recovery processes. The integration of green engineering and robotics stands out as a transformative force, significantly contributing to the overarching objective of minimizing environmental impact.[6] Embracing a circular economy in electronics involves several key strategies like shown in Figure 24. Firstly, adopting a modular design approach ensures products have standardized, easily disassembled structures, promoting recycling and reuse. This shift includes substituting rare elements with alternatives like REE-free magnets and lead-free solders. Additionally, enhancing fabrication efficiency, especially for rare elements, is crucial, utilizing novel metal deposition methods and increased synthetic efficiencies. Redesigning manufacturing processes to incorporate recycled materials minimizes energy consumption and waste, contributing to a sustainable supply chain. Implementing e-waste recovery technologies, akin to HP's successful cartridge return program and policies like the WEEE Directive, fosters higher recycling rates. Establishing infrastructure for efficient e-waste component separation, possibly through electronic indexing for automated sorting, streamlines the recycling process.[7]

This is important so that, the synergy of green engineering, robotics, and circular product design paves the way for a sustainable electronics industry, prioritizing durability, recyclability, and reduced toxicity.

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[3] cf. Kirschner, 2022.

[4] cf. ibid.

[5] cf. Shittu/Williams/Shaw, 2022.

[6] cf. Connor/Zimmerman/Anastas/Plata, 2016.

[7] cf. ibid.

6.2 Rare Earth Recycling

The term 'Rare Earth Elements' (REE) refers to scandium, yttrium, and 15 elements from the lanthanide series. This section will discuss the health and environmental challenges posed by REEs, as well as recycling opportunities. These elements have unique physical properties that make them useful in various applications, particularly in electronics. Key components such as silicon chips, displays, and permanent magnets contain REEs.

Despite their advantageous properties, the use of these elements has a negative impact at different stages of their lifecycle. Mine workers and those who regularly handle REEs are at the greatest risk of health problems due to direct contact with chemicals and dust. Additionally, primary recovery and processing can cause environmental issues. Toxic materials, chemicals, and rare earth materials pollute the air, groundwater, and subsoil. This pollution harms wildlife, vegetation, and human populations in extraction areas. Radioactive elements such as uranium and thorium, which are present in mining minerals, are particularly alarming. At the end of their lifecycle, large amounts of e-waste are inadequately dumped, leading to additional pollution.

The rising demand for rare earth elements (REE) and their concerning environmental impact have encouraged research into recycling technologies. The main challenge is the small amounts of rare earth elements distributed across many different products. Efficient recycling is essential for economically sensible and broad application. Various approaches exist for this purpose. The first approach is shredding, which has the advantage of being able to process many kinds of e-waste on a large scale. However, only a small percentage of rare earth elements (REE) can be extracted through the process, leaving a significant amount of shredded waste that is both unused and harmful. In addition, harmful substances, metals and chemicals create a working environment that is hazardous to people's health.[8]

The second method is manual extraction. Sprecher compared the virgin production, shredder, and manual recycling of neodymium in hard drives. Both recycling methods deliver better results in terms of energy use and human toxicity than mining. However, shredding leads to recovery rates below 10%.[9] The recovery rate and environmental advantage of manual recycling can also be transferred to robotic applications. Industrial robots may be decisive for efficiency in this area. Robotic recovery of rare earth elements (REE) faces a significant challenge due to the wide range of electric products. Recycling involves four main steps: collection, dismantling, separation, and processing. One possible solution is to focus on a specific product, such as smartphones,

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[8] cf. Shin/Hyun-Ock/Kyung-Taek, 2019.

[9] cf. Sprecher/Yanping-Xiao/Walton/Speight/Harris/Kleijn/Visser/Kramer, 2014.

and program the robot to dismantle and separate these devices. However, this approach requires increased pre-sorting effort and is only efficient for large-scale products. Detection software and AI could gradually expand the range of models and devices that can be processed in future.

6.3 Repairability for Prolonged Use

Every year, 35 million tonnes of waste, 30 million tonnes of resources and 261 million tonnes of greenhouse gas emissions are generated in the EU as a result of products that are tossed away prematurely but can actually still be repaired.[10] The best way to save resources is to utilise resources that have already been used for as long as possible, i.e. to extend the lifetime of products. The goal of extending the lifetime is largely determined by the reparability of the products. "Repair is key to ending the model of 'take, make, break, and throw away' that is so harmful to our planet, our health and our economy" (Frans Timmermans, Executive Vice-President for the European Green Deal - 22/03/2023).[11] The possibility of repair starts with the replaceability of components such as the battery or the display, which is made more difficult by gluing instead of screwing and continues with the availability of the components to be exchanged, which must be available individually and inexpensively. To push forward the conservation of resources in this way, the EU has introduced the "right to repair". This was adopted by the European Parliament on 21 November 2023. This gives consumers the right to request a repair for products such as washing machines, hoovers, smartphones or also bicycles even after the warranty period has expired. If a product cannot be repaired, a reconditioned appliance will be offered instead.[12] One of the largest sectors in electronics is the smartphone industry, with over one billion devices sold every year.[13] In order to improve the repairability of smartphones, different manufacturers take different approaches. The manufacturer Apple primarily offers repairs in its own stores, but since December 2022 Apple has also been offering self-service repairs. For now (2022), this service is available in eight European countries, including Germany and France. This service offers the purchase of original spare parts and the loan of professional tools to facilitate repairs at home. Figure 25 shows the Apple Self Service repair kit for the iPhone.[14] In the top left corner, for example, you can see a device that is used to heat the glue in order to remove the display.[15]

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[10] cf. European-Commission, 2023b, accessed: 07.01.2024.

[11] cf. ibid., accessed: 07.01.2024.

[12] cf. European-Commission, 2023a, accessed: 07.01.2024.

[13] cf. Statista, 2023, accessed: 07.01.2024.

[14] cf. Apple, 2023, accessed: 07.01.2024.

[15] cf. Apple, 2022, accessed: 07.01.2024.

Figure 25: Apple Self Service-repair-kit for iPhone13, Source: Apple(2023)

Figure 26: Fairphone components, Source: Fairphone (2023)

Another approach that has repairability as a top priority is used by the manufacturer Fairphone. It uses a modular design to make repairs from home as easy as possible. Figure 26 shows all components, such as battery, display, camera, processor, speaker, etc., which can be easily exchanged with a single screwdriver.[16] This increases the lifetime of the mobile phone not only because it is easy to repair, but also because individual components can be replaced, for example to improve the camera quality or processor performance. This means that the other components of the mobile phone, whose performance is still sufficient, are not thrown away but reused.

6.4 Robotic Innovations

A large amount of rare earths and speciality elements are used in the field of electronic technologies. Many innovative strategies are needed to recover these materials from complex waste streams. One strategy to promote the vision of a circular economy has already been described in chapter 6.1 Circular Economy in Electronics. There in step 6 robots can help to collect and separate e-waste components. One example of such a robot is Apple's recycling robot "Daisy", shown in Figure 27. It is able to disassemble 23 different iPhone models in just 20 seconds.[17] At the end of 2022, two examples of "Daisy" already existed. One in Breda, Netherlands and the second in Austin, Texas.[18]

To disassemble the iPhone, the robotic arm grabs the mobile phone and guides it into a holder to detach the display. In the next step, the glued battery is removed with a blast of ice-cold air and a targeted push. The screws and other components are then removed by punching them out. Finally, the individual parts are sorted and stored.[19]

6.5 Closing the Loop

6.5.1 Strategies for closing the circular loop

Nowadays is crucial for that manufacturers of electronic components focus on escaping from the regular practices of manufacturing process and reanalyse it through prism of lifecycle of the product, allowing the circular economy to be applied. To make use of circular economy the reverse logistic system should be

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[16] cf. Fairphone, 2023, accessed: 07.01.2024.

