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Sustainability Indicators in Industrial Robotic Systems

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Nowadays, the application of industrial robots in manufacturing is widespread to automatize tedious and repeatable precision-sensitive processes. Modern robotic cells compete with the human workforce and specialized industrial machines in general efficiency. Additionally, robotic cells can be typically reprogrammed for different tasks, thus providing flexible applications, especially compared to more traditional methods. Advanced autonomous and intelligent capabilities are widespread in modern robotic systems, supplying quantitative factors like higher availability, fault tolerance, precision, and system flexibility. Robotic systems typically work measurably more efficiently regarding resource usage, electrical power, and waste than other industrial production line systems. New intelligent and interconnected methods (e.g., cooperative robotics, big data analysis, cyber-physical systems) contribute further to the operation efficiency. Recently, sustainability has become a significant question in robotics: modern technical society faces problems such as decreasing availability of natural resources, workforce scarcity, and environmental challenges. This work focuses on industrial robotic systems as a primary pillar for sustainability efforts in numerous production sectors, such as metallurgy, assembly lines, and construction. This paper aims to review and analyze possible sustainability indicators of the industrial applications of robotics. Based on the analysis, the paper presents a manufacturing process model with industrial robots that considers sustainability indicators. This model highlights the relationship between industrial robotization and sustainability from a quantitative and qualitative perspective. The model indicates that energy efficiency and data interconnectivity play a crucial role in the sustainability of industrial processes. The aim of the model is to help identify indicators playing a role in the sustainability of industrial robot-based manufacturing lifecycle and maintenance.

1. Introduction

Industrial production has always been characterized by technological and technical advancements. One of its significant steps was the development of industrial robot systems, automatic manipulators, and programmable material handling devices in the 1960s (i.e., the 3rd Industrial Revolution). The fourth industrial revolution has been actively discussed, involving the integration of individual production elements and units with an extremely high level of automation and robotization, also intensively integrating data, information, and communication technologies. These technological developments related to the Industry 4.0 paradigm aim to increase efficiency, usability, and productivity in manufacturing processes (Jatin et al., 2022) and in lifecycle-related applications in general (Bilad et al., 2022). On the other hand, their role in a sustainable future is often overlooked.
The program-controlled automatic manipulators surpassed human labor in speed, load capacity, and precision, thereby securing their place among the long line of production tools. However, their size, speed, and limited environmental sensing capabilities render industrial robots hazardous to human workers. The progress of technology and the results of the fourth industrial revolution have, in part or entirely, provided solutions to these issues. With the emergence of collaborative robotics, the environmental sensing capabilities of robots have significantly improved, enabling the perception of human presence and further ensuring safe working conditions. The other challenge related to productivity was not brought about by technology but rather by changing economic demands. The lifecycle of manufactured products was significantly shortened, product diversity grew

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tremendously, and a need to produce custom-made products to satisfy unique customer demands arose. In these cases, the focus shifted from producing large quantities rapidly to the flexibility of production, adaptability to changes, and speed of accommodating these changes.

The relationship between robotics and sustainability is traditionally identified with sustainable technologies or areas implemented using robotic devices. Such technologies or areas typically include agriculture, waste management, marine research, logistics, and transportation.

Agricultural applications (i.e., agro-robotics) have evolved into a distinct field where robots, autonomous robots, drones, and self-driving machinery operate to enhance production efficiency, precision farming, and the implementation of chemical-free or reduced-chemical technologies (Khort et al., 2019). In the field of waste management, the utilization of robots' traditional capabilities for sorting, selecting, and neutralizing the ever-increasing amount of waste has become even more prevalent (Kiyokawa et al., 2022). Previously, robots were not used in this area simply because a significant portion of the waste was disposed of through incineration or burial, rendering robot usage unnecessary. However, as this process has become increasingly unsustainable, recycling and reusing waste has gained significant priority. Accomplishing this with human labor is expensive and yields questionable efficiency. On the other hand, employing robots also incur significant expenses as well, but their efficiency is guaranteed.

