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Abstract. Sustainability in the production value chain needs to address also the design of the production system and the value chain of the equipment in the production system. This paper presents results from green design of one of the most common pieces of equipment used in production, robot cells. Three case studies of robot investment projects, one lab-robot for additive manufacturing, one glueing robot and one painting robot application were studied. The research evaluated the existing investment through workshops and a Green Design Event (GDE) method to simulate a process to find potential for further advances in eco-design, or green design, of production equipment. The findings suggest that several eco-design intentions are already incorporated into policies and general design guidelines at companies but may not be fully implemented in practice. With a structure and learning process for all parties on how to implement green design principles, there exists potential to realise more of the intended eco-design in the production system equipment value chain. Further research is suggested for other production investments where the green design process is followed to enhance learning.

1. Introduction & Background

There is an increasing urgency to implement changes for net-zero climate emissions, meaning that each industrial enterprise should adopt changes that, in total, will lead to a net-zero anthropogenic climate footprint [1]. Here frontloaded decrease of CO2-emmissions aligned with other sustainability targets is essential [1]. Industrial production accounts for a large part of global climate emissions and needs to be at the forefront of reductions. A sustainable production system ultimately produces sustainable products in sustainable production processes [2]. Non-productive resource use and emissions giving climate change and other adverse environmental impacts are not value-adding, and can thus, from a lean production perspective, be reduced to zero, or avoided, if possible [3]. If not avoidable, wasted resources may be circulated, and material substituted with new, less hazardous or climate-impacting material to reduce the environmental impact [3]. Although significant changes can be made as continuous improvements while operating industrial production, the largest part, probably 70-80%, needs to be designed into the production system in early design phases [4]. The production system entities need such eco-design, or green design, like any other products with high environmental impact, across lifecycle phases and value chains.

In green management strategy, eco-design is applied to products, services and production processes [5]. Eco-design is advised by the EU and in the Eco design directive, e.g. energy efficient design has been required since 2009 [6], and in the new ESPR regulations, durability and repairability, as well as minimising hinders for circularity and decreasing environmental footprint, have additional requirements [7]. Since most products' environmental performance has improved, the environmental footprint of the products production system and materials extraction becomes increasingly important. A critical task is thus to implement eco-design also of the production processes and the equipment used in the processes. Such eco-design means that the production equipment wastes a minimal amount of energy and material resources in the conversion of raw material into products, and such equipment is adapted for materials with low negative environmental impact and circular products. In addition, they also adhere to their own construction to use materials and components with low environmental impact. They are also prepared for circularity of the equipment itself through reconfigurability and modularization [2].

Green design and eco-design are often applied to energy and material-intensive production equipment, like ovens, or quenching processes, to implement energy-efficient design and reduce the use of fossil fuels and hazardous materials. For electrical equipment, where no hazardous materials are used, green design is performed to a lesser extent. In these, motors usually give over 80% of input electricity as output axle power [8], but substantial losses come with movement of parts, velocity and friction [9]. Substantial standby losses, e.g., in electronic systems when not in use, are common in robots and automated movements. Robot cells, where robots are used for joining, assembling or moving components, are one of the most common processes in industry. The robot density (robots per industrial workers) in e.g. Germany, France, Spain and Sweden doubled between 2005 and 2019 [10]. As single-operation robot cells together with assembly and material handling are considered low environmental impact level as they have relatively low energy costs and usually almost non-existent usage of chemicals [11], but since robot cells occur so often in all types of production, it is still important to improve the environmental impact of all robot cells. Longevity and circularity of products, of production system equipment, and infrastructure are another often forgotten significant reduction path [2,12]. Such actions could bring not only environmental benefits but also economic benefits [13]. Production processes and production systems are large and complex systems; they are usually constructed of metals and plastics and consume energy and process materials in their use phase. They also affect the productive materials' material efficiency and give significant impacts on the environment [14]. As expensive items and used in business, they are often utilised for a long time, in the time frame of 10-100 years, and it may be difficult or at least expensive to change the process after the production equipment is built and installed.

Due to these impacts, and their common and increasing use, it is important to do green design of robotized production processes. The goal of this paper is to do a practical investigation of how and when green design can be performed in a Green Design Event (GDE) for industrial robot systems and highlight common green design opportunities of robot cells. By demonstrating easy and cheap measures to improve the eco-design of robot cells, it may also be possible to reach insights into why well-known eco-design measures of equipment are still not implemented "en mass". Two research questions are raised and answered:

RQ1 When and how can a "Green Design Event" method be applied in the equipment development process to identify environmental aspects for robots and find routes to improve robot design?