[17] Apple, 2018, accessed: 08.01.2024.

[18] cf. futurezone, 2024, accessed: 08.01.2024.

[19] cf. futurezone, 2023, accessed: 08.01.2024.

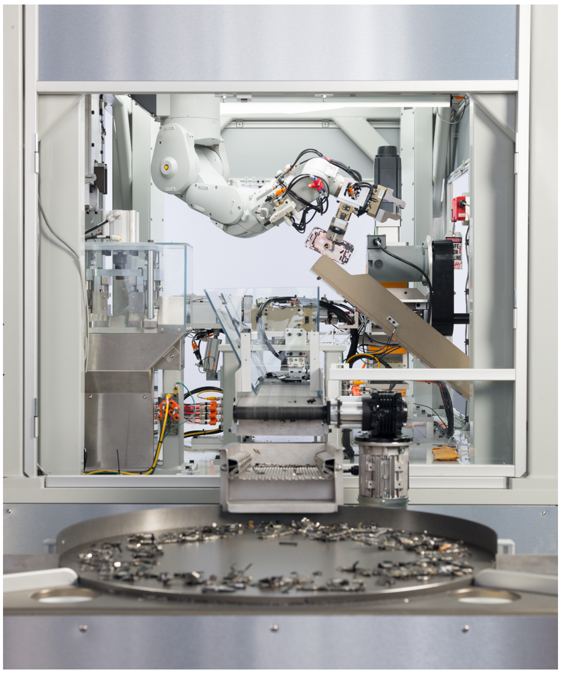

Figure 27: Apple's recycling robot "Daisy", Source: Apple (2018)

Figure 28: Apple's recycling robot "Daisy", Source: Apple (2018)

established. By that it means rethinking the forward logistics flow “suppliers → producers → distributors → customers” in a way that it creates a return flow of end-of-life products, components and materials. Manufacturers and suppliers may utilize recycled components or materials from distributors and customers as secondary resources in their manufacturing processes for creating recycled end product.[20]

Developing a particular strategy within the companies should enable the processes to close the circular loop. Essentially, there are two primary areas that the closing strategies should focus on:

- minimization of waste
- maximization of reuse, recycling and regeneration of materials and resources.[21]

To accomplish both of these objectives, the primary focus should be on recycling and reuse rather than disposal. After the end-of-life of the product the following recycling types could be applied:

1. Direct recycling or reuse: refers to the process of using a product once more for the same or a different purpose without undergoing significant additional processing.[22]

Significant role here plays the design of the product. Changing of the design of the product to ease disassembling, repair and recycling enables the lifespan of a final product and decreases the possibility for waste generation. Excellent illustration of successful application of such a concept is the product line of a company Fairphone that was already discussed in chapter 2.3 Repairability for Prolonged Use.[23]

2. Remanufacturing: refers to the process of repairing a product so that it, along with any of its parts or subassemblies, can be used once again.[24] It requires creation of the necessary infrastructure for the recycling of materials and components from dismissed products. One of the proper examples could be a Hewlett-Packard with their robust recycling and resource recovery programs that was discussed in chapter 2.1. Circular Economy in Electronics.[25]

3. Reprocessing of recyclable material: In this instance, goods are broken down into parts that can be utilized again right away or as raw materials to make similar or better goods.

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[20] cf. Alvarez-de-los-Mozos/Arantxa, 2017, p. 55-62.
[21] cf. economic-donut, 2023, accessed: 10.01.2024.
[22] cf. Alvarez-de-los-Mozos/Arantxa, 2017, p. 55-62.
[23] cf. FasterCapital, 2023, accessed: 10.01.2024.
[24] cf. Alvarez-de-los-Mozos/Arantxa, 2017, p. 55-62.
[25] cf. FasterCapital, 2023, accessed: 10.01.2024.

4. Low-level material separation: to provide raw materials that, when processed further, can be utilized to create new devices.[26]

6.5.2 Robotic contribution to close the loop

Including robotics into the recycling, disassembly and reintegration processes introduces the full/partial automation of it, which can solve some of the challenges associated with:[27]

1. Efficiency of disassembling and sorting

Before beginning more damaging procedures like shredding and grinding, the e-waste stream needs to be separated, the constituent goods need to be deconstructed and sorted in order to decrease complexity and maintain material quality. Unfortunately, most of the products are not normally optimized for easy disassembly, lacking the possibility to handle or recognize it.[28] One of the challenging industries in this aspect is recycling lithium-ion batteries from electric vehicles. Because of no standardization in design of battery packs it creates a wide range of different battery packs to be handled. Therefore, the computer vision algorithms are very beneficial to sorting and dismantling process, especially when accompanied with machine reading features, such as RFIDs, QR-Codes etc.[29]

2. Improvement of workers safety

Recycling e-waste sometimes requires handling dangerous materials, which can be harmful to the safety of workers. Since automated robots can operate in isolated hazardous environments, worker safety is guaranteed. Huge improvement was made in dismantling of LCD screens, that could be potentially dangerous for people due to sharp-edged parts and consisting of a mercury and other toxic gases. Therefore, company Votechnik has developed a system based around a Kuka industrial robot to handle the dismantling process of LCD screens and monitors. Within this robotic cell the hazardous gases are extracted and sharped-edged elements are removed. Not only this process eliminates the need for human contact in dangerous environment, but also increases throughput from five to 60 devices per hour and can work 24/7.[30]

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[26] cf. Alvarez-de-los-Mozos/Arantxa, 2017, p. 55-62.

[27] cf. eSmartRecycling, 2023, accessed: 10.01.2024.

[28] cf. Iliev, 2022.

[29] cf. Harper/Sommerville/Kendrick/Driscoll/Slater/Stolkin, 2019, p. 75-86.

[30] cf. Robotics-and-Automation-News, 2022, accessed: 10.01.2024.

3. Enchased material recovery

Robotic systems are able to optimize e-waste material recovery. Advanced sensing technologies allow robots to recognize and distinguish between different components, making recycling more efficient.[31]

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[31] cf. eSmartRecycling, 2023, accessed: 10.01.2024.

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7 Food and Agriculture

7.1 Circular Economy in Food and Agriculture

By applying Circular Economy principles, a path towards a resilient and environmentally friendly future is found in every stage of food production and consumption. Circular Economy promotes the minimization of waste and environmental impact and also the regeneration of resources. In future the efficiency, innovation and sustainability should be brought into reality. Key Principles applied to food and agriculture are:[1]

1. Nutrient Looping:

Implementing closed-loop systems in agriculture involves reusing organic waste as compost or high-value biomass and employing precision agriculture to optimize resource use. Converting organic waste into a source of value begins with effective collection systems and pure waste streams. By closing the nutrient loop, farmers can reduce dependence on synthetic fertilizers and enhance soil health.[2]

2. Zero food waste:

A big challenge for circular economy is the big amount of food wasted through the whole supply chain. Circular Economy principles encourage strategies such as surplus redistribution, composting, and innovative packaging to minimize waste and ensure that every gram of produced food contributes to feed people rather than landfills.[3]

3. Regenerative agriculture:

The circular economy promotes regenerative agricultural practices that prioritize soil health, biodiversity and ecosystem resilience.