The field of marine research is not traditionally associated with robot applications besides reconnaissance operations. Robots are employed to conduct measurements and investigations in areas beyond human reach regarding depth and time. Again, here is evident the utilization of robotics as a tool rather than the robots being a source of sustainability. Logistics and transportation are undergoing significant changes (Ližbetin et al., 2015). Besides robotizing packaging and warehousing tasks, introducing self-driving vehicles, whether for intralogistics or on the roads, represents a new frontier for robotics. In comparison to previous applications, sustainability, in this case, primarily emanates from the robots themselves, considering aspects such as reducing harmful emissions, optimization, and energy efficiency. These considerations are more pronounced compared to how they are currently emphasized, and this approach can be extended to various other tasks that robots have been performing for an extended period.

Nowadays, the development of robots keeps progressing and has reached a stage that requires the examination of new indicators of their overall usefulness and efficiency. From their previous role as profit-boosting production equipment, they have recently become one of the pillars of sustainability. Previous contributions attempted to overview industrial and mobile robots from a sustainability perspective, typically focusing on a specific indicator (Soori et al., 2023) or qualitative measurements (Guo et al., 2023), instead of providing a perspective overview. However, no previous contribution has provided a concise overview of indicators that permit the evaluation of sustainability in industrial robot-based manufacturing. For instance, the sustainable indicators and the trade-off between energy efficiency and computation capabilities have not yet been overviewed from a high-level perspective. This work aims to explore the sustainability aspects of industrial robots by reviewing available contributions in literature and the experience from ongoing research in a laboratory setting. This article presents a lifecycle-model draft of industrial robot manufacturing processes to aid in identifying sustainability indicators in current and future industrial robot cells. Based on the reviewed research, the model proposed in this work helps to identify sustainability indicators of manufacturing and maintenance in legacy, current, and future industrial robot systems.

2. Methodology

This work is based on reviewing articles that discuss the newest achievements of industrial robots and cyber-physical systems and their contribution to sustainable production. From the robotics perspective, fundamental (Siegwart & Nourbakhsh, 2004) and recent research on industrial robotic systems (Jatin et al., 2022) are reviewed. From the industrial production perspective, the fundamental processes from a cyber-physical perspective (Griffor et al. 2017) and Industry 4.0 viewpoint processes (Bilad et al. 2022) have been investigated. To help with the overview of the most important indicators, a lifecycle model is introduced, which is based on the fundamental robotic cognitive process and extended with the identified sustainable factors. The identified priorities are deduced based on the authors' experience combined with the most important factors appearing in the reviewed articles.

According to our research, sustainability has been modeled more as specific factors of industrial robot design rather than an overview from a sustainable viewpoint. The main characteristic of the approach presented in this article is to highlight and apply sustainable indicators to industrial robots while considering their traditional values, such as precision, speed, reliability, and - most importantly - providing consistently high-quality and continuously available work compared to human labor.

3. Sustainability indicators of industrial robots

In contrast to the conventional approach, our research perspective does not merely view robots as serving tools for a specific technology but as sustainable production tools and methods. In the following sections, traditional and new technological characteristics supporting the main sustainability assertions are further explored. Analyzing these fundamental features from a new perspective will provide a solid foundation for the sustainability analysis of industrial robots. Technological innovations within robotics often enhance the significance of robots in terms of sustainability on their own. The following subsections discuss these fundamental characteristics and their assessment from a sustainability viewpoint.