RQ2 What common environmental impacts of a robot cell can be avoided, reduced or substituted away from the production system design?

After this background, the paper presents method development of the GDE-method and how the three case studies were performed. Then the findings from the cases are presented, and finally discussion and a conclusion.

2. Methodology

2.1 Research approach and method development

To reach net zero in the production system, it is important to affect process and equipment design [4]. Therefore, design thinking, with an emphatic, integrative, optimistic, collaborative and experimental view [15] has been an important approach in the study. The study of robot cell development in different phases of the implementation process has been used to develop the GDE-method in two tracks. One track developing the event as a workshop using the Green Performance map (GPM), starting with a life cycle thinking and value chain perspective as described in Lindahl et al [16] and further developed into a short design event workshop format [17]. Meanwhile, a tool supporting such an event was developed (the GDE-tool), building on the Green Kaizens green lean approach and adapting it to the capital investment process as described in Magnusson [18] and Magnusson et al. [19] and merged into the GDE-method with support from the GDE-tool in Excel. Here, it is acknowledged that there exist several similar tools that could support the design event process, such as e.g. the Eco design strategy wheel [20, 21, 22], and a principal part for practical eco-designs is the base in these types of tools on life cycle thinking and life cycle management [23].

2.2 The Green Design Event method

The GDE-method has two significant features. It is a *participatory* and a *cross-functional* design event workshop facilitating participatory activities [24] where people with different competencies discuss environmental issues of the design of equipment or processes, similar to other design events [25]. Regular design events, performed in planned conditions, are often performed with a cross-functional team with set agendas and a prepared information collection of known sets of data [17]. The GDE-method has support material in the form of visual models and checklists, like other green design methods [5], such as the aforementioned Eco-design strategy wheel. The GDE-method was developed from the Green Kaizen method for operational improvements [26]. Its foundation is based on green lean, where production processes are analysed with regard to their losses or "muda". Here, the lean "muda" concept is used, where anything other than the minimum amount of equipment, materials, parts, and workers (working time) which are absolutely essential to production is regarded as a surplus [27]. In lean, the "muda" often focuses on waste of time, whereas in green lean, the focus is on the other side of the coin, the waste of natural resources and unnecessary emissions or losses [28]. Here, the Green Performance Map (GPM) is used as a visualisation of eight categories of possibly wasteful inputs and outputs [29] as support to identify design improvements (see figure 1)[30]. It divides the production operation into four types of input (energy, product material, process material, and water) and four types of output (products and by-products, emissions to air, waste materials, and emissions to land or water - including risks of emissions) and uses lean notion of value adding or non-value adding. In addition, a checklist with almost a hundred support questions has been constructed to inspire participants to find three types of solutions. The three solution types include 1. Lean solutions, avoiding or reducing the amount of resource use or emission, 2. Circular solutions, circulating the wasted resource (material or energy) for a secondary use, and 3. Substitution solutions where resources used are exchanged for less hazardous resources, giving less hazardous outputs to the environment, as presented in [3]. The GDE-method is proposed to be used with the Excel-based tool, the GDE-tool (where support questions etc are listed), in equipment procurement projects at different stages of the procurement [19].

In this study, a general description of the production equipment development process published by Bruch et al [31] has been used, where the development process is divided into seven phases (pre-study, concept development, procurement, detailed design, equipment build, installation/start, and full operation). Although a general green design event can be performed at any time during the development process, four different timings was proposed, at time x of the Green Design Event (GDEx). GDE0 before a project starts, or at start, GDE1 before signing a

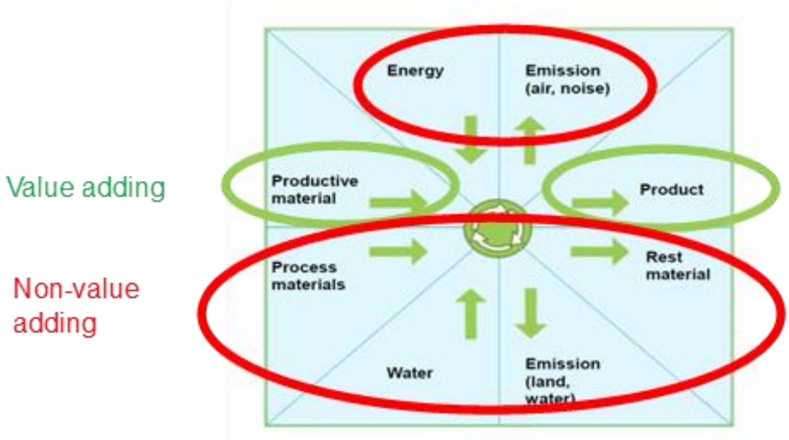

Figure 1. The Green Performance Map and the lean notion of non-value adding (redrawn from Romvall et al [30]).

