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Holger Kohl
Günther Seliger
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Safe and Sustainable Value Creation by Design

Proceedings of the 21st Global Conference on Sustainable Manufacturing (GCSM 2025) September 10–12, 2025, Bologna, Italy - Volume 2

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Preface

We are pleased to publish a collection of papers presented at the 21st Global Conference on Sustainable Manufacturing (GCSM), held on September 10–12, 2025, in Bologna, Italy. The conference is annually sponsored by the International Academy for Production Engineering (CIRP), committed to excellence in the creation of sustainable products and processes. GCSM 2024 was jointly organized by the Institute for Machine Tools and Factory Management (IWF) at the TU Berlin and Fraunhofer Institute for Production Systems and Design Technology (IPK) together with the University of Bologna.

The GCSM 2025 brought together more than 160 attendees from over 30 countries providing a global forum of academics, researchers, and specialists from universities, research institutes and industry from across the globe, working on topics related to sustainable manufacturing. A unique feature of the GCSM conference series is its integration of industrial engineering perspectives, sustainable manufacturing applications in emerging and developing countries, as well as education and workforce development for advancing sustainable manufacturing. Plenary keynote speeches by experienced personalities from academics and industry, paper sessions presentations and workshops of student teams from different countries offered new insights and chances for exchange of ideas. The conference featured five keynote speakers who shared recent advances in cutting-edge research and industry practices; these prominent and internationally recognized experts elaborated how technologies in the product, process and system domains can enable sustainable manufacturing.

This volume documents over 120 contributions presented at GCSM 2025 in 24 sessions held over three days. The proceedings are organized according to the conference program, classified into four broad categories as: Sustainable Processes, Sustainable Manufacturing Systems, Sustainable Manufacturing Products, and Crosscutting Topics in Sustainable Manufacturing. The papers cover a variety of topics in these areas related to modelling and simulation of manufacturing processes, product design for sustainability, metrics for sustainability assessment, energy efficiency in manufacturing, strategies and business models, as well as education and workforce development for sustainable manufacturing. All papers published in these proceedings have been single-blind reviewed by experts from the international scientific committee, which are listed in the next section. These reviews resulted in an overall acceptance rate of 60.6%.

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End-of-Life Calculator: Aircraft Seat Case Study

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Abstract. Manufacturing has traditionally prioritised cost, lead times, and quality over sustainability. However, increasing awareness of environmental impact demands greater accountability. The concept of sustainability often lacks clarity, and companies struggle to prioritise environmental goals.

This paper presents the development of an end-of-life (EoL) calculator based on selected key performance indicators (KPIs), divided into three areas—economic, environmental, and social—to evaluate EoL options such as disposal, recyclability, and raw material recovery, providing performance scores to support decision-making. This study includes a proof-of-concept case focused on the aviation sector, where non-operational factors contribute significantly to its carbon footprint. Aircraft cabin components, making up 10% of an airliner's empty weight and replaced multiple times during an aircraft's lifespan, create substantial waste, a significant portion of which is not recycled.

To validate the calculator, a Discrete Event Simulation (DES) model of the supply chain was developed to assess the recyclability of aircraft seats. This study highlights the challenges and opportunities of implementing circular economy practices in regulated sectors like aerospace.

Despite its limitations, the calculator establishes a practical framework for sustainable decision-making in manufacturing and supply chains.

Keywords: Circular Economy · Decision-Making · Aerospace

1 Introduction

Historically, manufacturing companies have prioritised cost, lead times, and quality over sustainability. However, increasing awareness of the environmental impact of human activities has highlighted the urgent need for industries to incorporate environmental responsibility into their definitions of success [1]. Despite this, debates continue over the concept of sustainability and how to assess it. Many companies struggle to determine the best processes for prioritising environmental responsibility and require structured methodologies to support decision-making towards a circular economy [2].

Globally, growing volumes of electrical and electronic equipment contribute to increasing end-of-life (EoL) waste [3]. Some products become obsolete due to wear

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and technological advancements, while others are deliberately designed with a limited lifespan to encourage frequent replacements [4]. This has historically contributed to a significant EoL product stream.

The traditional economic model follows a linear 'take-make-dispose' approach, where raw materials are extracted, processed, used, and ultimately discarded as waste [5]. While this system has driven economic growth, it also leads to issues such as resource depletion, pollution, and increasing landfill waste. In a linear economy, EoL typically involves discarding, sorting, and final disposal via landfill, incineration, or recycling—each with varying environmental implications [6].