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[1] cf. Cairns/Patel/Jessop/Mullen, 2021, accessed: 19.01.2024.

[2] cf. Ellen-MacArthur-Fundation, 2019, accessed: 19.01.2024.

[3] cf. Gustavsson/Cederberg/Sonesson, 2011, accessed: 19.01.2024.

4. Resource efficiency:

The goal of resource efficiency is to reduce the overall environmental footprint. This can be achieved with water recycling systems and sustainable packaging solutions. Sustainable food production involves optimizing resource from energy, raw materials and water.[4]

5. Circular supply chains:

Building circular supply chains requires fostering collaboration between all stakeholders, from farmer and food processors to consumers. To promoting the overall sustainability of the industry and transparency local sourcing, shortening supply chains and introducing circular business models are important areas.

Embracing Circular Economy principles in the food and agriculture sector is not just an option but a necessity for a sustainable future. By integrating these principles into our practices, we can cultivate a resilient and regenerative system that not only nourishes the growing global population but also nurtures the planet we call home.

7.2 Robotics for sustainability

Modern agriculture has one of the biggest shares in global greenhouse gas (GHG) emissions. According to the Consultive Group on International Agricultural Research (CGIAR) agri-food-supply chains consume about 30% of the world's total energy consumption. They are therefore responsible for about one-third of global annual GHG emissions, whereas methane (CH4) and nitrous oxide (N2O) must be particularly emphasized as highest contributors. However, due to dependence of the agricultural sector on fossil fuels, CO2 emissions cannot be neglected.[5]

To mitigate climate change, a reduction of GHG emissions throughout the whole agricultural sector is clearly necessary. However, the increasing demand of food due to the steady population growth and with that an increasing energy demand, decreasing biodiversity and monocultures propose certain challenges. Promoting sustainable agriculture and emission reduction must not have a negative impact on the food security, which means the availability of adequate, safe, and food for all people.[6]

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[4] cf. European-Commission, 2015, accessed: 19.01.2024.

[5] cf. Grojian/Fakhraei/Gorjian/Sharafkhani/Aziznejad, 2022, p. 154ff.

[6] cf. Pearson/Camacho-Villa/Valluru, 2022, p. 57ff.

7.2.1 Robotics in Agriculture and Agri-Food-Supply-Chains

Applications of agricultural robotics and the use of artificial intelligence (AI) provide multiple opportunities for reducing GHG emissions, increasing energy and yield efficiency and can support farmers though the use of automation in food processing and packaging.[7]

In the work of Pearson et al. five focus themes are identified where the use of agri-robotics could have a lasting impact on the transition to sustainable agriculture:

1. Increase of nitrogen use efficiency to reduce N2O emissions
2. Accelerated breeding of crops
3. Transition to lightweight robotic machines to regenerate soils and reduce compaction
4. Transition to electrified robotic vehicles
5. AI to reduce farm waste, including losses due to pests and disease[8]

Particularly noteworthy is the use of robotics in precision farming. Through the usage of optical and soil sensors robotic technologies can detect the required nutrients in the soil, and therefore reduce the amount of fertilizer which leads to an immediate reduction of N2O emissions. It is also possible to measure the moisture content of the soil, thus determine the optimum required amount of water and reduce water wastage. Overall food wastage can also be reduced by the usage of robotics to selectively harvest crops, control pests and weeds or to improve the well-being of animals (i.e. through the swifter detection of illness).[9]

To reduce CO2 emissions, fossil-based machinery in certain areas should be replaced with smaller, lightweight solar-powered agricultural machinery and farm robots. This would not only help the transition towards renewable technologies, but also reduce soil-compaction. Where high energy densities for heavy machinery is required hybrid fuel cell robotic vehicles, powered by H2 could offer an alternative.[10]

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[7] cf. Sparrow/Howard, 2020, p. 820.

[8] cf. Pearson/Camacho-Villa/Valluru, 2022, p. 58.

[9] cf. Sparrow/Howard, 2020, p. 822.

[10] cf. Grojian/Fakhraei/Gorjian/Sharafkhani/Aziznejad, 2022, p. 160.

In the work of Sparrow et al. a list of applications for the use of robotics in agriculture is given. Some examples are:

- GSP-enabled and autonomous tractors and harvesters
- Precision farming systems, especially for pest control and optimal fertilizer usage
- Robotic and automatic feeding stations for livestock
- Robotic milking stations
- Use of robotics for automation in food handling, processing, or packaging[11]

7.2.2 Future development of robotics in a sustainable agriculture

The use of robotics in agriculture offers a lot of benefits, but also must face certain challenges. Some examples for challenges resulting from agri-robotics are high investment costs, thus leading to a further concentration of ownership and benefiting large farms, protecting biodiversity, and securing employment (especially in remote areas). To face these challenges and ensure sustainability, Sparrow et al. suggest the development of robots which are suitable for small-scale, local, and biodiverse usage. Robotic vehicles must be able to sufficiently perform in unstructured environments and deal with various environmental influences. Therefore, the usage of semi-autonomous systems which require human oversight should be prioritized.[12]

7.3 Food Waste Reduction

The use of robotics technology to combat food waste is a promising strategy. The first point of focus is in the agricultural sector. Precision agriculture is the combination of agriculture and robots equipped with new sensors and satellite navigation, working in conjunction with the Internet of Things. This allows for the monitoring and improvement of agricultural production, for example by measuring the nutrient content of the soil and then working precisely at these locations with the exact dosage of fertilizers. Similarly, automatic adjustment of animal feed supply can lead to greater efficiency. Robot technology also helps to

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[11] cf. Sparrow/Howard, 2020, p. 819.

[12] cf. ibid., p. 822.

improve production in harvesting and packaging of food.[13] The second point involves the integration of robotics technology in the processing of food surpluses and waste. Robots are intended to help optimize resources and minimize waste. One idea to reduce waste is to focus on the food categories of bakery products, fruits, and vegetables, as they make up more than half of the wasted food.[14] For example, robots could autonomously process bread and baked goods into durable bread crumbs or croutons after the store closes, while fruit could be turned into jams or compotes. Additionally, the remaining vegetables could be used to create a powdered soup base or vegetable chips. Another idea is to integrate robots with existing software applications to combat food waste. To name just a few of the many apps: To Good To Go or Foody Bag. With these apps, consumers can purchase discounted bags of good surplus food. In conjunction with modern robot technology, robots could help evaluate the surplus food, assemble such bags, and even deliver them. Future applications could include analysing consumer behaviour and coordinating or directly communicating with precision agriculture to ensure efficient use of food resources. Overall, the use of robotics technology offers a promising opportunity to reduce food waste and ensure sustainable food supply.

