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Robotics: Enabler and inhibitor of the Sustainable Development Goals

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ABSTRACT

Robotics has the power to help our society in managing many current and foreseeable challenges, and contribute to a responsible future, as formally structured in the United Nations' Sustainable Development Goals (SDGs) initiative. Prior work has already investigated the impact of Artificial Intelligence (AI) on the SDGs, using a systematic consensus-based expert elicitation process. However, the existing literature has not focused on the intricacies of robotics and the unique dynamics this domain presents regarding the SDGs. In this vein, this work adapts an established approach, to focus on and dive deeper into the field of robotics and social responsibility. We introduce a multidisciplinary analysis of both the enabling and disabling roles of robotics, in achieving the SDG-presented, major economic, social and environmental priorities. The United Nation's 17 SDG and the 169 Targets, were individually examined within the context of state-of-the-art robotics already documented in scientific literature. The significance and the quality-of-evidence of enabling/inhibiting impacts, were assessed by an international panel of experts, to quantify the positive or negative effect of the applied robotic systems. Results from this study indicate that robotics has the potential to enable 46 % of the Targets, particularly for the industry and environment-related SDGs, forecasting a huge impact on our production systems and thus on our entire society. Inversely, robotics could inhibit 19 % of the SDG Targets, mainly through exacerbation of inequalities and tensions in the SDGs. The objective of this paper is to assess and grade the current impact of the robotics megatrend on the SDGs, provide comparable data, and encourage the robotics community to work on these targets, in a unified way and eventually improve the quality of the related outcomes.

1. Introduction

In 2015, 93 countries agreed on the UN Sustainable Development Goals (SDGs), to contribute to a better future for all of Humanity (United Nations General Assembly, 2015). The SDGs address global challenges, fundamentally affecting the future of our society, including poverty, inequalities, climate change, environment degradation, prosperity, productivity, peace and justice. Arguably, robotics will have a great impact on our society/economy, as it has become a megatrend (Haidegger et al., 2019), and it has the potential to speed up progress

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towards these development targets, while also bringing complex challenges along (Fig. 1).

In a recent article by Vinuesa et al. 2020 in Nature Communications (Vinuesa et al., 2020), the role of AI was assessed as either an enabler or inhibitor in achieving the SDGs. Their method can be summarized as a consensus-based expert elicitation process. A similar study was also conducted for energy (Fuso Nerini et al., 2017) and climate change (Laumann et al., 2022). Other publications focus on Industry 4.0 (Lupi et al., 2022), energy solutions (Zhang et al., 2022) and climate actions (Fuso Nerini et al., 2019). As the number of robots keeps growing (IFR, n.d.), their impact on society increases subsequently. However, apart from a recent consultation (Guenat et al., 2022) with 102 experts on the impact of robots and robotic systems on the SDGs, no evidence-based investigation has been undertaken.

Importantly, in Vinuesa et al. 2020, the definition of AI was focused only on software technology. In our research, we applied a similar methodology, but focusing on robots, i.e., physical machines in the real-world environment with sense–think–act capabilities, instead of just being algorithms or agents, following a more exact definition of a robot (Haidegger, 2021). In this article's context, robotics is the engineering science and technology of robots that involve the design, manufacture, control and programming of robots; the study of the control processes, sensors and algorithms used in humans, animals and machine; the application of these control processes and algorithms to the design of robots and the use of robots to solve problems. The professional work experience, skills and insights of the robotics community can make a catalytic impact in reaching a sustainable future. The dissemination of *sustainability and robotics* best practices will be an important tool since politicians, civil society and trade unions will need to take these scientific studies as the basis for developing the guidelines that allow robots to be used in ways to elevate and support social responsibility.

This study aims to fill this gap by assessing the enabling or disabling role of robotics towards the achievement of the SDGs, based on an existing method, the consensus-based expert elicitation process (Vinuesa et al., 2020). It is built on interdisciplinary collaboration among different research fields, with experts from academia, industry and government – aiming for diversity regarding gender and geography. Authors also contributed to a preparation paper for a United Nations panel discussion (IATT report for the STI Forum) (Boesl et al., 2021), and organized an IROS 2021 Workshop "The Role of Robotics in Achieving the UN Sustainable Development Goals", for which, a report was published in the IEEE Robotics & Automation Magazine (Mai et al., 2022) to increase the involvement from the robotics community.

The major contributions of this original work include:

- assessing robotics' enabling and inhibiting potential per SDG and for each Target;
- creating comparable quantitative outcomes, which allows to be matched against other analyses already published;
- providing evidence that robotics has strong potential to contribute to global development, but also that disabling factors need to be further taken care of;
- documenting the feasibility of systematic assessment of "impact" in the societal, environmental and economic sense of a technological domain;
- enlarging the applicability of the assessment methodology, thus allowing researchers to further use it to assess the potential impact of their own works.

By documenting the enabling and inhibiting impacts of robotics on the economy, society and environment, the authors are dedicated to raise awareness, and to contribute to a necessary discussion on accountability within the robotics community (Yang et al., 2018).

2. Background of the research

Prior literature analyzed the role of AI in achieving the SDGs (Vinuesa et al., 2020), followed by related publications exploring the links between these targets and technologies, such as Industry 4.0 methods, energy solutions and climate actions. As the number of robots deployed in the world keeps growing, their impact on society increases subsequently.

The authors reviewed the available literature on Web of Science, PubMed, IEEE Xplore and Google Scholar, and while numerous hits

Fig. 1. The authors' illustration of sustainable development goals for robotics (Mai et al., 2022). Robotics (Boesl et al., 2021) and Artificial Intelligence (AI) (Khamis et al., 2019a; Khamis et al., 2019b) are in the spotlight with high anticipation regarding major contributions in achieving the SDGs.

emerged for "sustainability" AND "SDG" AND "robotics", the number of detailed analyses was found to be limited to the above referred publications, identifying a gap in the literature.

Moreover, an additional round of literature review was performed with the keywords "sustainability" AND "consensus-based expert elicitation" to review the pervasiveness of the chosen evaluation and assessment method. This search resulted in a limited number of articles identified, of which the ones related to SDG or technology trend assessment were reviewed for additional inputs on the method. Studies published in the past few years have been focusing on the sustainability of AI, energy and environment domains, analyzed by this method (Fuso Nerini et al., 2017; Mogha and Hasteer, 2023; Jiang et al., 2022; Hannan et al., 2021; Khosla et al., 2021; Schoormann et al., 2021; Holzinger et al., 2021). The findings strengthen the applicability of *the consensus-based expert elicitation* process.

Apart from (Vinuesa et al., 2020), which is considered to be a role model in this particular domain, some recent articles addressed the SDGs' presumed enabler and inhibitor role across various domains (Lawrence, 2020; Iizuka and Hane, 2021; Adeshina and Aina, 2023; Gupta et al., 2021).

3. Methods

Due to the proximity of AI and robotics, authors chose to replicate and adapt Vinuesa et al.'s consensus-based expert elicitation process (Vinuesa et al., 2020) to identify the role of robotics as enablers or inhibitors for a sustainable future. The group of experts was selected based on their international role in robotics R&D, field of expertise and willingness to contribute to the research (). All of the experts who took part in the entire process were invited to contribute to this article, and therefore became co-authors (total: 9 m/f: 7/2).

Consensus-based expert elicitation process The expert group was asked to evaluate and rank the SDGs and the related Targets according to their own knowledge, how much these are enabled/inhibited by current robotic technology. Data was collected in a standardized tabular format (attached as Supplementary Dataset). Experts were asked to provide proof for their judgment in the form of peer reviewed scientific references, wherever possible.

The experts focused on all the 16 SDGs and their 150 Targets. In the Stockholm model (Fig. 2), SDG 17 (Partnerships for the Goals) was singled out, as it is not included in the clusters, yet it is framed as a cross-sectional goal (*The SDGs wedding cake*, n.d.). SDG 17 was also handled separately here, since it is inherently organizational, and less directly impacted by robotic technology.

Identifying and quantifying the impact of a field as broad as robotics on each of the SDGs requires an adaptable, yet rigorous methodology. The one employed herewith was designed in five steps, based on the state of the art (Vinuesa et al., 2020). All underlying and supporting materials are available as Supplementary Data. The evaluation method was as follows:

1. **Building a database to identify impacts.** A group of eight researchers was assigned in pairs to each SDG, and requested to list potential impacts related to robotics applications for each Target. To span as broadly as possible, the quality requirements for sources were kept low: anecdotal evidence or expert knowledge were accepted – where indicated. This process lasted several months, and benefitted from the organization and participation of the researchers to regular meetings and workshops on robotics and the SDGs (Mai et al., 2022). Other senior researchers were also invited to review, comment and add content.
2. **Articulating individual impacts through a per-SDG summary.** Each group of researchers was then asked to write a summary of the impacts they had identified for the SDGs they were assigned to. While this step decoupled the impacts from the targets, it produced a first articulation of the impacts through structured and nuanced arguments.
3. **Consolidating the claims through literature review.** Every impact claimed in the paragraph was verified through a scoping literature review, such that each impact was supported by at least one source, ideally more. Overall, 319 references were found, which were analyzed in detail, and are listed in the Supplementary Database. This allowed the experts to select the most relevant references, to refine or correct the claims, when needed, and to expand their scope when new information was found.

