Assessment of end-of-life strategies for automation technology components

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Abstract

Automation technology components (ATCs) are often used in highly individual applications by manufacturing companies. The large variety of different use scenarios creates high uncertainty concerning most suitable end-of-life strategies. Typical strategies that can be implemented during the products end-of-life stage are reuse, repair, remanufacturing and recycling. As each of these strategies has a different effect on the products economic and environmental performance an assessment method is needed that respects relevant parameters. Most publications illustrate methods for environmental or sustainable product assessment. Much less is known about how end-of-life strategies can be assessed for a product. For this reason, the article discusses a procedure for the assessment of end-of-life strategies with an exemplary prototype tool for pneumatic cylinders.

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1. Introduction

Striving for a circular economy is a key element of future resource availability and resource conservation. Access to raw materials at stable prices is a crucial point for companies in highly material-intensive sectors. Those companies are operating and sourcing on global markets and are part of complex global value chains that consists of multiple tiers [1]. Providers of automation technology components typically provide a broad product portfolio to act as suppliers for multiple applications. Often, automation technology components (abbreviated as “ATCs” in the following) are also part of environmental burdens associated to manufacturing processes. But providers of ATCs currently have only limited influence on the product’s life cycle after ATCs have been sold to customers.

In the light of a circular economy it is the goal to evaluate how different end-of-life strategies for ATCs perform from an environmental and economic perspective. Therefore, a methodological framework is proposed that allows to analyze multiple product life cycles. The results are intended to derive information about the performance of the end-of-life strategies for the analyzed ATCs. The aim is to support decision-making within product development. Furthermore, the results might be used for the sustainability assessment of different end-of-life strategies with regard to an entire product portfolio.

2. Theoretical background and state of research

Towards assessing end-of-life strategies for ATCs from an environmental and economic perspective, the state of research will be presented. Building upon an introduction about general terms and streams in the research field, the focus of this section lies on methods for environmental and economic evaluation.

The consideration of end-of-life strategies of products is strongly linked to the concept of a circular economy, e.g. promoted within the European Union. Its overall goal is the increase of reuse and recycling opportunities for products towards reducing environmental impacts and increasing the
main aspect is allocation, in this context referring to the consideration of the end-of-life affects all phases of LCA. One assessment as well as the interpretation phase [6]. The procedure according to ISO 14040 it consists of four phases production and use phases, to the end of life. In its standardized product’s life cycle, i.e., from raw material acquisition, via environmental impacts and resources used throughout a

Figure 1: Open- and closed-loop strategies for ATCs (based on [5])

Life cycle assessment (LCA) is a method to assess the environmental impacts and resources used throughout a product’s life cycle, i.e., from raw material acquisition, via production and use phases, to the end of life. In its standardized procedure according to ISO 14040 it consists of four phases – goal and scope definition, life cycle inventory, life cycle impact assessment as well as the interpretation phase [6]. The consideration of the end-of-life affects all phases of LCA. One main aspect is allocation, in this context referring to the distribution of environmental burdens between different products and life cycles. Nicholson et al. review different allocation methods for an open-loop recycling [7]:

- **Cut-off method:** Loads directly caused by a product are assigned to that product.
- **Loss of quality method:** Loads are assigned to products according to their relative loss of quality in each step.
- **Closed-loop method:** Applicable if no significant loss is experienced through recycling.
- **50/50 method:** Virgin material production and waste treatment are shared between first and last product in the life cycle cascade
- **Substitution method:** Recycled material substitute’s primary, accounts for lost material and recycling burdens.

They further point out that for most products there is no strict classification of them within the life cycle cascade. Thus, a combined approach that relates to the specific case should be considered.

The benefit of closed-loop systems over open-loop systems has been studied by Rose et al. They identify wear out life and technology cycles as crucial for the selection of appropriate end-of-life strategies. Their findings indicate that open-loop recycling is beneficial when long technology cycles occur [8]. Cooper and Gutowski link end-of-life strategies according to design strategies, e.g. easy access to components that experience wear out [9].