7.4 Composting and Waste Management

7.4.1 Composting in Austria

Composting describes the biological breakdown of biomass by fungi and bacteria, making it a central component of natural cycles. The result of this process is compost or humus, the oldest and most natural fertilizer known to us.[15] Bio-waste, the starting material, includes the corresponding biogenic waste according to the EU Waste Framework Directive, such as biodegradable garden and park waste, food and kitchen waste, waste from the food and feed industry, roadside greenery, and so on. In Austria in 2021, approximately 3,253,000 tons of biogenic waste were generated, of which approximately 2,559,000 tons were separately collected. Of these, 1,830,000 tons are "pure" biogenic waste, 729,000 tons are other separately collected biogenic waste, and about 694,000 tons are found in mixed municipal waste.[16] These numbers illustrate the potential for commercial and automated processing, which generates data through digital systems to optimize the process in the future and improve the quality of the end product.

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[13] cf. Schrijver, 2016, p. 4.

[14] cf. Obersteiner/Luck, 2020, accessed: 10.01.2023.

[15] cf. Kompost-und-Biogas-Verband, 2019, accessed: 16.01.2024.

[16] cf. Klimaschutz Umwelt Energie Mobilität Innovation und Technologie, 2023, p. 160.

7.4.2 Commercial Composting

In the process of commercial composting, bio-waste is piled up in long compost rows, called heaps.[17] To obtain nutrient-rich soil from them, it is necessary to maintain the right temperature, humidity, and aeration, requiring regular mechanical turning of the heaps. This mechanical turning is currently carried out by an operator using a diesel-powered compost turner or conventional loader. The operator is exposed to challenging conditions due to high ambient temperatures, released gases, and odors.[18] The strict regulations of commercial composting are governed by the Compost Regulation and require traceability of the starting material, as well as regular temperature measurement and documentation of individual compost heaps. Manual measurement using specialized probes and documentation results in a significant amount of time and effort.[19]

7.4.3 Autonomous and Electric Compost Turner

Subsequently, a project related to this topic conducted at TU Graz is presented, involving the Institute of Technical Logistics, the Institute of Geodesy at TU Graz, the Institute of Logistics and Material Flow Technology at Otto-von-Guericke University in Magdeburg, and the companies Pusch & Schinnerl and Sonnenerde.[20]

Projects "ANTON" and "ANDREA"

The goal of the "ANTON" project and its follow-up project "ANDREA" was to automate composting using satellite-based navigation technologies (GNSS) and to develop and test a navigation module and control module for an autonomous, electrically powered compost turner. Furthermore, it was evaluated whether an autonomous compost turner would bring about increased efficiency compared to a manually operated vehicle.[21]

The compost turner features two GNSS antennas and image-based sensors, allowing for highly accurate machine orientation. The use of Real-Time Kinematic GNSS (GNSS-RTK) enables high-precision real-time positioning down to centimeter accuracy in previously unknown environmental conditions. The fusion of GNSS-based position data with acceleration sensors, gyroscopes, and

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[17] cf. Bensa-Cruz, 2023, accessed: 16.01.2024.

[18] cf. Technische-Universität-Graz, 2024, accessed: 16.01.2024.

[19] cf. Bensa-Cruz, 2023, accessed: 16.01.2024.

[20] cf. ibid., accessed: 16.01.2024.

[21] cf. Technische-Universität-Graz, 2024, accessed: 16.01.2024.

Figure 29: Autonomous and electric compost turner, Source: Futurezone (2023)

magnetometers in an Extended Kalman Filter increases the system's robustness.[22] A LiDAR sensor, also known as laser radar, is used for positioning and 3D mapping, enabling obstacle detection and avoidance. If a new obstacle is detected, the 3D map is updated simultaneously.[23]

Initially, the compost turner autonomously explores the area with the piled heaps and creates a 3D map. The operator of the facility then specifies when each heap should be turned, and the robot autonomously generates an optimal route using an algorithm and follows it. During this process, the temperature is measured by a sensor, automatically logged, and fed into a database. The conditions and temperatures of the compost heaps are thus continually visible,[24] and the traditional manual temperature measurement and logging are eliminated.[25]

Outlook

After successful testing of a prototype, the automation in the "Conclusion" project will be increased. The goal is for the compost turner to know which heap to turn next without human input, thus operating completely autonomously.[26]

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[22] cf. Technische-Universität-Graz, 2024, accessed: 16.01.2024.
[23] cf. Bensa-Cruz, 2023, accessed: 16.01.2024.
[24] cf. ibid., accessed: 16.01.2024.
[25] cf. Technische-Universität-Graz, 2024, accessed: 16.01.2024.
[26] cf. Bensa-Cruz, 2023, accessed: 16.01.2024.

7.4.4 Foreign Substances in Compost

The removal of foreign substances from organic waste poses a particular challenge. Conventional sorting methods often face limitations in this regard. One issue is the high moisture content of the waste, making sorting via air pressure discharge impossible. After compressing the moist materials, moisture levels decrease, allowing for the removal of thin plastic films through air separation. However, rigid plastics, glass, and metal remain.[27]

Steinert, with its UniSort Unibot, provides a solution for sorting using robots in this context. The unique feature here is the attachment: Unlike conventional ″pick and place″ robots commonly used for sorting plastics and other recycling materials, a newly developed ″pick to pick″ attachment is employed. This prevents over-sorting due to adhesion and precisely sucks up the finest contaminants. This attachment is self-cleaning, low-maintenance, and designed for continuous use.[28] The sensor technology is shared by the Unibot with other sorting machines in the Unisort EVO 5.0 series. Steinert uses a sensor combination of high-resolution hyperspectral NIR (Near-Infrared) and color cameras.[29] NIR covers a spectrum of light between 760 and 2500nm, allowing the detection of material-specific patterns based on molecular vibrations when excited by light.[30] Furthermore, AI-based recognition software is employed. This software utilizes ″Intelligent Object Identifiers″ that, in addition to the visually identifiable characteristics, also recognize and consider the optical appearance of objects. This leads to an improvement in the sorting process and an increase in sorting efficiency.[31] A modern high-speed delta robot, paired with the ″pick to pick″ attachment described earlier, allows for up to 60 picks per minute. The robot cell is customizable and can be expanded with an additional delta robot to further increase throughput.[32]

7.5 Handling Food Products

The integration of robots into the food industry has revolutionized production processes and resulted in enhanced efficiency and precision. Robots have been employed in food manufacturing since the 1980s. Since then, the market for food robotics is expanding, with most food producers utilizing at least one robotic system. As technology continues to advance, regulatory bodies such

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[27] cf. EU-Recycling, 2024, accessed: 17.01.2024.

[28] cf. ibid., accessed: 17.01.2024.

[29] cf. Circular-Technology, 2021, accessed: 17.01.2024.

[30] cf. Steinert, 2024, accessed: 17.01.2024.

[31] cf. Circular-Technology, 2021, accessed: 17.01.2024.

[32] cf. ibid., accessed: 17.01.2024.