Consolidating the claims through literature review. Every

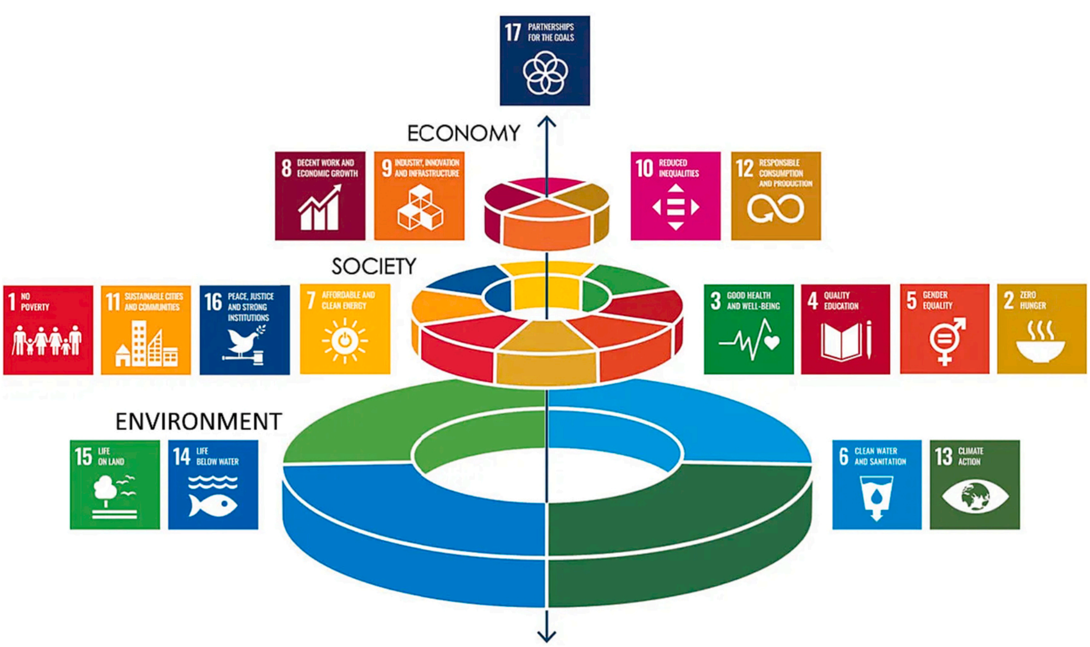

Fig. 2. The Stockholm Resilience Centre categorization of the Sustainable Development Goals. Their model breaks down the first 16 SDGs to 3 cluster domains related to economy, society and environment.
(Modified from *The SDGs wedding cake* (n.d.).)

impact claimed in the paragraph was verified through a scoping literature review, such that each impact was supported by at least one source, ideally more. Overall, 319 references were found, which were analyzed in detail, and are listed in the Supplementary Database. This allowed the experts to select the most relevant references, to refine or correct the claims, when needed, and to expand their scope when new information was found.

4. **Quantification of the impact significance.** Each impact was isolated from the rest of the original publication's text. Independently, three researchers were asked to rate their significance on a scale as proposed by Vinuesa et al., based on the following criteria: scale of the impact, strength of the impact, and credibility of the sources:

   Type A: References using robots commercialized and implemented to refer to this particular issue and with the possibility to be generalized

   Type B: Studies based on robots for a particular issue, but with limited generalizability

   Type C: Anecdotal qualitative studies and methods or robots under development

   Type D: Purely theoretical or speculative references

   Arguably, other classifications could also be possible. For such soft-metrics based assessment of technologies, McKinsey used to provide the McKinsey Horizons (Blank, 2019), Gartner recommended the Hype Cycles (Steinert and Leifer, 2010), and popular with funding agencies, there are the Technology Readiness Levels (TRL) (Bruno et al., 2020). TRL-based classification could be translated to the method employed hereby as:

   TRL 1–3 Basic/foundational research

   TRL 4–6 Prototype stage/component development

   TRL 6–9 Real-world application (deployed robotic system or automation solution)

   Provided the imperfections of these classification methods, and for consistency, the same method was implemented as in Vinuesa et al. (2020), which does not rely on e.g., TRLs. Applying a systematic metric for robotics is extremely challenging, since this domain is harder to scale than e.g., software. Creating a successful robotic product from a prototype is a huge challenge, and typically stretches over many years and dollar-millions in investment.

   To establish a single score, the researchers met after the round of individual assessment, and reached consensus on the final grades through moderated meetings.

5. **Quantification of the impacts on the targets and goals.** From the list of evaluated impacts produced at step 4, three researchers individually selected the most relevant impacts for each Target. The impact of robotics on each Target was given the grade of the most significant relevant impact. The researchers were given the option to lower the grade, if the impact was estimated as only indirectly related to the target. The scores for each target were then averaged over the three reviewers (A = 3, B = 2, C = 1, D = 0), slightly adjusting the original scale to include zero influence as well. Finally, the impact of robotics on each SDG was computed as a percentage, by dividing the sum of the Targets' scores by the maximum achievable score per SDG.

A summary of the results is visualized in Fig. 3. Supplementary materials present the full data, providing a complete list of all the SDGs and Targets, together with the 319 references and detailed results from this analysis.

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4. Results

In this section, the evidence on the direct and indirect connections between robotics and the economical, societal, and environmental SDGs is analyzed. Following the *Stockholm Resilience Center*'s approach, the SDGs were divided into three Clusters (*The SDGs wedding cake*, n.d.): Economy (SDGs 8, 9, 10, 12), Society (SDGs 1, 2, 3, 4, 5, 7, 11, 16) and Environment (SDGs 6, 13, 14, 15). SDG 17 is cross-sectional and therefore was not assigned, but addressed separately in the Discussion.

Fig. 3 summarizes the overall quantitative results of this study. It presents the enabling and inhibiting impacts of robotics towards the SDGs (following the steps described in Methods). Overall, taking into account the significance of the impacts, it was derived that robotics is likely to enable 46 % of the Targets, and inhibit 19 % of them, having an overall positive influence on reaching the SDGs. The enabling potential of robotics reaches 53 % in the environment cluster, against 47 % for the society and 42 % for the economy clusters. The inhibiting impacts are

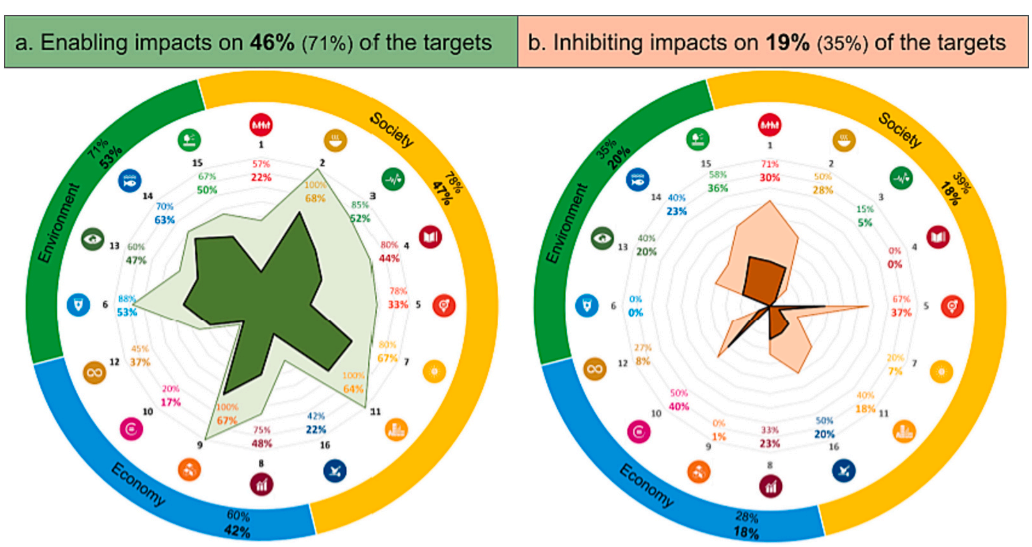

Fig. 3. Representation of the (a) enabling and (b) inhibiting impacts of robotics towards the SDGs.
The inner plots indicate the proportion of targets which are impacted by robotics for each SDG, while the outer circle clusters the SDGs according to the three main groups, Society, Economy and Environment. The percentages and light toned areas indicate the proportion of targets within an SDG for which at least one robotics work had an influence on, whereas for the bold percentages and dark toned areas, the significance of the evidence was factored in. Note, that SDG 16 was assessed separately, as described above.

more uniformly distributed, with 20 %, 18 % and 18 % on the environment, society and economy clusters, respectively. In the next section, the impact of robotics on each cluster and each Target is described. All the sources used to document each and every impact are available in the Supplementary material herein.

4.1. Cluster 1 – robotics and economic outcomes (SDGs 8, 9, 10, 12)

The main enabling impacts of robotics in the economy cluster are likely related to their capacity to automate distributed, complex tasks to increase productivity, monitor and maintain infrastructures, and assist workers for a safer, more inclusive workspace. On the other hand, the disruptions they create in labor markets can significantly increase inequalities and worsen working conditions. These impacts are represented in Fig. 4, and detailed in the following paragraphs.