3.1 Material usage

Industrial robots' material usage and technological solutions have also undergone significant changes over the past decades. However, it can be confidently asserted that the production methods and materials employed are typically associated with mass production, resulting in cost-effective, material-efficient manufacturing. Industrial robots are typically produced in large series with consistent designs, regardless of their specific application or task. This mass production approach is driven by economic interests and the need for an adequate quantity of robots within a given timeframe, which, in turn, necessitates well-optimized and material-efficient design and manufacturing processes. As a result, industrial robots commonly consist of cast and machined steel, aluminum components, and standardized and optimized gearboxes and motors. The electronic elements in the control cabinets are not the result of unique design and production efforts but are mass-produced and scaled standard systems, allowing for material-efficient manufacturing and process optimization.
This characteristic can be effectively compared to the solutions used in custom machine manufacturing, where unique design, manufacturing time, and special equipment may compromise efficiency and optimization opportunities. In summary, it can be concluded that producing equipment in large series over an extended period, driven by economic necessity, results in better sustainability indicators than equipment lacking such characteristics. The widespread application of such tools inherently carries better sustainability metrics.

3.2 Energy Efficiency (Energy Consumption)

Focusing on industrial robots, the question of energy efficiency could be discussed both as a fundamental aspect and within the realm of modern technologies (Soori et al., 2023). Research results and technological solutions to achieve more efficient energy consumption for robots continue to emerge, and we can expect further advancements in the future (Merlo et al., 2023). From a fundamental standpoint, it can be stated that industrial robots predominantly use electrical energy to generate motion. At the same time, the operation of actuators or end-effectors typically involves the use of compressed industrial air, usually in a pneumatic manner, which can vary depending on the technology used. This fundamental characteristic does not show significant differences with other industrial equipment or machining tools concerning energy usage.

3.3 Lifecycle

When considering the lifecycle of industrial robots, two aspects can be considered: operational lifespan and applicability timespan. The operational lifespan refers to the period during which the equipment is functioning, providing full functionality and the expected operational parameters. On the other hand, the applicability timespan is examined in the context of the manufactured product, applied technology, or performed tasks. An equipment's lifespan cannot be defined for a more extended period than the usefulness of its designated tasks. Regarding the operational lifespan – which also validates the sustainability of their applicability – FANUC demonstrated, based on an internal survey, that the operational lifespan of a general-purpose industrial robot in production can reach or exceed 25 years. This figure is not particularly exceptional from the perspective of other manufacturers or machining equipment with a similar lifespan. However, unlike these machines, robots can keep pace with the technological advancements in their environment (e.g., universal machining equipment) while retaining the fundamental functions and consistency of their movements, providing the possibility for upgrading the technological tasks.

3.4 Programmability (Flexibility)

Robots, as universal and general material handling and technological servicing devices, inherently possess the concept of programmability. This flexibility, along with the factors already discussed concerning their operational lifespan, constitutes a compelling argument for recognizing them as a value in terms of sustainability. Just as a fundamental sustainability program involves the reuse of materials and waste, this capability is a conceptual attribute of robots, with the added value that reusability extends beyond individual components to the entire device in its complexity (Kataoka, 2023).

During reusability, there is no need to invest energy in disassembling and re-manufacturing. Moreover, the energy invested in the initial manufacturing is not wasted because the device can be reused without needing re-manufacturing. Thus, by making a single material usage and manufacturing energy investment, we obtain a device that can be self-reused and repurposed. This efficiency and sustainability cannot be achieved by any other recycling method, as it is not inherently destructive.

3.5 Collaboration

For many, the emergence of collaborative robots represents a significant milestone in developing industrial robotics. The goal was to create a robotic tool capable of performing human work processes without the previous safety risks. From a sustainability perspective, this provides the possibility of simplifying manufacturing or manipulation devices, reducing their footprint, and further increasing their universal usability. Of course, achieving this goal required sacrifices, and the developments did not all point in the same direction. In the interest of safety, speed and load capacity had to be compromised. However, this compromise is not permanent, as it is not a settled area, and developments continue to progress. Each subsequent step results in more efficient, more universal, and more sustainable tools.