Pandey and Thurston follow an entropy approach to determine the effective age of remanufactured products that become especially relevant in large-scale treatment systems, where it is not known how and with which intensity the product was used in its first life cycle [10]. Another aspect in the assessment are efficiency increases due to technology cycles that might influence the performance of closed-loop towards open-loop strategies [9, 11].

Besides environmental impacts of end-of-life strategies economic impacts need to be considered as well. Life cycle costing (LCC) is an established method in this field. Lichtenvort & Rebitzer distinguish between

- Conventional LCC: assessing cost related to the actors along the analyzed product or system life cycle
- Environmental LCC: Incorporation of external cost, not directly related to actors of the product life cycle
- Societal LCC: Extension of environmental LCC by future external costs [12]

Whereas Herrmann et al. evaluated maintenance strategies during use phase from an environmental and an economic perspective [13], the current research will apply the presented methods of LCA and conventional LCC in order to identify favorable end-of-life strategies for ATCs.

3. Challenges of end-of-life strategies in the sector of ATCs

ATCs or capital goods in general differ from consumer goods because they are part of complex value chains as well as complex machines and production lines. Furthermore, they have a broad application range and are often customized and sold in small units. [1] In spite of the customization of ATCs, the supplier’s knowledge regarding the use and end-of-life phase is limited. Besides well-known key branches for ATCs (e.g. automotive, food and beverage, electronic, handling, biotech, pharma or process industry) there are far more possible application fields that lead to knowledge gaps regarding how the ATCs are used and to which intensity.

In nowadays companies it can be found, that end users have to fill out a declaration of contamination when sending an ATC back to repair. Such declaration contains information about the chemicals the ATC got in contact with during usage. Besides toxic, flammable or acid chemicals even radioactive or biologically hazardous substances may come in contact with the ATCs. [14] With such exemplary process relevant information of the usage phase can be collected and helps to minimize health risks of workers during the end-of-life phase and in the repair department, respectively.
What is yet known about the end-of-life phase of ATCs is that some industry sectors established their own after markets for their production lines, e.g. through relocating whole plants and production lines to developing countries in order to operate them once more. However, it is very probable that most end users have service providers who collect their defective machines and also disassemble entire production lines when they are not needed anymore. For confidentiality reasons it occurs that end users with knowledge-intensive value creation processes ask for evidence that the entire production line is destroyed after the disassembly and that sensible details are not traceable anymore. When discussing end-of-life strategies, most end users consider aspects regarding the entire production line, but rarely take each ATC of the production line into account. To enable an end-of-life strategy from a supplier’s point of view it is necessary that the end users ATC is separated from the production line.

In summary there are four major challenges regarding the end-of-life of ATCs to point out:

- Knowledge gap of use and end-of-life phase at the supplier
- OEMs/end users have own after market for machines/lines
- Service providers collect defective ATCs and disassemble lines and machines
- ATCs have to be removed separately

4. Procedure for the assessment of end-of-life strategies

The developed procedure for the assessment of end-of-life strategies contains several steps (Fig. 2): First of all an allocation of steps to each end-of-life strategy has to be conducted (A). This method is named as “MorphoCheck” in the following. After an analysis of the economic and environmental input per end-of-life strategy (B) and the extension per end-of-life strategy (C), the results are visualized in different diagrams (D).

![Figure 2: Procedure for the assessment of end-of-life strategies](image)

4.1. MorphoCheck

MorphoCheck is an advancement of the morphological box as it is not only a systematic way to identify path constellations but also a method for end-of-life strategy assessment. For the assessment of end-of-life strategies a clear understanding of the alternative strategies is relevant. MorphoCheck helps to consider possible end-of-use scenarios and helps to define possible end-of-life strategies with a detailed perspective on each step.