4.1.1. SDG 8. Decent work and economic growth

Automation of tasks could contribute to increased productivity, reinforcing economic growth. On the physical work side, robots, such as exoskeletons and cobots (collaborative robots) are developed to improve employment conditions and workers' ergonomics, and robotic assistive technologies can promote inclusivity by supporting workers with disabilities. These robots can be deployed in sectors such as manufacturing, agrifood, mining, services or tourism.

The deployment of robotics technology will precipitate the disappearance of certain jobs, occupied in particular by vulnerable workers, with lower levels of education or skills. It will also likely radically change the content of other jobs, and could also lead to creation of new positions. This will still happen at a slower pace than in the case of AI-powered, Large Language Model (LLM) technologies, such as ChatGPT. Allowing employees to adapt their skills in this rapidly changing work market will be necessary, and will require lifelong-learning strategies in the workplace.

4.1.2. SDG 9. Industry, Innovation and Infrastructure

Automation and robotics can lead to higher productivity in various industries. Robots can fill a need in many countries facing labor shortages or struggling to find skilled workers. As well as, showcase their ability to access hazardous places that humans cannot and to withstand difficult conditions. Drones and legged robots are already often used in the inspection of buildings or critical infrastructure. Robots are beginning to be employed directly in construction processes, where they replace workers in repetitive or dangerous tasks (e.g., in raw material management). They are also used for assisting with the 3D printing of houses and bridges. Robots' involvement in all areas of industry is growing annually, by approximately 13 % (IFR, n.d.).

4.1.3. SDG 10. Reduced Inequalities

Robotics may increase income inequalities within countries. Robots typically require a significant investment, and lead to revenue for the capital owners and also sometimes to the high-skilled workers who cannot easily be replaced by robots. Other workers, usually less skilled or under-educated, who are already at the lower part of the national income distribution, can instead experience decreasing wages or even face unemployment. A tax on robot workers is often proposed as a potential way to reduce the skilled–unskilled wage gap.

Inequalities could also rise in countries due to the adoption of robotics in industry, mainly through the process of reshoring, or relocation of work operations, or even entire factories, from low-wage countries back to the developed, industrialized countries. Several studies investigated the relation of robot adoption to wages, and suggested that the burden of job losses due to robotization is likely to be primarily borne by low-wage countries, as the traditional advantage of low labor costs is eroded by automation (McGaughey, 2022).

Robotic prostheses and assistive mobile manipulators can empower and promote social, economic inclusion of people with physical disabilities. Social robots could also support social inclusion of individuals, in particular children with autism.

4.1.4. SDG 12. Responsible consumption and production

By supporting local and flexible production of manufactured goods, robotics can reduce the impacts of transportation and provide custom products which better target the needs of the consumers. In food production, using robots for the selection of plants during harvest or soft robots for better handling of products in the supply chain can significantly reduce food waste. Robot-supported vertical farming and precision farming allow more sustainable agricultural models, and weed removing robots can help reduce the use of pesticides. Robotics can have a clear advantage in the automation of complex food processing (Mason et al., 2023). On the consumer side, domotics and robotic food dispensers can also reduce food waste and encourage responsible food consumption. Robots are also increasingly used in recycling centers for the challenging disassembly and waste-sorting tasks. However, the sustainable production of robots is a major challenge by itself, due to the need for expensive raw materials, such as rare-earth elements in their electronics. The robots' disposal leads to creation of challenging e-waste at the end of the life-cycle, although some researchers explore the possibility of creating biodegradable robots and the use of recyclable and

Fig. 4. Representation of the impacts of robotics on the SDGs of the economy cluster, on the SDG target level.
Each element represents the targets related to the respective SDG. For each SDG, the enabling impact of robotics was illustrated by a gradient of green on the top line (darker colors represent stronger impact as in the legend at the bottom), whereas the inhibiting impact is represented on the bottom line in an orange gradient. A grey color indicates that no impact was identified in the literature relative to this target, according to this study's methods.

self-healing materials, to increase the lifespan of robots (Terryn et al., 2017).

4.2. Cluster 2 – robotics and societal outcomes (SDGs 1, 2, 3, 4, 5, 7, 11 and 16)

The potential for massive, distributed automation, sensing and monitoring capacities gives the robots enabling impacts on SDG 1 (No Poverty), 2 (Zero Hunger), 7 (Affordable and Clean Energy) and 11 (Sustainable Cities and Communities). Additionally, robots' precise control capabilities can be instrumental in SDG 3 (Good Health and Well-Being). However, it is the social relationship between humans and robots which weighs strongly in both the enabling and inhibiting roles of robotics towards SDG 4 (Quality Education), 5 (Gender Equality) and 16 (Peace, Justice and Strong Institutions). Fig. 5 represents the impacts of robotics on the societal SDGs on the target level, while the details are provided in the following paragraphs.

4.2.1. SDG 1. No poverty

Robotics could improve productivity, reduce the price of goods, and free up personal time, which could reduce the proportion of people living in poverty. In acute poverty situations, the deployment of drones for dropping goods in hard-to-reach areas was seen as potentially beneficial, although robots should not be considered a structural solution, when they just provide material aid.

So far, there has been no ideal model established for revenue sharing, regarding what percentage of the income generated by robots, is to be given back to society, to end poverty and how to address shareholder interests. As described for SDG 10 on inequalities, current social vulnerabilities and inequalities (unequal opportunities, unemployment) are at great risk of amplification.

4.2.2. SDG 2. Zero hunger

As countries develop, the share of the population working in agriculture is declining. While more than two-third of the population in poor countries works in agriculture, less than 5 % of the population does so in rich countries (Roser, 2013). This increased productivity in richer countries is due to, among other factors, the introduction of automation and robotization. Robotics increases profits, improves the livelihoods of farmers, enhances the health and wellbeing of livestock, and reduces environmental impacts of agriculture. On the other hand, agricultural technologies entrench land degradation, capital accumulation, and the exploitation of marginalized and racialized laborers, by landowners, governments and corporations. However, due to the increased capabilities of robots, more sustainable paradigms such as precision agriculture, vertical farming or pixel cropping are becoming possible. During the processing and distribution, robots are increasingly used to help productivity and reduce food waste.

4.2.3. SDG 3. Good health and well-being

In the medical field, dominantly robot-assisted surgery offers less invasive, potentially more accurate, and even remotely executed interventions for different pathologies (Fichtinger et al., 2022; Haidegger et al., 2022). Robots are used to facilitate the checkup and control of patients through telepresence and telemedicine, and can even automate lower complexity parts of a surgical treatment (Nagy and Haidegger, 2022). Robotics, in the form of exoskeletons, can support both patients in their mobility, and healthcare workers in their daily physical heavy work. Drones are also used to deliver medications, blood or medical equipment to inaccessible areas.

In rehabilitation, robotic systems are supporting the recovery of patients. They will enable long-term treatment at home and robotic prosthetics can already replace missing body parts.

In mental care or long-term care settings, social assistive robots can already – under supervision – support patients to learn new skills, find information, ask assistance, and offer elements of companionship. They are also used to support the well-being of people and children with special needs.

Fig. 5. Representation of the impacts of robotics on the SDGs of the society cluster, on the target level. The interpretation of the figure is the same as for Fig. 4.

As demonstrated during the COVID-19 pandemic, robots can also help with public health and epidemiologic threats (Khamis et al., 2021). In direct prevention, they were used to disinfect or identify sick individuals. Indirectly, they alleviated the burden of confinement measures through work at distance, telemedicine, delivery, laboratory work, and non-hospital care. More broadly, robotics can also prevent injuries and save lives. According to the International Labor Organization (ILO), 2.78 million workers die each year from occupational accidents and work-related diseases. An additional 374 million workers suffer from non-fatal occupational accidents (https://unglobalcompact.org/take-action/safety-andhealth). This number can be reduced by creating safer working conditions with the use of robots, although automation at the workplace may be linked with higher mental health problems.

4.2.4. SDG 4. Quality education

Education is a key driver of economic growth, and a main catalyst for poverty eradication and sustainable development. Robots can play important roles in improving the quality of education globally, by contributing on two fronts: (1) robotics is a multidisciplinary field bringing together electromechanics, computer science and engineering, and (2) robotics enables innovative and effective learning methods such as constructionism-based learning, experiential learning, challenge-based learning (CBL), self-directed learning, personalized learning and games-based learning, even in hybrid or remote setups (Takacs et al., 2016). Modular robot kits, LEGO Mindstorms robots and Thymio II are examples of educational robots that can be used in constructionism-based learning settings.

However, affordability remains a barrier in developing countries, slowing down robotics' usage and adoption in education. At the same time, with the current paradigm shifts from ownership to usership or servitization (e.g., robots as a service), the wide availability of Massive Open Online Courses (MOOC), remotely accessible robotics labs and testbeds and the current wave of technology democratization through open-source tools, robots could have faster penetration into the educational systems of developing countries.

4.2.5. SDG 5. Gender equality

At the workplace, some physically demanding tasks are traditionally allocated to men. Robotics could help women integrate into these labor markets by reducing the physical requirements imposed on human workers, through human-robot collaboration or even exoskeletons. The introduction of robotics at home can decrease the time spent on household chores and since unpaid work in the home is mainly performed by women, allowing them better access to the paid labor market.