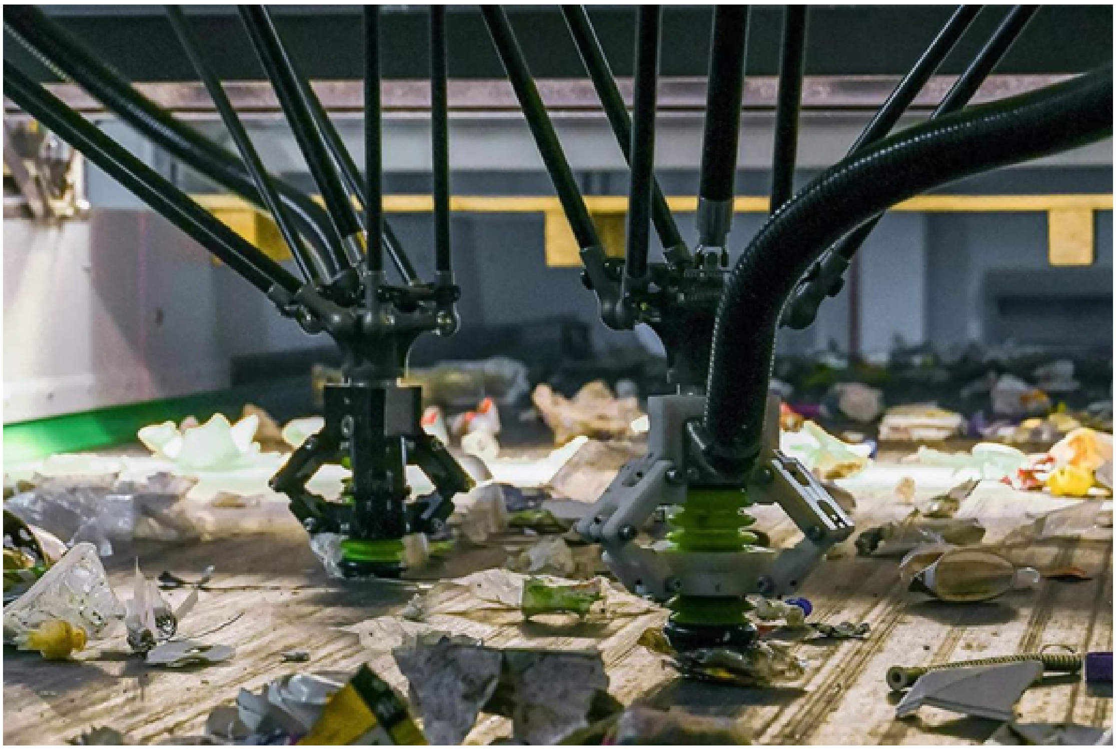

Figure 30: Steinert UniSort Unibot Sortierroboter, Source: Steinert (2023)

as the Food and Drug Administration (FDA) and the Occupational Safety and Health Administration (OSHA) play important roles in establishing guidelines to ensure the safety of robotic systems in contact with food products. Strict regulations are crucial to address hygiene, contamination, and worker safety concerns. This chapter explores requirements, regulations and challenges of robotics in the food processing industry.[33]

7.5.1 Requirements of robots in contact with food products

The integration of robots in food production systems must ensure safety, hygiene and compliance with food industry standards. Some requirements for robots in the food industry are described below: First of all, the robots must be safe. In a production system, people often work alongside or with robots. For example, moving parts of the machinery, sharp tools and hazardous chemicals pose serious dangers to employees. The safety of humans must be ensured all the time. This includes the processes installation and commissioning of the robots, food production, cleaning and disinfection as well as maintenance and servicing of the production machines. To minimize potential risks, it is

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[33] cf. Pilkington, 2023, accessed: 19.01.2024.

crucial to conduct risk assessments early in the development process. There are strict hygiene guidelines and regulations in the food industry. Cleaning and disinfection are done regularly to minimize the risk of bacteria growth. Therefore, one further requirement for the design of food handling robots is the ability of easy cleaning. All surfaces must be thoroughly cleaned, no spaces should be overlooked, and the cleaning process should be enabled very fast. In some cases, the disassembling of a robots is needed for a perfect cleaning result. Additionally, self-cleaning systems are solutions of recent technological developments.[34]

Heat is a huge problem in the field of handling food products due to the danger of bacterial growth, which causes illness. Moving parts and electricity in robots and machines causes heat. The so-called danger zone lies between 40 and 140 degrees.[35] It is the temperature range where food becomes unsafe, and bacteria grow most rapidly. For this reason, minimizing heat production should definitely be taken into account when designing food industrial robots and production systems. Another requirement on the design of robots in food industry is to limit the power of the robot.[36] Natural food products need to be handled gently and delicately. The mechanical damage of fresh fruits leads to faster spoilage, less sales and possibly to health problems. The robot's parameter selection of force and power limitation must be adapted to the respective product. In conclusion, while the outlined requirements are crucial for robots in contact with food products, it is important to acknowledge that there are many additional aspects to consider when designing and implementing robots in the food industry.

7.5.2 Regulations of robots in contact with food products

The FDA[37] primarily regulates food safety. While there may not be specific regulations for robots, the general guidelines related to food contact materials and equipment must be followed. Manufacturers of robots used in food production should ensure that their products comply with FDA regulations. This includes rules for continuous sanitation, cleaning and inspections. Annually, 76 million illnesses, 350,000 hospitalizations, and 5,000 deaths occur due to food-related diseases in the U.S. Over 250 diseases like E. coli and Hepatitis A are transmitted through food. Using robotics and automation in food processing can help curb the introduction of these harmful bacteria. Contamination of food can happen at various stages, starting from the farming or sourcing of raw

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[34] cf. Newton, 2021, accessed: 15.01.2024.

[35] cf. Food-Safety-and-Inspection-Service, 2017, accessed: 15.01.2024.

[36] cf. Newton, 2021, accessed: 15.01.2024.

[37] cf. Stachowicz, 2024, accessed: 19.01.2024.

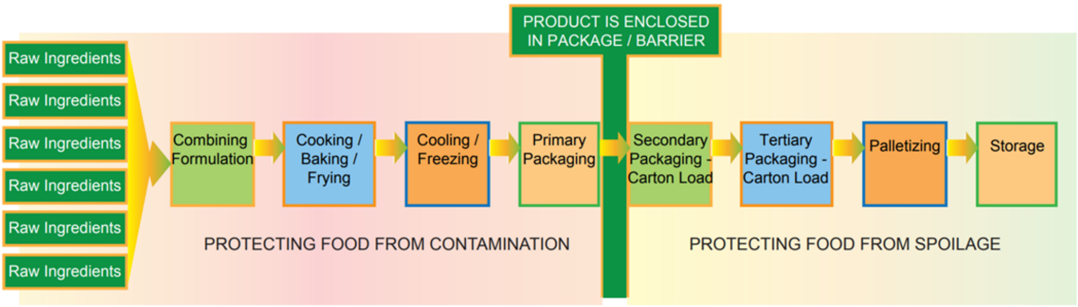

Figure 31: Critical steps in the manufacturing and processing food products, Source: Anuga FoodTec (2023)

materials, continuing through manufacturing and distribution, and extending to storage at home or in restaurants. Cross-contamination and inadequate temperature control are the primary factors along this chain that often contribute to foodborne illnesses. In recent years, an improved understanding of the causes of food-borne illnesses has prompted the development of systematic approaches like Hazard Analysis and Critical Control Points (HACCP). HACCP serves as a management system that addresses food safety by analyzing and controlling biological, chemical, and physical hazards throughout the entire food production process. As seen in Figure 3 Sanitation requirements are most stringent during the early manufacturing steps, gradually reducing once the product is sealed in the primary package. Attention then shifts to maintaining product temperature and ensuring timely delivery for fresh products on store shelves.[38]

7.5.3 Challenges of robots in contact with food products

The integration of robots in food production opens up many opportunities and brings with it many advantages like more sterilized production environment, higher quality results and faster production systems. However, there are also various challenges to overcome with this new development. One of the most important points in handling food products is hygiene. A robot has to withstand daily cleaning and disinfection procedures with water and chemicals. Furthermore, the food itself can cause corrosion (water, salt, acid). Traditional industrial robots are not built for this aggressive environment. Therefore, material selection plays an important role in the development of robots specialized in food production. Robots in contact with food need a special protective cover. But even with this solution, the robot will sooner or later become a wearing part and thus a cost factor.[39]

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[38] cf. Newton, 2021, accessed: 15.01.2024.