First of all possible end-of-use scenarios have to be defined. For ATCs the end-of-use scenarios “Defect of the ATC” and “System is not used anymore” were identified to be most relevant in practice. As depicted in Fig. 1, the open-loop strategies “Recycling and new ATC” and “Ultimate recycling” as well as the closed-loop strategies “Reuse”, “Local repair”, “Central repair” and “Remanufacturing” are considered for ATCs in this article. In Fig. 3 the two practical relevant end-of-use scenarios are linked to these six possible end-of-life strategies with a black circle (●).

Secondly, the probability of occurrence of the different end-of-life scenarios (X %, Y %) in combination with the end-of-life strategies (a-g %) can be defined on the basis of derived best practice data. If a defect is the reason for the ATC’s end-of-life, a local repair, a central repair e.g. in the supplier’s headquarter, remanufacturing or the disposal of the old and purchase of a new ATC are logical consequences.

![Figure 3: MorphoCheck as a basis for the assessment of end-of-life strategies](image)

Thirdly, each possible step per end-of-life strategy has to be determined based on literature or the experience of experts. Herrmann et al., for instance, developed a reference model for closed-loop supply chains that defines the basic process steps “Re-Distribute”, “Source Codes”, “Identify/Sort”, “Re-Make”, “Deliver Cores”, “Re-Integrate Product”, “Plan Reverse Flow”, “Enable Reverse Flows” as substantial for reverse logistics [15]. Based on literature knowledge, the knowledge of experts and industry specific vocabulary, 30 detailed steps of the discussed strategies were defined and listed in the left column of the MorphoCheck (see Fig. 4).

In the second column from the left, the steps are marked and classified regarding their cost category (grey) and environmental impact (green). For the allocation of costs within the LCC it is necessary, that steps, that take place at different stakeholders, are highlighted in different colors. Processes that take place at the end user are marked in blue. Red marked steps indicate that the ATC is on transportation, white marked steps take place at the supplier and orange
marked steps take place at the recycler. Figure 4 shows the MorphoCheck 3-6 for the discussed end-of-life strategies.

![Figure 4: MorphoCheck as a basis for the assessment of end-of-life strategies (MorphoCheck 3-6)](image)

Instead of applying the 50/50 method or the cut-off method of open-loop recycling of LCA where the environmental impact is partitioned on two systems at a defined place, this method treats a product that is operating multiple lifetimes as one system until the “Ultimate recycling” takes place.

4.2. Analysis of input per end-of-life strategy

When analyzing the input costs per strategy, a separation between the categories fixed costs, type specific and weight specific costs is necessary for the calculation (see classification of cost category in column two and three of the MorphoCheck in Fig.4). Fixed costs depend on product independent processes. In order to estimate the fixed costs per step, the working time that is needed per step has to be estimated in hours. The values can be based on the experience of experts or can be derived from similar existing processes in the analyzed company. Type specific costs differ depending on the type of the ATC. The removal of a pneumatic cylinder or a pneumatic maintenance unit from a system, for example, takes less time than the removal of an electrical cylinder or controller. The payout amount of the used ATC to the owner could be based on actual market prices. Another example for type specific costs is the disassembly time of the ATC into its parts. To determine disassembly and recycling cost computerized tools such as the RRR Agent can be used [16]. A pragmatic way to model the disassembly time is to disassemble the ATC in real life and measure the time. Examples for weight specific costs are transportation costs, packaging or storage costs.

The green highlighted boxes in the MorphoCheck show which environmental impact (EI) is considered for which step. Type specific environmental aspects are related to the ATC itself and its spare parts, respectively. The EI of spare parts for repair can be modeled through a full or simplified LCA. Weight specific environmental impacts are caused by transportation options. In order to approximate the environmental impacts of each transportation option, the distances from the end user to the second market distributor for used ATCs (s2M) and to the nearest local repair center (sLR) have to be assumed due to the company’s facilities. Formula (1) describes the environmental impact of the transport to the local repair center (EL_LR) by truck.