An important and under-considered aspect is the fact that robots are not always designed for women, which can result in inequalities: for example, exoskeletons are not sufficiently designed for a female body. Robots are also often attributed a gender and race, implicit or explicit (e.g., name, voice, form, behaviors), which can reinforce existing gender stereotypes. Their appearance should thus be designed in a thoughtful way. As the proportion of women in STEM (Science, Technology, Engineering and Math)/STEAM (Science, Technology, Engineering, Art and Math) (and thus robotics) is relatively small, more diversity in the design teams could result in more inclusive products. Role models encouraging women to take an interest in robotics are needed, and associations like "Women in Robotics", "Top 50 women in robotics" recognition and numerous Women in Engineering (WIE) initiatives exist to support these.

4.2.6. SDG 7. Affordable and clean energy

To be reliable and affordable, sustainable energy demands a significant amount of automation. Indeed, renewable energy source applications such as solar panels and wind turbines are often distributed systems, in contrast to coal, gas, and nuclear power plants or hydroelectric dams. Monitoring and inspection can be performed by a team of robots. Robots are also employed for maintenance, for example by cleaning solar panels or wind turbine blades, and even to automatically repair small defects.

On the other hand, robots need energy to work, and their large-scale deployment will have significant impacts on energy demand. Using a stock-accounting model, a 2017 study estimated an increase of 0.5 to 0.8 % of total US electricity demand due to robots by 2025, even if savings can be made by, for example, reducing lighting and heating in fully automated, "lights out" factories. Onboard renewable energy sources can also power some mobile robots.

4.2.7. SDG 11. Sustainable cities and communities

Urban robots will impact the structure of our cities, as they will be present in many important urban domains such as mobility, services, logistics, or surveillance and security. In transportation, the increasing level of autonomy of vehicles can make mobility safer and more inclusive. Fully autonomous ground and aerial vehicles coupled with ride sharing could also bring significant benefits to cities, such as potentially lowering costs and improving the reliability of public transport systems, with positive impacts on traffic and pollution (Takacs and Haidegger, 2022). More broadly, robots can be deployed for cleaning and collecting waste, leading to cleaner cities, or for security, for safer urban areas. Robots are also being developed to improve cities' resilience to fires and natural disasters, let it be assisting in decision making with monitoring and mapping, or reaching places human rescue teams cannot for first aid deliveries or critical actions.

Nevertheless, automation can also make transportation by assisted driving and autonomous vehicles overly attractive, thereby increasing congestion and pollution (Khamis and Malek, 2023). More generally, automated urban services could lead to reduction of human contact, loss of control and privacy. The use of autonomous vehicles and systems such as security robots and drone patrol systems for surveillance and patrolling can also raise important ethical questions.

4.2.8. SDG 16. Peace, justice and strong institutions

Intelligence, surveillance, target acquisition and reconnaissance robots can be enablers to promote peace and end different forms of violence. For example, robots equipped with advanced sensing and actuation technologies are actively used in concealed target detection and neutralization of human-made dangerous objects such as explosive remnants of war (ERW), landmines, unexploded ordinances (UXOs) or improvised explosive devices (IEDs). These technologies can also aid in operations of trapped and concealed victims.

Robot soldiers and peacekeeping units could also assist with the UN's general conflict resolution initiatives. Research even shows that people are willing to accept robotic peacekeepers, as long as they remain polite. Mobile robots, in particular drones, are used by police forces to monitor or detain threatening individuals. While they can help ensure security, such systems currently face challenges of acceptability in the wider population.

These technologies can be used by different parties with different aims. The recent war in the Ukraine showed numerous improvised use cases for retrofitted robots. Easily accessible commercial drones, for example, can be turned into simple, low-cost weapons, increasing the potential for violence or weakening states' institutions when abused by violent groups.

The possibility for robots to autonomously decide on taking a human life raises significant ethical concerns, and threatens fundamental human rights, although the practical difference in that respect with other types of weapons is not always clear. Initiatives like the *Campaign to Stop Killer Robots* and *Ban Lethal Autonomous Weapons* intend to regulate the use of AI and robotics and support the creation of new international laws on killer robots. A particular challenge is that military budgets are major sources of funding for these research projects.

4.3. Cluster 3 – robotics and environmental outcomes (SDGs 6, 13, 14 and 15)

The sensing and information gathering capacities of robots play a critical role in the enabling potential of robotics for the environmental SDGs, allowing better knowledge and monitoring of ecosystems, catastrophe prevention, or informed decision-making during emergency response. Robots can also automate repetitive tasks to mitigate the impacts of human activities on the environment, or to support the ecological transition. On the other hand, the environmental footprint of robots and their use for applications with heavy environmental impacts can significantly inhibit the achievement of these SDGs. The impacts of robotics on each environmental SDG are represented in Fig. 6, and detailed in the following paragraphs.

4.3.1. SDG 6. Clean water and sanitation

Autonomous robots are developed to monitor the quality of water and the development of algal blooms. They can also be used to clean tanks and to inspect critical infrastructure endangering or protecting drinking water resources (pipelines, mining fields, tailing fields, dams or sewer systems) (Chutia et al., 2017). Robots are being prototyped to clean beaches and remove plastic from rivers. They can help to clean toilet bowls or encourage good hygiene among children in the bathroom. There are also examples of robots used to teach water plumbing and toilet building skills to women in rural Indian villages, supporting sanitation while overcoming cultural inhibitions.

4.3.2. SDG 13. Climate action

Robotics support resilience and adaptation to climate-related disasters, in particular, disaster monitoring and mapping, search and rescue missions, wildfire fighting, etc., and also long-term mapping of the changings due to global warming.

Robotics can facilitate mitigation strategies, for example with planting trees, or monitoring the efficiency of greenhouse gas emission reduction strategies. Robotics enables alternatives in sectors, which produce a significant part of the emissions: in transportation, they can make public transportation more attractive with autonomous trains or buses or by using shared autonomous cars to solve the "last-mile" problem in delivery.

While the inhibiting effects of robotics on SDG 13, are mainly indirect, they can be significant. Robotics can improve the productivity, attractiveness or economic competitiveness of industries or processes which should be replaced by alternatives with lower greenhouse gas emissions. For example, robotics can be used in the fossil fuel industry, from underwater exploration and offshore operations to infrastructure maintenance. This could make such energy more attractive, and therefore slow the transition to sustainable energy production. A general deployment of robots will also induce a higher demand for energy, resulting in an increase of greenhouse gas emissions.

4.3.3. SDG 14. Life below water

Robotics can enable ecosystem protection, by helping authorities to detect violations and to enforce marine laws, and restoration, by recollecting solid waste and underwater litter, cleaning rivers and oceans, or hunting invasive species.

For example, mobile robots inspect and repair movable or immovable infrastructure, such as ships or offshore oil platforms (cf. SDG 13), thus preventing potentially catastrophic accidents. Robotics enables sustainable fishing practices, by better targeting species and locations to minimize the impact on underwater ecosystems (Mustapha et al., 2021). They allow knowledge gathering on underwater ecosystems and their challenges, to effectively guide potential actions. By mapping and monitoring coasts, they assist in protecting areas and animal or plant populations.

The usage of robots in land industries that are already damaging oceanic and marine ecosystems may worsen and amplify the negative impacts. For example, automation of land agriculture can lead to a higher release of pollutants. Using robots to explore or exploit underwater natural resources (minerals or fossil fuels) can lead to ecosystem disturbance or even disasters. If inappropriately regulated, robots for fishing may exacerbate overfishing and ecosystem destruction.

4.3.4. SDG 15. Life on land

Robotic systems may help to map or evaluate the state of ecosystems or animal populations, and better understand the interactions between the actors of the ecosystems. They allow the detection of invasive species and illegal activities such as poaching or unauthorized logging or mining. Robots can also be used to prevent or reduce the impacts of human activities. Precision irrigation, for example, can reduce water demand and prevent droughts and desertification. Forestry using legged robots can reduce the damage on the ground due to heavy rolling equipment. Finally, robots can be used to restore environments, automating tasks in tree planting or land remediation, for example. They can also help pollination by automating beehives.

Robotics can also act here as an inhibitor, through improving the appeal of projects or activities that negatively impact ecosystems. For example, using robots to detect primary resources can encourage their exploitation, and cause environmental damage. Similarly, using robots

Fig. 6. Representation of the impacts of robotics on the SDGs for the environment cluster, on the Target level. The interpretation of the figure is the same as for Fig. 3.

to detect animals of interest for poaching purposes, can accelerate the extinction of endangered species.

Finally, the use of robots can also make it harder to enforce environmental regulations, for instance they can help in detecting law enforcement agents or develop new smuggling techniques.

5. Discussion

5.1. Methodological limitations and representational insights

Robotics can be applied to a vast variety of real-world problems, and while the R&D community made a significant effort to demonstrate working prototypes and models, many times, those remain undocumented in scientific terms. This research aimed to identify applications as broadly as possible, but evidently, it could not possibly capture every one of them. The impacts of each application and their direct and indirect relationships with the SDGs and the Targets are also complex to evaluate, and the described *systematic consensus-based expert elicitation process* may have resulted in missing some associations. These results are thus in no way intended to be exhaustive, but to provide a representative assessment of the impacts of robotics on the SDGs, comparable to the state of the art.