3.6 Integration with Mixed Reality Systems

Together with modern advances in informatics, an exciting phenomenon emerged recently that studies the user space split into the real environment and the virtual data space. Some applications appeared in different proportions in one or the other space. This duality was already present with the emergence of robotics. However, it gained significant importance because the robot's activity (movement) surpassed all previous technological levels in real space, while the movement generation occurred entirely in the virtual data space. Thus, neither of the two could be interpreted in isolation, only together. This resulted in the need for a complex and specialized knowledge system for the application of robots, where the user could integrate information from these two spaces within themselves and continuously apply the created matrix to program and operate robot applications. Of course, this integration, as well as its depth and extent, varied depending on the level of application, which meant different challenges for operation, reprogramming, commissioning, application development, or product development. This fact limited the possibility of widespread adoption of robots and incurred difficulties and costs that exceeded the expected business returns in specific industries or fields. (Wolf et al., 2023)

Integrating mixed reality methods with robotics aims to unify this fragmented real environment and virtual data space by using data visualization tools that make it unnecessary for the user to merge the two distinct spaces mentally or cognitively. Consequently, this integration eliminates obstacles to the further proliferation of robots effectively, enhances their efficiency, and significantly increases their sustainability value. Recent research focused on applying mixed reality systems in the manufacturing process (Egger and Masood, 2019) or to allow more convenient programming of tasks (Stadler et al., 2016).

3.7 Comparing Robots to Other Manufacturing Factors

The following subsection presents the comparison of robotic systems with the human workforce, highlighting the mechanical and human factors.

- **Demographics:** Numerous studies, news reports, and statements indicate that accessing the workforce required to sustain and expand production processes is increasingly challenging (United Nations, 2022). This presents an interesting contrast with the significant growth in the world's population, but the availability of labor does not show a homogeneous distribution in space and time. Robotic systems can address this sustainability challenge; many companies are using robots not just to replace labor but also to fill the gaps in the workforce.
- **Education and training:** Similar, to the problem of demographics, training also requires resources and time, and it poses additional risks regarding production safety. Of course, using robots also demands skilled labor, but research is underway to address the arising risks, as mentioned in subsection 3.6.
- **Social Upward Mobility (Problem of Performing Lower-Level Jobs):** Besides demographic issues, it is also essential to consider that workers in modern societies are increasingly oriented towards higher-skilled, knowledge-based tasks. This creates further shortages in jobs that require lower levels of knowledge. Mass adoption of robots provides a solution to this problem as well.

In addition to the above listing, further examination of other factors is possible and even necessary for a deeper analysis of the topic, highlighting manufacturing factors. Now, let us compare robotic systems with automated purpose-built machines differently.

- **Product Lifecycle vs. Machine Lifecycle:** This point is discussed in detail in Subsection 3.3. The lifecycle of a universal machine extends beyond the product it produces, which, in the current economic environment, is naturally designed for a short lifespan.

- **Design and Manufacturing Time:** Considering the time spent on designing and manufacturing an automated machine, which significantly exceeds that of a mass-produced device, is essential. This issue was mentioned in subsection 3.1.
- **Installation,** Operation**, and Maintenance:** Similar to design and manufacturing time, commissioning a custom machine can be challenging and quick since no previous example provides experience. Thus, one must account for design flaws and the need to acquire new knowledge. In the case of robotic systems, these issues are not only present to a moderate extent.