The distance one ATC travels from an end user to the central repair center of a company can be covered by plane (s2M) or truck (sLR), depending on the distance. These distances are measured and weighted with the country’s specific transport volume factor per year (Tv/sLvair). Formula (2) describes the environmental impact of the transport to the company’s central repair center (EL_cR) with i > 1000 km and j < 1000 km.

\[
EI\text{}_{\text{LR}} = 2 \cdot s_{\text{LR}} \cdot EI_{\text{Truck}}
\]

\[
EI\text{}_{\text{air}} = EI_{\text{air}} + 2 \cdot \left[ \frac{T_v}{s_{\text{air}}} \cdot s_{\text{air},i} \cdot EI_{\text{air}} + 1 \cdot T_v \cdot T_{\text{norm}} \cdot s_{\text{air},j} \cdot EI_{\text{air}} \right]
\]

4.3. Analysis of extension per end-of-life strategy

As the closed-loop strategies extend the ATCs lifetime, the energy demand of the ATC during lifetime and the lifetime itself is needed for the calculation of the environmental impacts per strategy.

The calculation of the energy consumed in the pneumatic drive system is usually based on the intake of compressed air under standard conditions [17]. As in standard mode, the cylinder chambers are always filled up to the supply pressure level, the air consumption V_{cylinder} of a drive can be estimated solely on the basis of its geometrical data. For pneumatic cylinders with piston rod the air consumption can be calculated with Formula (3) using \p_{\text{system}} = 6 \text{ bar}, \p_{\text{max}} = 1 \text{ bar}, \T_{\text{norm}} = 273 \text{ K} and \T_{\text{system}} = 293 \text{ K}.

\[
V_{\text{cylinder}} = \left[ 2 \cdot d_{\text{cylinder}} \cdot d_{\text{cylinder,v}} \right] \frac{T_{\text{norm}}}{T_{\text{system}}} \cdot \frac{\p_{\text{max}} + \p_{\text{max}}}{\p_{\text{max}}} \cdot \frac{\T_{\text{system}}}{\T_{\text{norm}}}
\]

The energy demand of the pneumatic cylinder is determined by multiplying the air consumption V_{cylinder} and the air pressure indicator (0,120 kWh/m³i.N.), which is an efficiency parameter for the generation of 1m³ compressed air volume, using electrical energy for the compressor [18].

The strategies “Reuse”, “Local repair”, “Central repair” and “Remanufacturing” extend the product’s lifetime by a certain factor. In the analyzed industry sector, repaired products
typically have a warranty of half of the lifetime of a new product. Based upon this practical knowledge, the lifetime extension for reuse and remanufacturing can be exemplarily approximated with 30% and 80% of the lifetime of a new product. An overview of exemplary assumptions for the input and extension analysis is provided by Table 1.

<table>
<thead>
<tr>
<th>Exemplary assumptions for the input and extension analysis</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Salary per working time</td>
<td>e.g. 50 €/h</td>
</tr>
<tr>
<td>Distance end user to second market s2M</td>
<td>e.g. 50 km</td>
</tr>
<tr>
<td>Distance end user to local repair center sLR</td>
<td>e.g. 500 km</td>
</tr>
<tr>
<td>Lifetime after reuse in cycles</td>
<td>e.g. 0.3 * lifetime</td>
</tr>
<tr>
<td>Lifetime after repair in cycles</td>
<td>e.g. 0.5 * lifetime</td>
</tr>
<tr>
<td>Lifetime after remanufacturing in cycles</td>
<td>e.g. 0.8 * lifetime</td>
</tr>
</tbody>
</table>

5. Case Study for a pneumatic cylinder

The explained procedure will be illustrated with the input data and visualization results of a pneumatic cylinder in the following. For this exemplary case study only the GWP that can be assessed with simplified LCA methods will be considered as environmental impact category.

In Figure 6 it can be seen that the optimal end-of-life strategy depends on the desired lifetime: If the desired lifetime lies in between 60 to 80 million cycles “Reuse” would have the least total process costs. In between 80 to 90 million cycles “Local repair” and over 90 million cycles “Recycling plus new ATC” would be the most economic strategy.

In order to identify the best end-of-life strategy, the staircase profiles of the strategies have to be compared at a certain amount of cycles. For the exemplary pneumatic cylinder the end-of-life strategies are compared at a lifetime of 100 million cycles (see dashed line in Fig. 6 and Fig. 7).