In engineering research, expert elicitation is a well-accepted method, providing the systematic synthesis of opinions of authorities of a subject domain, especially where there is uncertainty due to insufficient data or lack of resources (Slottje et al., 2008). Expert elicitation is considered to be a scientific consensus methodology, and it allows for parametrization of generic knowledge, quantifying uncertainties (Schwarzenegger et al., 2023).

Arguably, the quantification of the impacts of robotics on the SDGs is an approximation task. While the subjective nature of the grading was largely mitigated by the double revision process among pairs of researchers, the methodological choices of the scaling and aggregation of results could impact the values of the results. The assumption made that each Target is equally important within a given SDG (leading to the presented computation of percentages), is also debatable. Nonetheless, we found that the outcome of our methodology is coherent with the qualitative contents of the summaries for each SDG, and thus we are confident that the quantitative results faithfully represent the impacts identified.

5.2. Examining biases in the analysis enabling and inhibiting factors in Robotics Deployment Positive impacts: taking a step back

It is remarkable and was a somewhat expected outcome that the quantitative analysis of the expert review showed significantly higher impacts on the enabling side than on the inhibiting side. While robotics can indeed have positive effects on our society, economy and environment, in general, we shall address a potential bias in the results. It is well documented that scientific publications highlight positive effects more often than negative ones, which limits the strength of such studies. Impacts, both positive and negative, are also linked to funding and policy. Negative impacts result in stringent policy and reduced funding for research and development. Since most technologies are designed to produce a positive result for a particular problem, the negative impacts are often unintended consequences. In the case of robotics, such a bias is exacerbated by two factors: First, positive impacts are easier to identify and detect, as they are usually the direct objective of the technology deployment and scientific reporting. Negative impacts are often hidden, and thus need to be discovered instead: they require long-term studies along careful design, and additional funding and support. Second, robotics is a costly field, where large-scale deployments require significant external funding or a viable, scalable business model. Many references described small-scales research projects, showing the potential of robotics for a particular task, yet with low fidelity. In reality, crossing the "valley of death", by going from a proof of concept to an actual operational system, remains a significant challenge (*Fresh Consulting*, n.d.; Jacobs et al., 2018; Fichtinger et al., 2022) across industries. That said, since robotics is a nascent field, it would be prudent to consider and establish processes to monitor and document unintended negative impacts that may arise from robotics as a technology.

5.3. The complex relationship and contradictions between SDGs

Apart from the potential bias, there are also complex relationships and even contradictions between the SDGs. As an example, robotics can automate tasks to improve productivity in manufacturers or food facilities. On the widest spatial scale, robots can be deployed in unknown, remote locations to collect precious information about ecosystems and infrastructure, and when combined with advanced AI methods assist with complex decision-making. On the micro-scale, thanks to their precise controllability, robots are used routinely for surgical operations or to assist human beings in physically demanding tasks.

On the other hand, by perpetuating existing social biases, robotics could hinder advanced societal changes, such as gender equality. Notably, automated military tools could seed violence, and scale up their impact. Robots' ecological footprint was also underlined, from the required raw materials during production to the hazardous elements released at the end of their lifecycle.

Interestingly, however, the complex relationships between the different SDGs, and their possible tensions and contradictions (Hickel, 2019), lead to many of the potential inhibiting impacts of robotics. The deployment of robots in the workplace – to improve productivity and reduce poverty – could heavily disturb the labor market, with major impacts on unskilled workers and developing countries, and redraw the global logistic routes. Emerging smart mobility technologies and business models such as self-driving shuttles, robotaxis and seamless integrated mobility systems (SIM) make transportation safer, more accessible and affordable, but require expensive physical and digital infrastructure and a well-developed governance framework and can open the doors to serious cyber threats and attacks that may impact the society (Khamis and Malek, 2023). Agricultural robots help feed the increasing human population, but the resulting monoculture paradigm threatens biodiversity.

These examples do not only showcase the dual nature of the impacts of technology, but they also highlight the importance of policy in the societal choices that must be made to trade off the positive and negative effects of the deployment of robots. For example, as robots increase productivity, local incomes rise, and the price of goods is typically reduced. In that case, the profits could be distributed to shareholders and contribute to economic inequality (aka the gap between rich and poor), or be taxed to benefit society through healthcare, education or infrastructure. On the other hand, high taxes could discourage investment in robotics in the first place, reducing the potential positive impacts. While the arbitration of these trade-offs through policy lies in the responsibility of politics, it is the role of robotics experts, along with multidisciplinary researchers, to inform and educate society on the potential consequences, and honestly broker the alternatives to the population and the decision-makers (Pielke, 2012). This shall increase social responsibility and accountability in the engineering domain in general.

This is also in line with the objective of SDG 17 (Partnerships for the Goals), which calls for cross-sector and cross-country collaboration to "strengthen the means of implementation" of the SDGs, to give every country the means to create the policies needed to support the SDGs.

5.4. Standardization, interoperability, open source and SDG 17

As stated in relation to SDG 17, the SDGs can only be achieved with strong global partnerships and cooperation. In robotics, similar principles have fueled the development of numerous standards and regulations to facilitate the general adoption and safety of robots (Jacobs et al., 2018) for the past 60 years. Robot standards are mainly provided by

Standard Development Organizations (e.g., ISO, IEC, RAR, IEEE, ASTM) focusing on safety, reliability and performance, and through these, inherently addressing some aspects of sustainable development. Nevertheless, IEC now explicitly articulated it in its strategy: "*Elaborating sustainable development goals and increasing the efficacy of safety standards affords positive conditions for the enhancement of safety and should be integrated in the overall safety measurement paradigm.*" (*IEC white paper on safety in the future*, 2020), which is illustrated in Fig. 7. ISO also started to invest energy into sustainability, leading to related international standards and guidelines across various sectors (Takács et al., 2022).

Open-source robotics is another phenomenon with a deep impact on cooperation (Zhang et al., 2017). It allows a wider adoption of any particular technology, by decreasing the barriers to knowledge, increasing competition and collaborations, and promoting innovation against monopolization. Similarly, standards and interoperability allow more companies and stakeholders to benefit from and take part in the ecosystem.

5.5. Robo-ethics

While ethics (and robo-ethics specifically (Tzafestas, 2016; Mitcham, 1994; Coeckelbergh, 2020)) is sometimes overlapping with sustainable development, its necessity or impact is not explicitly mentioned in the SDGs. Robo-ethics addresses the impact of robotics as disruptive technology on society and its (potential) issues, such as privacy (Lutz et al., 2019), responsibility (Gunkel, 2020), safety (Haddadin, 2014) and fairness, being crucial for a beneficial deployment of robotic technologies (Boesl and Liepert, 2016). Several initiatives have recently been launched, in that direction, to define the outstanding challenges and propose standards and for instance, to manage those challenges (Bösl and Bode, 2018). Technical organizations, such as the Institute of Electrical and Electronics Engineers (IEEE) (Chatila et al., 2017; Prestes et al., 2021) and academic actors (Müller, 2021) have been working on robo-ethics related issues (which are closely related to AI ethics and trustworthy AI), representing growing fields of studies and actions (*IBM Res.*, 2021; Université de Montréal, 2018; Boesl et al., 2018).

Over the next 50 years, robotics, automation and AI will have similar impact on society and our world as the internet and mainstream IT have unfurled over the last five decades. Subsequently, as they are going to permeate all areas of daily life, our grandchildren will grow up as the first "Generation 'R'" of "Robotic Natives" – in daily contact with these technologies. Robo-ethics, as well as Sustainability, should be more taught across universities and companies – ideally together. As an example, in 2023 the authors co-organized a series of educational webinars on sustainability and robotics with trade and research associations (EU Robotics and the Confederation of Artificial Intelligence Research Laboratories in Europe). The aim was to provide a series of free, introductory educational content to raise awareness among robotics players of issues related to sustainability, the SDGs and the social and ethical implications of their projects (and how to identify and deal with them). Industry professionals, researchers, experts were asked to expose how they integrate sustainability in their projects or organizations, and explain what challenges they encountered and how they alleviated them. Members of the author group are also contributing to diverse policy-making efforts by consulting, e.g., the United Nations and the European Commission. As contribution to the 2021 United Nations Science, Technology and Innovation Conference on the Achievement of the SDGs and the 2021 European University Institute State of The Union, they published a list of policy recommendations which are provided in an amended form below:

- Explainability of technology

  The more technologies like robotics, automation and AI are permeating humankind's living realm, the more necessary is an educated discourse about their impact on society. To enable such an