4. Model-based overview

As a result of the research and based on the identified indicators, the sustainability advantages inherent in using robots can be best demonstrated through a process-oriented approach. Through multiple cycles of reuse and technological advancements, an industrial robot significantly contributes to achieving sustainable production. As a summary of all reviewed aspects, a lifecycle of industrial robots can be introduced (Figure 1). This is formulated with inspiration from the NIST Cyber-Physical framework (Griffor et al. 2017), general Industry 4.0 processes (Bilad et al. 2022), and the general sense-think-act cognitive model of robotics (described in Siegwart & Nourbakhsh I. R. 2004); moreover, this formulation is extended with the indicators identified in the literature review presented in section 3. The lifecycle input is a process (manufacturing task) that is provided by an operator through (remote) programming or collaborative work. The industrial robot creates the product using its actuators, its sensors, and external raw materials. The industrial robot generates a product that has its own lifecycle. The product lifecycle eventually provides feedback to fine-tune the operation of the industrial robot. The operation of the robot inherently costs electrical power. Any subprocess listed in the model can be fine-tuned with instrumental and utility data acquired during each subprocess, which, on the other hand, increases energy usage. The human operator acts as a collaborator based on data and interface feedback.
This lifecycle acts as a time-invariant cycle of operation to aid in identifying sustainable indicators and fine-tuning the efficiency of industrial robots. The process highlights that energy consumption also cross-relates to every subprocess and capability the industrial robot provides. Additionally, data is potentially available at every subtask that can be used to make operations efficient. Data is usually transmitted to data storage systems in remote (private) cloud systems. On the other hand, intensive data capabilities further increase energy usage, thus introducing a trade-off between each capability.

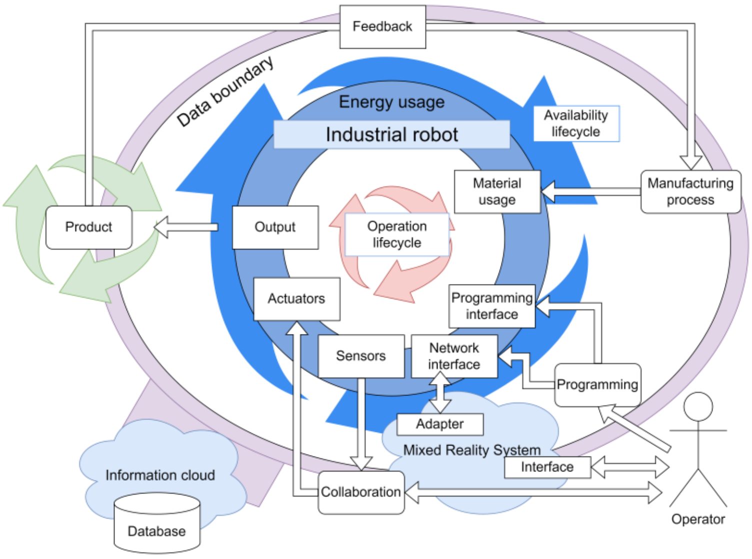

Figure 1: Overview of an industrial robot from a sustainability perspective

In summary, the evolution of robots indicates possibilities for even more significant benefits that can surpass the current advantages many times over. As a universally reusable and highly energy-efficient tool with an exceptionally long lifespan, robots are easy to operate and capable of handling complex tasks and therefore could become a foundational pillar of a sustainable and efficient production system. In conclusion, current robotic systems require fine-tuning of energy usage for all tasks and extensive information technology extension points.

5. Conclusion

The article analyzed the contribution of industrial robots to sustainability from a less explored perspective and viewpoint. Since their introduction and continuous technological advancements, robots have increasingly become essential elements of sustainable economic and environmental processes. The article introduced a new industrial robot lifecycle model inspired by existing cyber-physical and robotic frameworks and extended with sustainability factors. Based on the conducted analyses, it can be confidently stated that the application of robots contributes to the success of sustainability efforts on multiple fronts. Also, the fulfillment of sustainability factors requires information technology modules, that increase energy usage, implying a trade-off between each factor.
Further research, including measurements and investigations, could provide a more detailed elaboration of their contribution. Various scientific fields, such as engineering, economics, and social sciences, are involved in sustainability-related questions concerning the use of robots. Furthermore, the authors currently work on the ongoing research on robotic systems with Industry 4.0 and general human-robot (HRI) interaction research. This work presents the initial phase of the research concerning the formulation of the life-cycle model. Measurements and evaluation of the model will be provided in the future as a result of subsequent stages of the research. Another research includes the creation of a laboratory-grade industrial robot manipulator, that considers all sustainability factors from an information technology and energy efficiency aspect.

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