[39] cf. Anuga-FoodTec, 2023, accessed: 15.01.2024.

Another aspect is that food is made from natural ingredients. Natural products have irregular shapes and cannot be standardized. The robots have to be designed to distinguish reliable between edible parts and unwanted parts.[40] Examples are the separation of meat and bones or of stalks and core material of fruits. For this task, advanced machine learning can be used. Failure leads to loss of quality and subsequently to health problems. Therefore, this is a serious challenge in the design of food handling robots. In addition to the mentioned specific problems of robots in food production systems, there are some more general issues regarding robot production systems. There are high investment and maintenance costs. Employee displacement can have negative effects on social and economic systems. The use of collaborative robots always brings risks and hazards and requires high developed safety concepts. A production system with robots integrated, is vulnerable to technologically failure. This would lead to a lower production quality and expensive downtimes. Also, cyber security concerns should be considered.

7.6 Current Use of Robotics in Agriculture and Food Industry

The agricultural sector plays a crucial role in providing people with food and immunity and serves as a significant source of income for many governments. However, farmers throughout the food chain face significant challenges, particularly in labor-intensive agriculture, due to hard-to-access labor and rising labor costs. As the global demand for food continues to rise, innovative solutions are emerging to help optimize operations in agriculture and the production of foodstuffs. The exponential growth of the food industry, driven by online food delivery platforms, has also increased the demand for various food products.[41] These are just some of the reasons why robotics in the food and agriculture industry has been steadily increasing, offering innovative solutions to enhance efficiency, productivity, and sustainability. This chapter outlines the current use of robots in agriculture and the food sector.

7.6.1 Current Use of Robotics in Agriculture

In the Agriculture robotics plays already a big role and is poised to grow even further in the future. Robots are already milking cows, feeding animals, picking apples, harvesting lettuce or stripping weeds. Technological advancements have

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[40] cf. Newton, 2021, accessed: 15.01.2024.

[41] cf. Raffik, 2023.

enabled farmers to enhance efficiency, reduce costs, and improve overall yields. The cultivation of plant is one of the common fields where robotic is already established and will continue to gain in importance. In many agricultural industries automation and the digitalization of specific tasks play a crucial role.

The market offers already a variety of robotic concepts: Autonomous working tractors which can work different attachments are cultivating fields. Vehicles designed for plant treatment come equipped with spray heads for pesticide treatment or devices for weed stripping.[42] Other robotic systems are designed for harvesting or picking of fruits and vegetables.[43]

Robotics has also made considerable strides in animal husbandry, finding applications in livestock barns and pastures. In this domain, robotics is not only effective but also relatively easy to implement, leading to the existence of commercially viable robots for several years. For over two decades, milking robots have simplified and expedited the work of farmers. Autonomous robots that handle tasks such as feeding animals and cleaning barn-floors are now standard equipment in modern barns. In poultry farms, small vehicles autonomously collect eggs that hens have not laid in the designated laying cells.[44] Farmers in New Zealand and Ireland have even adopted drone technology for shepherding and herding, enabling them to monitor and track their animals effectively.[45] Another crucial aspect is the digitalization of agricultural work through robotics. With the collected data from the machines, farmers have the possibility to monitor their fields, plants or animals to increase the yield and efficiency. This approach provides them with the insights they need to make informed decisions regarding their agricultural practices. Examples are drones and ground-based robots, equipped with cameras and sensors, which are monitoring the fields and collecting data.[46] Combined with specialized software models, these technologies enable the identification of weeds, precise adjustment of pesticide application, and the optimal timing for harvesting.[47]

Robotic innovations like swarm technology, which involves multiple robots working in tandem, are already being used in practice. They can help to do the fieldwork in larger scales or contribute to the creation of nutrient maps by collecting soil samples.[48]

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[42] cf. Shamshiri, 2018.
[43] cf. Chao-Cheng, 2023.
[44] cf. Shamshiri, 2018.
[45] cf. Paul, 2020.
[46] cf. ibid.
[47] cf. Shamshiri, 2018.
[48] cf. ibid.

7.6.2 Current Use of Robotics in the Food Industry

In this Chapter the use of robots in the food industry is discussed with examples, that were found in scientific literature, published since 2020, to highlight the status quo in the industry. In the food industry, especially in small and medium-sized enterprises, the implementation of high-cost automation lines and complex robotic systems is challenging, because simpler and cost-effective systems are needed.[49] Numerous food items and handling tasks, like grasping extremely thin and delicate food, pose challenges for existing soft grippers. Consequently, these specific operations typically remain dependent on human workers.[50] Therefore, a robotic gripper system can be employed to address the growing complexity and increasing number of gripping positions associated with food-related tasks. To address this issue, a real-time computational framework is developed, integrating flexible tactile sensors on soft fingers. To efficiently identify object categories and 6-D target object poses among stacks of similar food samples an image processing system is incorporated. This enables the determination of an optimized path to achieve the best gripping performance. By integrating visual object recognition and tactile sensory feedback, the versatile soft robotic gripper enhances the autonomy of the food handling process.[51] Another robotic gripping system poses a dual-mode soft grip driven by pneumatic systems for additional hygiene reasons. The system combines the principles of friction and suction for handling food products. The use of entirely soft materials in the grip's construction helps minimize potential damage to food products during loading and unloading operations.[52] Another example for food handling can be found in robotic kitchen, such as Moley robotic kitchen. Moley Robotics, founded in 2015, utilizes a multifunctional cooking platform. These types of kitchens are equipped with robotic hands controlled by automatic arms and work with various components such as a steam oven, induction cooker, sink, mixer, and dishwasher. The robotic kitchen operates through a software platform, enabling independent food preparation and cooking. The key features include precise coding of physical movements, speed, and time management, ensuring that recipes are executed. (Barakazı, 2022) Furthermore, the adoption and exploration of robotics in the food delivery sector saw an increase, particularly during the COVID-19 pandemic. These robotic solutions played a crucial role in minimizing human contact by contributing to the mitigation of virus spread. Beyond their hygiene benefits, food delivery robots enhance customer experiences. To realize food delivery robots a possible approach is to utilizes a microcontroller equipped with DC motors, employing ultrasonic and IR sensors for tasks such as surface mapping,

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[49] cf. Wang, 2020.

[50] cf. Hashanjana, 2023.

[51] cf. Low, 2022, p. 3232-3243.

[52] cf. Wang, 2020.

Figure 32: Examples for the use of Robotics in agriculture and the food industry
Source: Redmond Ramin Shamshiri (2018) and P. K. Paul (2020)

motor control, internal monitoring, collision avoidance, and motion control.[53]

7.7 Challenges and recommendations

As in every other industry, implementation of new technology is faced with challenges. In the last couple of decades improvements mostly were made on increasing the possible size of the farming area, by increasing the machine size itself. With modern electronic aids, like autonomous vehicles or farming robots in general, the industry is undergoing big changes in every aspect. In the following paragraphs a couple of popular topics are discussed, that interfere with the implantation of such, while also providing possible solutions.