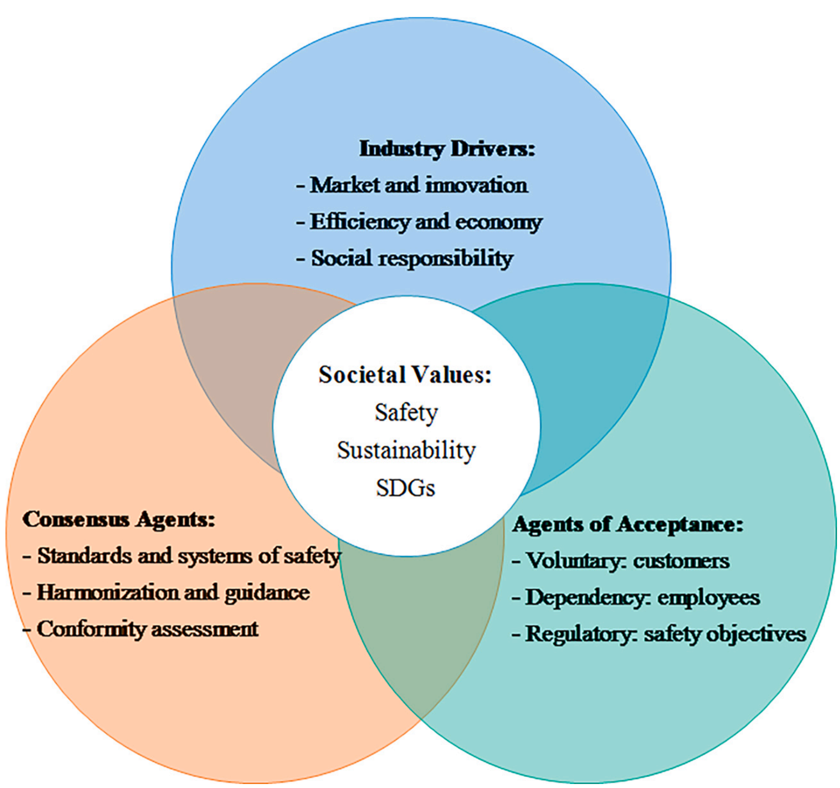

Fig. 7. Standards organizations as enablers for societal progress.
This mission is explicitly articulated in some of the major international standardization bodies' strategic documents (Based on the *IEC white paper on safety in the future*, 2020).

exchange between all affected stakeholders, the authors deem it crucial that accessible and understandable information about the constitution of respective technologies is supplied. Therefore, all entities involved in the research and development of technology should be pushed to provide descriptions of their work that are openly accessible and intellectual digestible by the general public; this should be laid down as a requirement for the assignment of, e.g., research grants or other (at least in the beginning) governmental funding.

- No hard regulation inhibiting innovation

  The European Commission, Parliament, and Council have recently passed the AI act, which follows an approach of regulation through legislation. This approach, while it can effectively protect citizens against the negative impacts of robotics, has the disadvantage of potentially threatening innovation in the robotics industry. An alternative approach which could be considered to regulate disruptive technologies, firstly using methods from the domain of soft-regulation like standardization, certification, self-regulatory principles including governance frameworks or innovation spaces similar to the Japanese concept of so-called "Tokku" Safety Areas (Weng et al., 2015), in which robotics applications can be evaluated in designated public areas under controlled, risk-mitigated conditions. Some of the authors have been consulting (and explicitly warning) the European Commission about the shortcomings and potential impact of the AI act as members of consulting groups and speakers, e.g., at the EU State of the Union Conference in 2021, and repeatedly at the 2023 European Robotics Forum, at the related workshop (co-organized by some of the co-authors).

- Emphasize the positive impact of technology and its empowering characteristics

  In public discourse and media, mostly the challenges, risks and threats of technology are depicted. The positive, enabling and empowering effects of technologies like automation, robotics and AI are often not adequately reflected or – sometimes even worse – overdrawn, so that they look and feel like science fiction. This is one of the drivers for restrictive policy making. We deem it crucial to drive a neutral, educated representation of technology in the general public that sheds light equally on the risks but also the – in many cases overwhelmingly – positive potential. In addition, driving "good" technology (i.e., technology with enabling, empowering and non-destructive applications in mind) has to become paramount for researchers and developers alike. We also see an additional research question for potential follow-up research in this aspect: How can the development of technology with positive target use-cases be fostered?

- Right to participate in (or elude) technological progress

  Discussing participation in technological progress, we usually have in mind how parts of society and humankind gain access to technology. This is an important aspect, especially when analyzing the achievement of the SDGs by the help of technologies. And, as our research shows, it is not such an obvious one, as many might think. Access to technologies like robotics, automation and AI might help to easier and faster achieve some of the SDG's (e.g., automated food production and vertical or indoor farming concepts to feed the increasing human population). At the same time, though, it can prove to be counterproductive or even inhibiting for others. Equal and fair economic growth is hindered by the mono- or oligopolistic ownership structure controlling the latest innovations in the domains of computer technologies (incl. AI, cloud/edge/fog computing etc. (Haidegger et al., 2019)) and automation (affordable robotics, sensorics etc.). In this case, access to technology is important to ensure balanced, equally distributed economic growth – but if the first world is not making its technology freely available to the third world, the UN predicts an increase of the digitalization and automation gap instead of contributing to its mitigation.

5.6. *Future of sustainable robotics*

The authors are heavily involved in ongoing research activities aiming to sketch and alter the future of *sustainable robotics*. Beyond the above mentioned initiatives, there is an ongoing large study (delayed by COVID) conducted by the IEEE Robotics and Automation Society (RAS) to grasp the key attributes of robotics in 2050. The experts contributing to Robotics 2050+ will be asked to look into the various sectors, providing their view on the role of automation in the respective fields, as indicated in the study design board (Fig. 8).

In late 2023, the euRobotics aisbl – Europe's centralized robotics platform – Sustainability Topic Group (https://eu-robotics.net/sustainability-topic-group/) held a series of workshop to sketch the roadmap for Sustainable Robotics. The outcome of the work will be presented at the 2024 European Robotics Forum.

6. Conclusions

As this research highlights, robotics have a growing impact on our societies, economies and environments. They also raise complex challenges at the same time. Robotics is not a de facto solution to complex global problems, such as systemic economic crises, climate change or the transformation of work, yet it offers a partial remedy. Through the framework of the United Nations' Sustainable Development Goals (SDGs), this article identifies and illustrates how and where robotic technology-driven solutions might appear to better mitigate risks and contribute to a more sustainable and socially responsible robotics domain.

Moving towards sustainable robotics requires a rigorous multidisciplinary approach to understand how sustainability, technology and societal challenges are intertwined. The UN's 17 SDGs and 169 Targets were individually assessed within the context of state-of-the-art robotics, already documented in the Scientific Literature. The significance and the quality of evidence of impacts were assessed by an international panel of experts, to quantify the positive and/or negative effects. Results indicate that robotics has the potential to enable 46 % of the Targets, particularly for the industry and environment-related SDGs, forecasting a huge impact on our production systems and thus, on our entire society. Inversely, robotics could inhibit 19 % of the SDG targets, mainly through the exacerbation of inequalities and tensions among the SDGs. Having already been demonstrated for AI, robotics is a double-edged tool, with both positive and negative impacts.

This article demonstrates the need to work together with multidisciplinary experts, identifying the direct and indirect impacts of future deployments in the field of robotics. To conclude, to enable the sustainable development of robotics, the robotics community would greatly benefit from efforts in raising awareness, building tools and sharing knowledge.

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Conceptualization: CMM, AK, VM, DB, BV, BR, TH
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Visualization: VM, LL, BV, TH
Project administration: CMM, BV, TH
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Writing – original draft: AK, CMM, VM, LL, DB, AJ, BV, TH

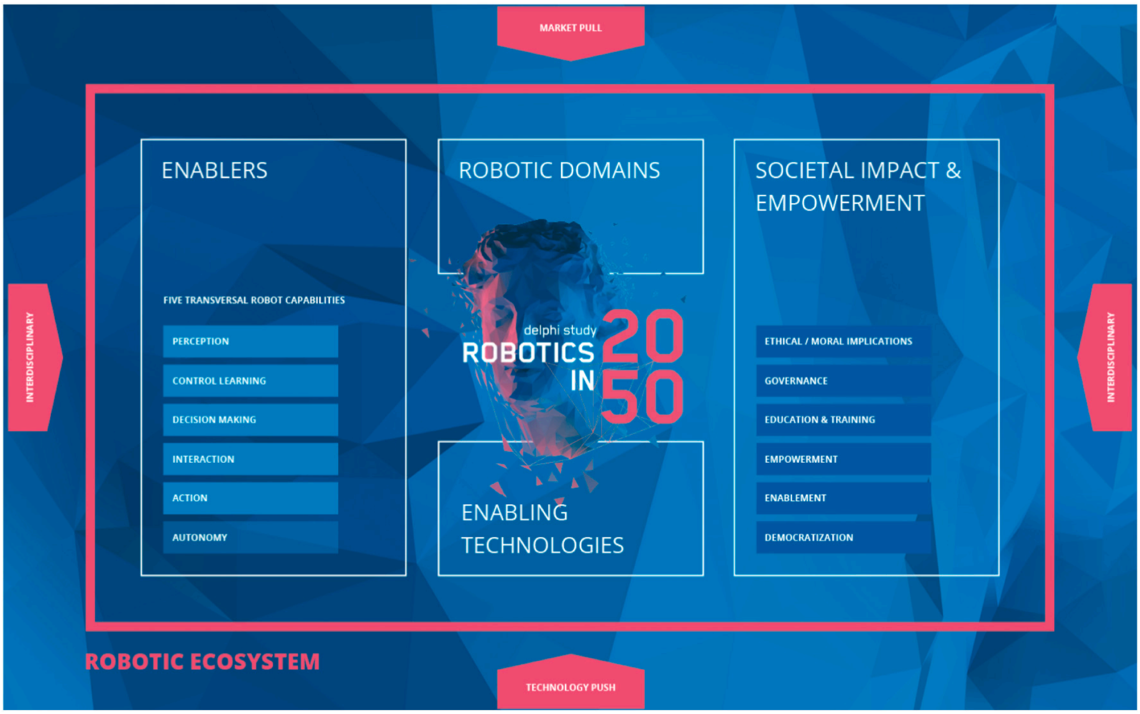

Fig. 8. Methods and components of the Robotics in 2050 Delphi Study.
The IEEE RAS has an ongoing initiative to systematically assess the enabling and inhibiting components of the future of robotics (Hutchinson, 2021).