contract with the supplier, GDE2 during the contract with the supplier, and GDE3 after installation when equipment is taken over by operations, but before the development project is closed (see figure 2). Cases have been chosen to fit some of these. Case C performed a green design event before a production development had formally started (GDE0), Case A performed an event after the production development project had started, but before the supplier was contracted (GDE1), then a follow-up green design event was performed after the production was started (GDE3). Case B included one workshop with the supplier and one with the customer while the project was ongoing (planned as GDE2), although in reality the event was performed later in the process (closer to GDE3).

2.3 Case study setup

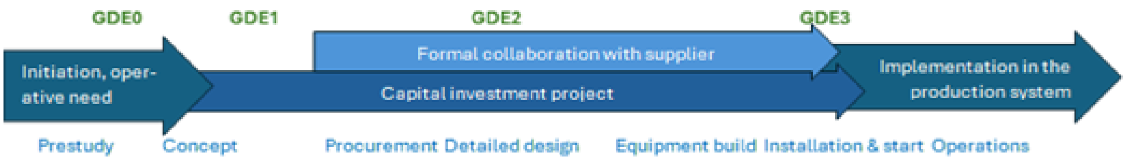

Figure 2. The production equipment development process, redrawn from [30] and the different timing of green design events (GDEs).

This research has been performed through three case studies with four different organisations described further below. In all of the cases, the "Green Design Event" methodology was used. The cases were used to find green design opportunities in robot cells and evaluated in the GDE-tool. Case A only performed GDE1 and 3 without the GDE-tool, while the two other cases utilised the GDE-tool in one of the timings each. Together, the cases covered all four GDEx and also involved both customer and supplier. However, in Case A, the methodology was used in a more immature setting, closer to Instant green design event, as in Bengtsson et al [17] or Lindahl et al [16], where open questions rather than specific questions in the GDE-tool were used. The timing of the event in the investment was before RFQ were sent out. Case A also included results one year after the procurement, with a reflection of the design outcome. In Case B, the methodology was applied at the end of a project where little could be changed. This case was used as a reflective case, involving both the user and the equipment supplier. Case C was used in a pre-study phase where an exact project is not decided. The case was also mainly focused on reuse and reconfiguration of existing equipment, keeping capital investment as low as possible.

Case A was a replacement of an existing robot in a Paint robot cell for large vehicle parts. The cell existed, but the robot and some equipment were approximately 20 years old and were due to be replaced. (The first author also brought experience from environmental assessment of the previous robot investment, 20 years ago). At the time of Case A, it was already decided that a replacement and improvement of the paint cell was needed, the GD-event was under development, and the event was performed with four people in accordance with Lindahl et al [16] in a similar way as in the other cases, but without the standardised set of questions in the exel-tool. A follow-up event one year after the event was performed to observe and discuss/evaluate the resulting design of the robot.

Case B was a study where a new pilot line at a large vehicle manufacturer was installed for a glueing process for a new large vehicle part. It was performed in accordance with Magnusson et al [19]. At the time of the study, the equipment was already specified and constructed why it was more of a retrospective case. The questions in the GDE-tool however, was already developed, and only fine-tuning of the questions differs from the other cases. The case was performed in two steps. First, one event with four people, including the project manager and the technical director at the supplier company. Then a second event with four people, including the project leader and an environmental manager at the customer company.

Case C was a full-size robot pilot cell for trials of glueing and additive manufacturing of large plastic parts at a Manufacturing testbed run by a research institute in collaboration with Swedish manufacturing companies. It was performed at a single occasion as GDE0 in accordance with Magnusson et al [19]. The new cell was planned, but no investment decision had yet been formalised. In this setting, the production cell was to be designed from scratch, but most of the equipment was already planned to be reused, reconfigured and upgraded from an existing robot cell.

A cross-case comparison between findings was finally performed to find green design improvements generally applicable for robots (RQ2) and how to implement GDE in the equipment development process.