To visualize the costs related to the input and extension per end-of-life strategy a staircase profile is used. The sum of the input costs characterizes the vertical step whereas usage costs and lifetime define the horizontal line of the diagram. An analogous visualization can be done for the environmental results. Figure 6 and 7 represent an economic and environmental break-even analysis for the second and third life of the cylinder. Both visualizations have the restriction that the axis label of cycles is displayed in million cycles and that the energy demand during lifetime is set to 0.

Figure 5: Pneumatic cylinder as exemplary application

Product specific parameters and assumptions that are input data for the exemplary assessment are listed in Table 2.

Table 2. Product specific parameters and assumptions of a pneumatic cylinder

<table>
<thead>
<tr>
<th>Product specific parameters and assumptions [19]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dcylinder in mm</td>
<td></td>
</tr>
<tr>
<td>dpiston_rod in mm</td>
<td></td>
</tr>
<tr>
<td>lhub in mm</td>
<td></td>
</tr>
<tr>
<td>Weight of the product in kg</td>
<td></td>
</tr>
<tr>
<td>GWP of product in kgCO2eq</td>
<td></td>
</tr>
<tr>
<td>GWP of spare parts for repair in kgCO2eq</td>
<td></td>
</tr>
<tr>
<td>GWP of spare parts for remanufacturing in kgCO2eq</td>
<td></td>
</tr>
<tr>
<td>Lifetime in cycles</td>
<td></td>
</tr>
</tbody>
</table>

Figure 6: Economic break-even analysis for a pneumatic cylinder

Figure 7: Environmental break-even analysis for a pneumatic cylinder

In order to identify the best end-of-life strategy, the eco-efficiency portfolio, developed by BASF [20]. The scale of the axis is inverted so that the top right-hand quadrant represents the optimal strategy. A strategy is the more eco-efficient the less environmental impacts and the less costs are caused [21]. The eco-efficiency portfolio in Figure 8 is set up with costs from a customer’s point of view. As a result of the eco-efficiency portfolio it is seen that the strategy “Reuse” and the strategy “Recycling plus new ATC” are the cheapest regarding their costs for the customer. However, the high environmental impact of the current end-of-life strategy “Recycling plus new ATC” becomes strongly obvious through this graphical representation.
Due to the fact that the ATC’s actual lifetime in practice is a factor with multifaceted external influences, the manufacturer cannot control, this demands for a separate overview of the input per end-of-life strategy which can also be visualized with a normalized bar chart. For the exemplary pneumatic cylinder this bar chart is shown in Figure 9. Due to the fact that the exemplary cylinder is of small size and has a low level of materials, the strategy ‘Remanufacturing’ is more costly than ‘Recycling and new ATC’ regarding its process costs. For a more material intense product this result could be opposite.

![Eco-efficiency portfolio for 100 million cycles of a pneumatic cylinder](based on 20)

Figure 9: Input per end-of-life strategy for a pneumatic cylinder

Additionally the precise breakdown of the steps in the MorphoCheck allows a clear allocation of individual stakeholder costs. These can be reflected as a basis for business model innovations (e.g. reuse or remanufacturing).

6. Conclusion and outlook

In this article a procedure for the assessment of end-of-life strategies is presented. With the knowledge about the most suitable end-of-life strategy per ATC, suppliers of ATCs are supported in their attempt to contribute to a circular economy with minimizing costs and environmental impacts. For a realistic and absolute representation of end-of-life strategies for all pneumatic cylinders of the same type and size on the market the occurrence of probability of end-of-use scenarios at the customer have to be considered. In order to target the uncertainty of occurrence of the end-of-use scenarios at the customer (see Figure 3) proper data acquisition and a Monte Carlo simulation are recommended for the further proceeding. After decision makers identified the preferred end-of-life strategy for each ATC and ATC type, the ideal end-of-life strategy for the whole company could be defined as a next major step.

References