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Data and materials availability

The database created is provided as supplementary material 2 and will be made openly available on the authors' website www.sustainablerobotics.org.

References

Adeshina, Steve A., Aina, Oluwatomisin, 2023. The role of AI in SDG: an African perspective. In: The Ethics of Artificial Intelligence for the Sustainable Development Goals. Springer International Publishing, Cham, pp. 133–143.
Blank, Steve, 2019. McKinsey's three horizons model defined innovation for years. Here's why it no longer applies. Harv. Bus. Rev. 1–5.
Boesl, D.B.O., Liepert, B., 2016. 4 Robotic Revolutions - proposing a holistic phase model describing future disruptions in the evolution of robotics and automation and the rise of a new Generation 'R' of Robotic Natives. In: 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Daejeon, Korea (South), pp. 1262–1267. https://doi.org/10.1109/IROS.2016.7759209.
Boesl, D.B.O., Bode, M., Greisel, S., 2018. Drafting a Robot Manifesto – new insights from the robotics community gathered at the European Robotics Forum 2018. In: 2018 27th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN), Nanjing, China, pp. 448–451. https://doi.org/10.1109/ROMAN.2018.8525699.
Boesl, D.B.O., Haidegger, T., Khamis, A., Mai, V., Mörch, C., 2021. Automating the Achievement of SDGs: Robotics Enabling & Inhibiting the Accomplishment of the SDGs. The UN Interagency Task Team on Science, Technology and Innovation for the SDGs (IATT), New York (NY), pp. 122–126. http://real.mtak.hu/131796/.
Bösl, D.B.O., Bode, M., 2018. Roboethics and robotic governance – a literature review and research agenda. In: Ollero, A., Sanfeliu, A., Montano, L., Lau, N., Cardeira, C. (Eds.), ROBOT 2017: Third Iberian Robotics Conference. ROBOT 2017, Advances in Intelligent Systems and Computing, vol. 693. Springer, Cham. https://doi.org/10.1007/978-3-319-70833-1_12.
Bruno, Ilenia, Lobo, Georges, Covino, Beatrice Valente, Donarelli, Alessandro, Marchetti, Valeria, Panni, Anna Schiavone, Molinari, Francesco, 2020. Technology readiness revisited: a proposal for extending the scope of impact assessment of European public services. In: Proceedings of the 13th International Conference on Theory and Practice of Electronic Governance, pp. 369–380.
Chatila, R., Firth-Butterflied, K., Havens, J.C., Karachalios, K., 2017. The IEEE global initiative for ethical considerations in artificial intelligence and autonomous systems. IEEE Robot. Autom. Mag. 24, 110. https://ieeexplore.ieee.org/abstract/document/7886245.
Chutia, Swagat, Kakoty, Nayan M., Deka, Dhanapati, 2017. A review of underwater robotics, navigation, sensing techniques and applications. Proc. Adv. Robot. 1–6.
Coeckelbergh, Mark, 2020. AI Ethics. The MIT Press, Cambridge, Massachusetts, USA.
Fichtinger, G., Troccaz, J., Haidegger, T., 2022. Image-guided interventional robotics: lost in translation? Proc. IEEE 110 (7), 932–950.
Why robotics companies fail, Fresh Consulting. available at. https://www.freshconsulting.com/insights/white-papers/why-robotics-companies-fail/.
Fuso Nerini, F., et al., 2017. Mapping synergies and trade-offs between energy and the Sustainable Development Goals. Nat. Energy 3, 10–15. https://doi.org/10.1038/s41560-017-0036-5.
Fuso Nerini, F., Sovacool, B., Hughes, N., Cozzi, L., Cosgrave, E., Howells, M., Tavoni, M., Tomei, J., Zerriffi, H., Milligan, B., 2019. Connecting climate action with other Sustainable Development Goals. Nat. Sustain. 2, 674–680.
Guenat, S., Purnell, P., Davies, Z.G., Nawrath, M., Stringer, L.C., Babu, G.R., Balasubramanian, M., Ballantyne, E.E.F., Bylappa, B.K., Chen, B., De Jager, P., Del Prete, A., Di Nuovo, A., Ehi-Eromosele, C.O., Torbaghan, M. Eskandari, Evans, K.L., Fraundorfer, M., Haouas, W., Izunobi, J.U., Jauregui-Correa, J.C., Kaddouh, B.Y., Lewycka, S., MacIntosh, A.C., Mady, C., Maple, C., Mhiret, W.N., Mohammed-Amin, R.K., Olawole, O.C., Oluseyi, T., Orfila, C., Ossola, A., Pfeifer, M., Pridmore, T., Rijal, M.L., Rega-Brodsky, C.C., Robertson, I.D., Rogers, C.D.F., Rougé, C., Rumaney, M.B., Seeletso, M.K., Shaqura, M.Z., Suresh, L.M., Sweeting, M. N., Buck, N. Taylor, Ukwuru, M.U., Verbeek, T., Voss, H., Wadud, Z., Wang, X., Winn, N., Dallimer, M., 2022. Meeting sustainable development goals via robotics and autonomous systems. Nat. Commun. 13, 3559.
Gunkel, D.J., 2020. Mind the gap: responsible robotics and the problem of responsibility. Ethics Inf. Technol. 22, 307–320.
Gupta, Shivam, Langhans, Simone D., Domisch, Sami, Fuso-Nerini, Francesco, Felländer, Anna, Battaglini, Manuela, Tegmark, Max, Vinuesa, Ricardo, 2021. Assessing whether artificial intelligence is an enabler or an inhibitor of sustainability at indicator level. Transp. Eng. Aust. 4, 100064.
Haddadin, S., 2014. Towards safe robots: approaching Asimov's 1st law. In: Springer Tracts in Advanced Robotics, 1st ed. Springer Berlin Heidelberg, Berlin, Heidelberg.
Haidegger, T., 2021. Taxonomy and standards in robotics. In: Ang, M.H., Khatib, O., Siciliano, B. (Eds.), Encyclopedia of Robotics. Springer, Berlin, Germany, pp. 1–10. https://doi.org/10.1007/978-3-642-41610-1_190-1.
Haidegger, T., Galambos, P., Rudas, I.J., 2019. Robotics 4.0—are we there yet?. In: Proc. IEEE 23rd Int. Conf. Intell. Eng. Syst. (INES), pp. 117–124. https://doi.org/10.1109/INES46365.2019.9109492 (Apr.).

Haidegger, Tamas, Speidel, Stefanie, Stoyanov, Danail, Satava, Richard M., 2022. Robot-assisted minimally invasive surgery—surgical robotics in the data age. Proc. IEEE 110 (7), 835–846.

Hannan, M.A., Al-Shetwi, Ali Q., Begum, R.A., Ker, Pin Jern, Rahman, S.A., Mansor, M., Mia, M.S., Muttaqi, K.M., Dong, Z.Y., 2021. Impact assessment of battery energy storage systems towards achieving sustainable development goals. J. Energy Storage 42, 103040.

Hickel, J., 2019. The contradiction of the sustainable development goals: growth versus ecology on a finite planet. Sustain. Dev. 27 https://doi.org/10.1002/sd.1947.

Holzinger, Andreas, Edgar Weippl, A., Tjoa, Min, Kieseberg, Peter, 2021. Digital transformation for sustainable development goals (sdgs)-a security, safety and privacy perspective on ai. In: International Cross-domain Conference for Machine Learning and Knowledge Extraction. Springer International Publishing, Cham, pp. 1–20.

IEC white paper on safety in the future. available at. https://www.iec.ch/basecamp/safety-future.

The SDGs wedding cake. available at. https://www.stockholmresilience.org/research/research-news/2016-06-14-the-sdgs-wedding-cake.html.

Hutchinson, S., 2021. Robotics and Automation [President's Message], Future of robotics, automation and AI 2050. IEEE Robot. Autom. Mag. 28 (2), 6–8. https://doi.org/10.1109/MRA.2021.3076550. June 2021.

Trustworthy AI. available at, IBM Res.. https://research.ibm.com/topics/trustworthy-ai.

IFR. IFR presents World Robotics 2022 reports, IFR Int. Fed. Robot. available at. https://www.automation.com/en-us/articles/october-2022/ifr-presents-world-robotics-report-2022.

Iizuka, Michiko, Hane, Gerald, 2021. Towards attaining the SDGs: cases of disruptive and inclusive innovations. Innov. Dev. 11 (2–3), 343–364.

Jacobs, T., Veneman, J., Virk, G.S., Haidegger, T., 2018. The flourishing landscape of robot standardization. IEEE Robot. Autom. Mag. 25, 8–15.