3. Findings & Analysis

3.1 Case A

In Case A, the agenda of the first workshop, which was performed in time as a GDE1, was as follows: after participants introduced themselves, the project manager explained the scope of the cell, a short introduction to the green design method, followed by a short visit to the existing cell, after which environmental aspects were noted in a green performance map. Finally, environmental aspects were discussed to find out if any requirements could be introduced in the procurement regarding the use-phase, the production of the robot, or the end-of-life of the robot (Figure 3).

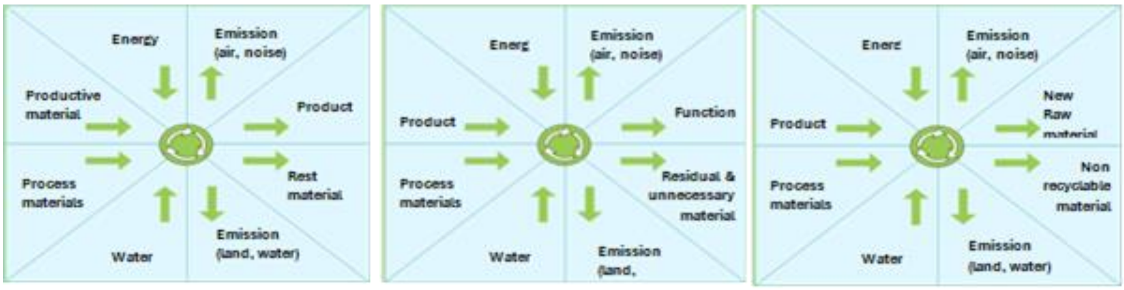

Figure 3. GPM in three lifecycle phases: production of the robot, use-phase & end of life.

The scope of the cell was a painting robot and a paint mix booth, with automated colour flow system from a paint-big bag system. The residual waste is non-hazardous and can, in the case of base paint (same colour for all), be recycled to some extent, but in top-paint (mixed colours) sent to incineration with energy recovery. Before the event, vacuum systems and ejector pumps for the paint were identified as being too energy demanding.

For the production phase of the equipment, it was concluded in the GDE1 to ask the supplier to what extent they use green energy in their production and to what extent they use recycled materials. A specific concern of risk of PFAS-content in lubricants was also raised (also as a concern in end-of-life phase). The climate footprint of the robot production (cradle to gate) was raised as a question to the supplier, without expectations of them providing an answer. For the end-of-life phase, the only raised issue was avoiding PFAS in the equipment.

In the use phase of the robot, several improvement ideas were raised. For energy efficiency, an aim to reduce the need for pressurised air by 50% was set, but to avoid it completely was deemed difficult (although the company's general specification of production equipment states that pressurized air was to be avoided and that all equipment can be turned off when not in use). Reduction of vacuum cleaning by 95% and avoiding a major part of vacuum use in the paint booth was a potential. For the actual paint pistols, the equipment was to be reused, but new mixing and handling could reduce paint spill and paint waste to incineration by 15%. Stops and failures were also supposed to be reduced with the new concept.

One and a half years after the GDE1, a revisit as GDE3 was performed. Most of the improvements had been implemented, especially on the vacuum system and ejector pumps, where eight large ejector pumps could be replaced by two smaller ones. This was also already planned before the GDE1 and would have been implemented anyway. A reprogramming of the pumps to stop when not needed gave 12MWh saving yearly. The automated colour switch has reduced the paint spill to “almost nothing” when changing colour. In total, 5% reduction of paint use per product due to minimized spill. Also total of 28MWh reduction of energy use, mainly in vacuum and paint system and reducing stop time energy. However, for the actual robot, it still requires 500W and cannot be turned off, and the robot require pressurized air (despite the general specification), the electronics are also cooled with an AC that releases heat. It was discussed both what improvements were initiated by the GDE1, and most of the improvements might have been implemented anyway, but the support of the cross functional discussion was appreciated. A connection with the GDE and the company's internal general specification for production equipment, and how to handle a negative supplier answer to that specification, was an unsolved matter.

3.2 Case B

Case B involved doing two GDE2 exercises during an ongoing investment project, one with the equipment supplier company and one with the customer company. In the first event, with the supplier, preparations included going through their own environmental policy and customer requirements and then by using the GPM and questions from the GDE support tool, ensuring that the design is as eco-efficient as possible, picking up any deviations, and additional opportunities. The results of the GDE2 at the supplier confirmed that the robot was planned for use in three years and then reconfigured to a new use; it was not over dimensioned in size, and the choice of glue and what to do with spill of glue is a major issue. A vision system was in place to qualify the glueing output. The only waste and emissions from the cell are excess glue that becomes combustible waste. The hot glue is pumped from a 200l-barrel which seems like a large volume for the task and affects the cleaning process. The system uses pneumatics for pumping the glue but not for robot movements. It turns automatically down to low energy standby when not in use. Protective gloves are needed due to the hot glue. Improvement potential remains on size of the heating and glue barrel.