- **Regulatory framework:** As the food and agriculture industry is a very globalized industry, with supply chains spanning over multiple countries, different problems must be faced. One of the biggest being the regulatory framework, that often differs between producing nations. An example would be the use of completely autonomous farm equipment, which is currently still heavily regulated in the European union. Especially safety issues are still a problem to overcome, making it almost impossible to use it in cost effective ways.[54] To overcome those regulatory issues, different steps must be taken. First the framework must be completely worked out, providing an equal and fair environment for companies and people in this industry. In order to avoid disadvantages faced by local regulations, this framework must be accepted on a global scale.

- **Complex Supply Chains:** Complicated supply chains make it more and more difficult to form a closed loop in the system. Specifically, the middle part of these chains, e.g. processing and logistics, is already well optimized, leaving room for improvements at the start and end point. Focusing on the start

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[53] cf. Reddy, 2022.
[54] cf. EU-OSHA, 2023.

Figure 33: Autonomous strawberry picking robot Rubion, Source: Octinion (2024)

point, the enhanced precision and effectiveness of new technologies used in the modern agriculture industry, can reduce the waste and byproducts created already on the farmland itself and therefore making it easier to enforce a more closed supply loop design.[55]

- **Environmental impacts:** As all the other industries, also the agriculture and food industry needs to improve on reducing negative impacts on the environment. Big machines, using high amounts of fuel and ejecting an excessive amount of fertilizer or pesticides, were and still are a common sight on many fields, having a negative impact on the environment.[56] But with the integration of new technologies its getting way simpler to reduce the amount of water needed, to conserve the soil, to limit carbon emissions and to reduce the amount of required input materials in general.[57]

Other major topics regarding challenges in the food and agriculture industry include the high resource intensity, requiring significant inputs such as water, energy, and fertilizers, which can contribute to environmental degradation. Additionally, investment in research and development is crucial for fostering innovation in farming practices, crop improvement, and sustainable solutions. Moreover, the personal commitment of consumers plays a pivotal role in influencing market demands for sustainable and ethically produced food. However, despite these challenges, numerous potential solutions, including advanced technologies, eco-friendly farming methods, and policy initiatives, have the potential to guide producers towards a more effective and sustainable agricultural future. Embracing these solutions collectively can pave the way for a resilient and environmentally conscious food and agriculture industry.[58]

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[55] cf. Pearson/Camacho-Villa/Valluru, 2022.

[56] cf. Ritchie/Rosado/Roser, 2022, accessed: 15.01.2024.

[57] cf. Lezoche/Hernandez/Díaz/Panetto/Kacprzyk, 2020, p. 117.

[58] cf. OpenAi, 2024, accessed: 15.01.2024.

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8 Urban Mining

8.1 Basics of Urban Mining

Natural resources are becoming increasingly scarce as their consumption has tripled in the last 40 years. Although the Earth has limited capacity to provide new resources, the extraction and use of raw materials is increasing, leading to an increase in waste and emissions. This has serious consequences for people and the environment, as the processing of raw materials causes around 30 percent of global greenhouse gas emissions.[1] In addition, the exploitation of natural raw material reserves affects the supply of the economy negatively, particularly due to the growing demand for rare raw materials.[2]

While the progress made in addressing these challenges is not particularly remarkable or exciting, it is important to emphasise the importance of urban mining. The recovery and reuse of each kilogram directly replaces a kilogram that would otherwise go through the environmentally, socially, and economically damaging processes of mining and production.[3]

Today, around half of the world's population lives in urban agglomerations; in the middle of the 20th century it was only 30%; in 2050 it is expected to be 80%. The modern urban infrastructure contains significant amounts of potential secondary resources.[4] Because of the long lifetimes of modern urban infrastructure these materials are bound for long periods of time.[5]

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[1] cf. Fluchs/Neligan, 2023, accessed: 05.01.2024.

[2] cf. Leal-Filho, 2019, accessed: 03.12.2023.

[3] cf. Aldebei/Dombi, 2021, accessed: 03.12.2023.

[4] cf. Leal-Filho, 2019, accessed: 03.12.2023.

[5] cf. Cossu/Williams, 2015, accessed: 03.12.2023.

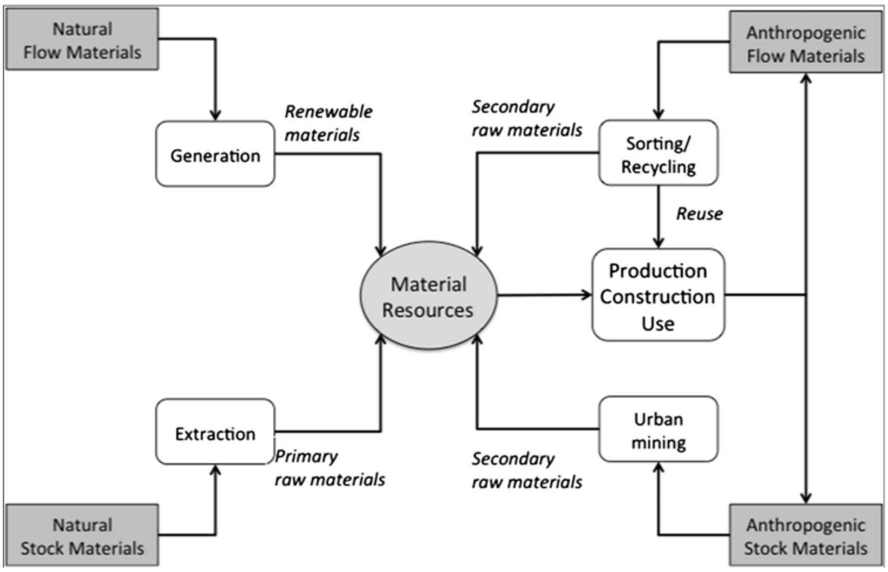

Figure 34: Material flows among different kind of sources of material resources, Source: Cossu (2015)

The streams that contribute to our total material resources can be described as follows: These four streams are displayed in Figure 34.

- **Natural Stock Materials:** These can be sourced through extraction from mines.

- **Natural Flow Materials:** These are generated over time and are often renewable materials.

- **Anthropogenic Flow Materials:** This category includes a continuous stream of potential secondary resources produced by human activities, commonly in the form of waste.

- **Anthropogenic Stock Materials:** These are resources created by human actions that become available irregularly.

Urban mining is therefore defined as the recovery of materials from anthropogenic, usually urban, deposits. For successful urban mining, it is not enough just to know the quantity, specification and location of secondary resources. It is just as important to have suitable technologies that enable valuable secondary materials to be separated from pollutants in a pure and economical way. There is a considerable need for research here, particularly in the development of separation processes (chemical, physical, chemical-physical) with lower material input and energy consumption. Urban mining in existing buildings can be divided into two main areas: The reuse of building elements and the recycling of building materials.[6]

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[6] cf. Leal-Filho, 2019, accessed: 03.12.2023.