Jiang, Shanshan, Jakobsen, Kine, Bueie, Jonas, Li, Jingyue, Haro, Peter Halland, 2022. A tertiary review on blockchain and sustainability with focus on Sustainable Development Goals. IEEE Access 10, 114975–115006.

Khamis, Alaa, Malek, Suzette, 2023. Smart mobility for sustainable development goals: enablers and barriers. In: 2023 IEEE International Conference on Smart Mobility (SM), Thuwal, Saudi Arabia, pp. 173–185. https://doi.org/10.1109/SM57895.2023.10112562.

Khamis, A., Li, H., Prestes, E., Haidegger, T., 2019a. AI: a key enabler of sustainable development goals, part 1. IEEE Robot. Autom. Mag. 26, 95–102.

Khamis, A., Li, H., Prestes, E., Haidegger, T., 2019b. AI: a key enabler for sustainable development goals: part 2. IEEE Robot. Autom. Mag. 26, 122–127.

Khamis, Alaa, Meng, Jun, Wang, Jin, Azar, Ahmad Taher, Prestes, Edson, Takács, Árpád, Rudas, Imre J., Haidegger, Tamás, 2021. Robotics and intelligent systems against a pandemic. Acta Polytech. Hungarica 18 (5), 13–35.

Khosla, Radhika, Miranda, Nicole D., Trotter, Philipp A., Mazzone, Antonella, Renaldi, Renaldi, McElroy, Caitlin, Cohen, Francois, Jani, Anant, Perera-Salazar, Rafael, McCulloch, Malcolm, 2021. Cooling for sustainable development. Nat. Sustain. 4 (3), 201–208.

Laumann, Felix, von Kügelgen, Julius, Uehara, Thiago Hector Kanashiro, Barahona, Mauricio, 2022. Complex interlinkages, key objectives, and nexuses among the Sustainable Development Goals and climate change: a network analysis. Lancet Planet. Health 6 (5), e422–e430.

Lawrence, Roderick J., 2020. Overcoming barriers to implementing sustainable development goals. Hum. Ecol. Rev. 26 (1), 95–116.

Lupi, F., Mabkhot, M.M., Finžgar, M., Minetola, P., Stadnicka, D., Maffei, A., Litwin, P., Boffa, E., Ferreira, P., Podržaj, P., Chelli, R., Lohse, N., Lanzetta, M., 2022. Toward a sustainable educational engineer archetype through Industry 4.0. Comput. Ind. 134 https://doi.org/10.1016/j.compind.2021.103543.

Lutz, C., Schöttler, M., Hoffmann, C.P., 2019. The privacy implications of social robots: scoping review and expert interviews. Mob. Media Commun. 7, 412–434.

Mai, V., Vanderborght, B., Haidegger, T., Khamis, A., Bhargava, N., Boesl, D.B.O., Gabriels, K., Jacobs, A., Moon, Aj., Murphy, R., Nakauchi, Y., Prestes, E., Rao R, B., Vinuesa, R., Mörch, C.-M., 2022. The role of robotics in achieving the United Nations Sustainable Development Goals—the experts' meeting at the 2021 IEEE/RSJ IROS Workshop. IEEE Robot. Autom. Mag. 29, 92–107.

Mason, Alex, Haidegger, Tamas, Alvseike, Ole, 2023. Time for change: the case of robotic food processing. IEEE Robot. Autom. Mag. 30 (2), 116–122.

McGaughey, Ewan, 2022. Will robots automate your job away? Full employment, basic income and economic democracy. Ind. Law J. 51 (3), 511–559.

Mitcham, Carl, 1994. Thinking Through Technology: The Path Between Engineering and Philosophy. University of Chicago Press, Chicago. https://doi.org/10.7208/chicago/9780226825397.

Mogha, Harshita, Hasteer, Nitasha, 2023. Challenges to implement artificial intelligence for environmental sustainability. In: International Conference on Trends and Recent Advances in Civil Engineering. Springer, Singapore, pp. 397–410.

Müller, V.C., 2021. Ethics of artificial intelligence and robotics. In: Zalta, E.N. (Ed.), The Stanford Encyclopedia of Philosophy. Metaphysics Research Lab, Stanford University. https://plato.stanford.edu/archives/sum2021/entries/ethics-ai/ (Summer 2021).

Mustapha, Umar Farouk, Alhassan, Abdul-Wadud, Jiang, Dong-Neng, Li, Guang-Li, 2021. Sustainable aquaculture development: a review on the roles of cloud computing, internet of things and artificial intelligence (CIA). Rev. Aquac. 13 (4), 2076–2091.

Nagy, Tamás D., Haidegger, Tamás, 2022. Performance and capability assessment in surgical subtask automation. Sensors 22 (7), 2501.

Pielke, R.A., 2012. The Honest Broker: Making Sense of Science in Policy and Politics, ISBN 978-0521694810.

Prestes, E., Houghtaling, M.A., Gonçalves, P.J.S., Fabiano, N., Ulgen, O., Fiorini, S.R., Murahwi, Z., Olszewska, J.I., Haidegger, T., 2021. The first global ontological standard for ethically driven robotics and automation systems. IEEE Robot. Autom. Mag. 28, 120–124.

Roser, M., 2013. Employment in agriculture (available at, Our World Data. https://ourworldindata.org/employment-in-agriculture.

Schoormann, Thorsten, Strobel, Gero, Möller, Frederik, Petrik, Dimitri, 2021. Achieving sustainability with artificial intelligence-a survey of information systems research. In: Proceedings of the 42nd International Conference on Information Systems (ICIS 2021).

Schwarzenegger, Rafael, Quigley, John, Walls, Lesley, 2023. Is eliciting dependency worth the effort? A study for the multivariate Poisson-Gamma probability model. Proc. Inst. Mech. Eng. Part O J. Risk Reliab. 237 (5), 858–867.

Slottje, Pauline, Van der Sluijs, J.P., Knol, Anne B., 2008. Expert Elicitation: Methodological Suggestions for Its Use in Environmental Health Impact Assessments.

Steinert, Martin, Leifer, Larry, 2010. Scrutinizing Gartner's hype cycle approach. In: Picmet 2010 Technology Management for Global Economic Growth. IEEE, pp. 1–13.

Takacs, Arpad, Haidegger, Tamas, 2022. Infrastructural requirements and regulatory challenges of a sustainable urban air mobility ecosystem. Buildings 12 (6), 747.

Takacs, Arpad, Eigner, Gyorgy, Kovacs, Levente, Rudas, Imre J., Haidegger, Tamas, 2016. Teacher's kit: development, usability, and communities of modular robotic kits for classroom education. IEEE Robot. Autom. Mag. 23 (2), 30–39.

Takács, Kristóf, Mason, Alex, Cordova-Lopez, Luis Eduardo, Alexy, Márta, Galambos, Péter, Haidegger, Tamás, 2022. Current safety legislation of food processing smart robot systems–the Red Meat Sector. Acta Polytech. Hungarica 19 (11), 249–267.

Terryn, Seppe, Brancart, Joost, Lefeber, Dirk, Van Assche, Guy, Vanderborght, Bram, 2017. Self-healing soft pneumatic robots. Sci. Robot. 2 (9), eaan4268.

Tzafestas, S.G., 2016. Roboethics. In: Intelligent Systems, Control and Automation: Science and Engineering, vol. 79. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-21714-7.

United Nations General Assembly, 2015. Transforming our world: the 2030 Agenda for Sustainable Development - resolution adopted by the General Assembly on 25 September 2015. available at. https://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E.

Université de Montréal, 2018. Montreal declaration for a responsible development of artificial intelligence. available at. https://www.montrealdeclaration-responsibleai.com/_files/ugd/ebc3a3_506ea08298cd4f8196635545a16b071d.pdf.

Vinuesa, R., Azizpour, H., Leite, I., Balaam, M., Dignum, V., Domisch, S., Felländer, A., Langhans, S.D., Tegmark, M., Fuso Nerini, F., 2020. The role of artificial intelligence in achieving the Sustainable Development Goals. Nat. Commun. 11, 233.

Weng, Y.H., Sugahara, Y., Hashimoto, K., Takanishi, A., 2015. Intersection of "Tokku" special zone, robots, and the law: a case study on legal impacts to humanoid robots. Int. J. Soc. Robot. 7 (5), 841–857. https://doi.org/10.1007/s12369-015-0287-x.

Yang, G.-Z., Bellingham, J., Dupont, P.E., Fischer, P., Floridi, L., Full, R., Jacobstein, N., Kumar, V., McNutt, M., Merrifield, R., Nelson, B.J., Scassellati, B., Taddeo, M., Taylor, R., Veloso, M., Wang, Z.L., Wood, R., 2018. The grand challenges of Science Robotics. Sci. Robot. 3, eaar7650 https://doi.org/10.1126/scirobotics.aar7650.

Zhang, Lin, Merrifield, Robert, Deguet, Anton, Yang, Guang-Zhong, 2017. Powering the world's robots—10 years of ROS. Sci. Robot. 2 (11), eaar1868.

Zhang, Qinan, Zhang, Fanfan, Mai, Qiang, 2022. Robot adoption and green productivity: curse or boon. Sustain. Prod. Consum. 34, 1–11.