The customer in Case B had similar general equipment specifications as the company in Case A, and e.g. pressurised air was to be avoided and the ability to shut down equipment when not in use (and start it fast and easy) was part of the general requirements. These requirements had been answered to the customer that the robot requires pneumatics, but no follow-up questions were raised by the customer. Discussion was made on avoiding over-dimensioning and the choice of materials for the robot. The supplier wished for a cross-functional GDE1 together with the customer, where real impact could be made for the future.

By the time the GDE2 at the customer was performed, the timing was close to GDE3. The scope covered the robot and glue application, including heating the glue. The robot is a standard robot applicable to other similar sized products. A vision system was included to be able to check quality and stop any erratic production immediately. The focus of using GDE is on energy and materials in the use phase of the robot. Still, this was mainly on the glueing device, not on the robot's energy use. When asked about why no follow-up questions had been put forward regarding pressurized air use, which was in opposition to the general requirement, the project team said they usually only follow up on that question for equipment considered to have high environmental impact. As customers, no focus had been on the material used to build the equipment, and the team seemed to lack knowledge of this and considered it something the supplier should know. These issues were found hard to change late in the process but could be used for learning before the next project and also to collect general learnings, e.g. for all robots. A common GDE2 with the supplier was deemed possible, but earlier than procurement can be challenging regarding IP-rights.

3.3 Case C

Case C was performed last, but for GDE0 in the planning of procurement of a robot cell in a production pilot cell setting. The robot scope is a robot for glueing and additive manufacturing of large thermoplastic structures. It also does machining of these structures. The robot was bought five years prior to the event and was now planned to be reused in this new application. Since the robot is reused, the material impact of the equipment is minimized. The lifespan of the robot depends on available electronic spare parts and on software upgrades. Minimising the size of the robot could save steel for robot arms and energy in the use phase. However, the robot needs to be flexible and reconfigurable and have a long enough reach, otherwise, it could need earlier replacement. Optimising robot movements saves time as well as energy.

The main energy and material losses in the use phase were when melting the thermoplastics, energy for robot movements and for machining. Machining gives dust and noise emissions. The choice of glue/plastic and how it is melted will have a large impact. Isolation of melter- extruder can lower losses. There was also pneumatic material transport, but the robot itself does not need pneumatics. The whole equipment is turned off totally when not used. There was a water cooling of the melter, but no air conditioning of the electric cabinets for the robot. There exists software to optimize faster movements, but maybe not more energy efficient. The GDE0 event gave opportunities to discuss the process and its environmental impact, a challenge and opportunity was that nothing had yet been decided.

3.4 Cross-case analysis

Summarising the findings from these different, yet similar cases, several eco-design highlights for the actual robots can be noted. Standardized and modularized equipment robots have the potential to be reconfigured and reused repeatedly. Still, their reuse depends on standardized electronic spare parts and software upgrades. With regards to the use phase, the energy use and possibly the use of lubricants are the major environmental impacts. Energy losses can be minimized by not using pneumatics, optimizing movements and making sure it is turned off when not in use, see table 1. Design of robot and control cabinets may be challenged to not need any air-conditioning-cooling. If cooling is needed, water cooling combined with heat recycling is a more sustainable option. The robot should be designed to be easy to clean and maintain. Selection of non-hazardous lubricants may reduce both the impact in the production phase, use phase and end of life phase. Hazardous lubricants may even prevent future reuse as worst case scenario. Material losses and emissions mainly depend on the tools operated by the robot, e.g. paint, glue, and AM-material in the three cases. Several design solutions exist that minimise environmental impact, but often optimal requirements were not applied.

Table 1. Summary of key findings from respective cases, including cross-case/general insights.

Dimension	Case A	Case B	Case C	Cross-Case conclusion
GDEx	GDE1, GDE3	GDE2	GDE0	0,1 solutions 2,3 learning
Involved actors	User	Supplier, User	User	Collaboration enhancement
Investment type	Upgrade	New	Reuse	Beneficial in all types
Environmental impact identified, solutions found	Pneumatic still used-remove, implemented turn-off, reduce spill paint, smaller ejector pumps, and cooling,	Did not remove pneumatic air. Volume, and heating glue barrel	Optimised robot movements, material choice glue/plastic, Reuse relies on spare parts and software upgrades.	General: optimise movements for energy saving. Alt. cooling options. Substitute haz. materials (lubricants, glue).