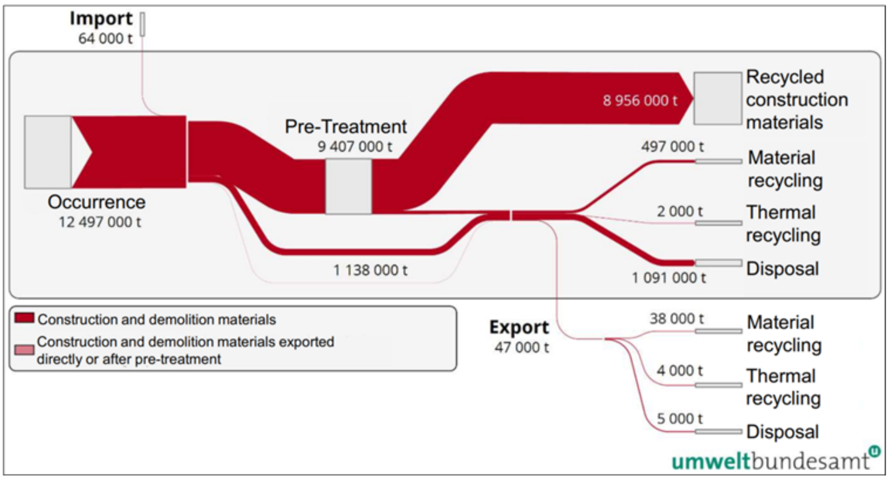

Figure 35: Material flow diagram for construction and demolition waste, Source: VOEB (2023)

8.2 State of the art

As the number of materials required for construction increases, the proportion of recycled materials needs to be increased. Construction waste in Austria currently accounts for 12.5 million tonnes of waste per year, or about 16 percent of the country's total waste. According to the Austrian "Bundes-Abfallwirtschaftsplan 2023" (Status Report 2023), the proportion of recycled materials in construction is around 70%, which equates to 9 million tonnes of waste.[7] This figure could be increased by up to 90% in the next few years.[8]

The amount of waste that is not recycled is currently used for thermal recycling, material recycling or disposal. Landfills, especially in urban areas, have limited capacity, which requires a reduction in the amount of waste stored. The main challenge in urban mining is the increasing number of composite materials, which makes pure separation difficult. As a result, the need for improved separation equipment is growing rapidly. Innovation in energy-efficient chemical, physical and physico-chemical separation processes is fundamental to future improvements.-[9]

8.2.1 Urban Mining Index

The Urban Mining Index (UMI) as a system for measuring and evaluating the circularity of building structures and buildings in new construction planning. The UMI takes into account parameters that reflect the materiality, construction

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[7] cf. Achatz/Margelik/Romm/Kasper/Jäger, 2021, accessed: 05.01.2024.

[8] cf. VOEB-Verband-Österreichischer-Entsorgungsbetriebe, 2023, accessed: 05.01.2024.

[9] cf. Cossu/Williams, 2015, accessed: 03.12.2023.

and economic efficiency of selective deconstruction, which is crucial for the recovery of unmixed recyclable materials. The Urban Mining Indicator quantifies the proportion of circular building materials in the total mass of all materials used in the life cycle of the building. Circularity rates of building materials are determined on the basis of specific parameters such as the proportion of secondary raw materials and the recycling potential. A differentiation is made between different quality levels of circular material utilization, both in the pre-use phase (before the planned use) and in the post-use phase (after the planned use). Materials that can be managed in closed loops with consistent quality (reuse and recycling) are categorized as having ″closed-loop potential″. Materials that can only be managed in open loops with a loss of quality (reuse and downcycling) are categorized as ″loop potential″. The dismantlability of components and products as well as the separation of recyclable materials by type at the design level are considered a basic prerequisite for the recyclability of materials. The economic efficiency of selective dismantling, measured by the residual value of the materials and the labor required to recover them by type at the end of their useful life, influences the probability of a high-quality or lower-ranking end-of-life scenario.-[10]

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[10] cf. Rosen, 2021.

8.2.2 Best practice

The Austrian Ministry of Environment has unveiled a report on circular economy strategies in the construction sector, presenting visionary ideas to revolutionize traditional practices:[11]

1. Leasing Building Parts: Introducing the concept of leasing building components, such as facades, allows for their removal and reuse, promoting sustainability and minimizing waste.

2. Brick Production from Construction Rubble: A pioneering approach involves transforming construction rubble into bricks, emphasizing resource efficiency and reducing the environmental impact of waste.

3. Unified Material Usage (Stone Wool): Embracing a singular material, such as stone wool, for various components like bricks, insulation, and electric canals, streamlines construction processes, optimizing material utilization and reducing the overall environmental footprint.

4. Concrete-Wood and Composite Material: The introduction of a concrete-wood composite material signifies a shift towards eco-friendly construction practices, combining the durability of concrete with the sustainability of wood for enhanced structural performance.

8.2.3 Demolition Robots

Robotic demolition is revolutionizing house teardowns, enhancing precision and safety. Equipped with advanced sensors and AI, these robots navigate tight spaces, minimizing collateral damage. This technology promotes sustainable practices by selectively removing materials for recycling, reducing environmental impact. Operators can remotely control and monitor the process, ensuring safer and more efficient demolition.[12]

Husqvarna stands out as a pioneering force in robotic demolition, showcasing advanced technologies. The company's innovations contribute significantly to precision, safety, and environmental sustainability in the demolition industry.

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[11] cf. Achatz/Margelik/Romm/Kasper/Jäger, 2021, accessed: 05.01.2024.

[12] cf. Husqvarna, 2021, accessed: 05.01.2024.

Figure 36: DXR Demolition Robots, Source: Husqvarna (2021)

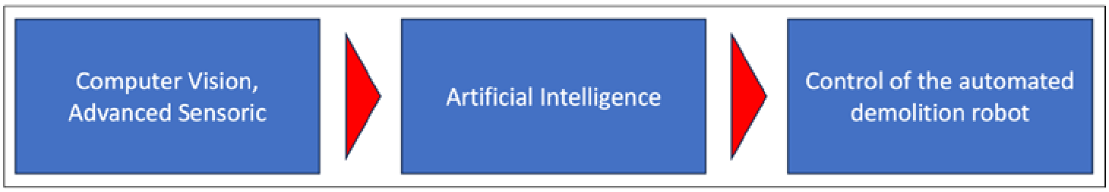

Figure 37: Evolutionary processs towards an automated robot, Source: own figure

8.3 Recommendations

The group discussed about the application of autonomy or remote-controlled demolition robots. The future of demolition robotics is poised for transformation with the integration of advanced sensor technologies like ultrasonic and eddy current devices. These sensors, mounted on the robot, provide real-time data on structural composition, enabling precise and efficient dismantling. Taking it a step further, the incorporation of Virtual Reality (VR) headsets delivers an immersive experience for operators, allowing them to make informed decisions based on the robot's sensor data. This innovative combination not only ensures safety by keeping operators at a distance but also facilitates intelligent material separation, contributing to sustainable waste management practices. As technology evolves, this integrated approach stands to redefine demolition processes with highest efficiency and environmental responsibility. Taking this visionary approach to the next level, further enhancement involves integrating an Artificial Intelligence (AI) system to entirely replace human participation (cf. Figure 37). This advanced AI system would harness visual and sensor data, enabling it to autonomously calculate the optimal method for building dismantling, with a focus on efficient material separation.

This not only maximizes precision but also exemplifies a futuristic synergy between technology and sustainability in the construction industry. The seamless integration of AI-driven decision-making adds a layer of efficiency to the process, aligning with the principles of innovation and environmental responsibility.

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