Summarising the GDE process, it gave more to the project in the early phases, GDE0 and GDE1, than late in the project as seen in table 1. In early phases, ideas could be transformed into implemented solutions. However, GDE2 and GDE3 gave opportunities for concrete reflection and learning, both on what options/solutions worked well, and what solutions that were not implemented but could have been. This was especially emphasised when user suppliers could reflect together. The learning was emphasized by the cross-functional design event setup, which was deemed probably more important than the tools/checklists used. The learning between project members and between projects may thus be a long term take away; the process will work better when project members are more used to it.

4. Discussion & Conclusion

With regard to the impact of the robot build and end-of-life, an increased collaboration in the equipment value chain is recommended. There is potential in making an end-of-use plan already in early design phases. This becomes especially important for investments with an intended short use span (as in case C). The interaction between supplier and customer of equipment, and how the two parties can work together towards a design with lower environmental impact, needs focus. It also becomes a question of timing when the supplier should and can be involved during the process. It is shown from the results that a collaboration is needed and that some competences are usually mainly available from the supplier. This is in line with recommendations in Bruch et al. [31]. The green design principles should be agreed upon, and support material could be freely distributed in the value chain. To introduce green design as early as possible is in line with Ramani et al. [4]. With a structure for all parties on how to implement the eco-design principles (like the avoid, circulate and substitute), there exists potential to actually implement more of the intended eco-design. Further research is suggested to evaluate and follow robot investments where the proposed GDE process or a similar structure is followed.

Additionally, the event was carried out for projects with varying purposes of upgrade, new investment and reuse and identified areas of environmental improvements for all cases. The GDE was also carried out in different places in the project in accordance with the suggested method with event 0,1,2, and 3. This shows as answer to RQ1 that the method can be applied in several places in the process and still identify opportunities for improvement. Even though it is possible, each event faces its own challenges. If the event is too late in on stage changes could be difficult to implement if specific requirements have already been looked at. However, the method is created to capture the variation of the stages of an investment to capture the maximum potential. The main aspects of identity in environmental potential are evaluated, even though not under perfect circumstances.

The findings suggest that several eco-design intentions are already in place in companies' policies and general design instructions but may not be implemented in practice for robots since they are regarded as equipment with “low environmental impact”, in line with [11]. However, with so many robots being installed [10], minimization of the environmental impact is needed anyway. Besides, even though some design changes have a small environmental impact, the solutions may be copied to more possibilities. For such cases learnings between projects is fundamental to reaping the benefits. Main solutions to minimize impact as answer to RQ2, were to avoid the need for pneumatics, avoid the need for cooling, reduce weight and optimize programming to reduce energy in the use phase. Here, optimisation of movements, velocity and friction [9] through robot programming and optimising the weight and size of robot parts is important. Most eco-design solutions in the use phase for a robot involve avoid-type solutions in Kurdve and Bellgrans notion

[3]. Since the robot itself does not add or subtract any material and does not consume process material, there are few relevant circular solutions [3] in the use phase. If cooling cannot be avoided, then heat recovery solutions can be applied. Substitution [3] may come into place for hazardous lubricants. The tool or the operation that the robot carries had significant material use and could be improved by all three types: avoid, circulate and substitute.

The circular solutions also come further into play for the raw material extraction, building of robots, and their end of life. Here, longevity and circularity of the robot are crucial [12], and it may be important to thoroughly investigate how long spare parts and software upgrades will be available. Standardization and modularisation can also be important to prolong the use of the robot parts. Substitution of materials with high environmental impact and use of renewable or recycled materials in the robot can leverage impact. Substitution of hazardous materials in order to avoid materials that may be classified in the future is also recommended.

To conclude, the Green design methods are a versatile approach that could be used in several stages of the investment process to identify environmental potential. It can be carried on one occasion and still give results, even though multiple occasions are encouraged. For robot investment, several common environmental impacts were identified and, to some extent, avoided or a discussion of how they could be avoided in the future was made. Prominent areas were cooling systems, material choices, and programming for effective operation.

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Author 1 participated in all parts of the research. Author 2 participated in research design, half of the empirics and documentation, then analysis and writing.

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