In contrast, the circular economy is a sustainable model based on designing products for durability, reuse, and recyclability. Materials for new products come from old ones, minimising waste through reuse, remanufacturing, and recycling. When disposal is unavoidable, energy recovery or safe disposal methods are used as a last resort [7].

Key considerations in a circular economy include:

- **Reuse and Refurbishment:** Functional components are recovered, repaired, or resold.
- **Recycling:** When reuse is not possible, materials such as metals, plastics, and glass are separated and processed for use in new products.
- **Circularity:** A broader systemic model aiming to maintain the value of products, materials, and resources in the economy for as long as possible and minimise waste. Includes reuse, repair, remanufacturing, recycling, refurbishment, and also design-for-disassembly, reverse logistics, regulatory alignment, and business model transformation.

Disassembly is considered crucial in a circular economy, as it allows materials and components to be recovered efficiently, reducing waste and environmental impact while improving resource efficiency and sustainability. However, determining whether disassembly is worthwhile requires careful evaluation of various factors.

Currently, most of the EoL processes focus on material recycling, such as shredding, rather than reuse. While this is preferable to landfill, it still requires raw materials to be reprocessed and remanufactured. Additionally, recycling processes are often inefficient and fail to capture all recyclable materials. Many products are not designed for easy repair or reuse, leading to premature disposal.

As products reach the end of their lifecycle, they present both challenges and opportunities. Strategic decisions on disposal, recycling, and sustainable innovation are essential to reducing environmental impact and promoting circular economy principles. Proper management of EoL products can help mitigate environmental harm and drive more sustainable practices.

2 Methodology

This section outlines the structured approach taken to develop and apply a decision-support tool for evaluating end-of-life (EoL) alternatives within a sustainable manufacturing context. It introduces the rationale for selecting key performance indicators

(KPIs) and explains how these informed the creation of an EoL Calculator. The following subsections describe the process of KPI definition, the functioning of the calculator, and the results obtained from its application in a case study.

2.1 Definition of KPIs

The selection of KPIs in this study was guided by the Triple Bottom Line (TBL) framework, which emphasises the need to balance economic, environmental, and social considerations [8].

This approach is particularly appropriate for evaluating circular economy strategies because circularity inherently spans these three dimensions: it aims to preserve economic value through resource efficiency, reduce environmental burdens through waste minimisation and emissions control, and support social outcomes such as job creation, worker safety, and ethical sourcing. TBL aligns conceptually with circular economy principles by recognising that sustainability cannot be achieved through economic metrics alone. It offers a structured yet flexible foundation for identifying relevant KPIs that capture the multidimensional impact of end-of-life (EoL) decisions. While TBL itself does not prescribe a specific measurement system, it supports a holistic evaluation framework [2].

Drawing on literature, prior projects, and discussions with our industrial partners, we defined a list of criteria to evaluate products' EoL alternatives. These KPIs, grouped according to the three TBL dimensions, are presented in Table 1.

Table 1. EoL Calculator: KPIs.

TBL Areas	KPIs	Description	Source / Standard	Rationale
Economic	Value of recycled material or subcomponents	Assess the market value of recovered materials or sub-components.	[9],[10]	Promotes material circularity and supports financial viability.
	Labour Cost	Cost of labour involved in the EoL process.	[11],[12]	Key operational cost that affects economic feasibility.
	Equipment Cost	Cost of machinery or tools required.	[13]	Impacts capital expenditure and business case.
	Facilities Cost	Space or infrastructure cost for EoL processes.	[14],[15]	Influences site selection and scalability.
	Time	Time required for processing or disassembly.	[16],[17]	Disassembly time affects efficiency and economic return.
	Energy Cost	Cost of energy used in the EoL process.	[18],[19]	Reduces operational costs and environmental burden.
	Demand for recycled materials or sub-components	Market demand and customers for recovered outputs.	[20],[21]	Encourages reuse and market-driven circularity.
	Throughput	Number of products processed per hour.	[22]	Reflects system capacity and impacts profitability.
	Disposal Fees	Fees/taxes for disposal of unrecyclable waste.	[23],[24]	Encourages alternatives to landfill; affects cost.
Environmental	Safe Disposal	Ability to dispose/recycle materials without environmental harm.	[25],[26]	Ensures minimal ecological impact and compliance.
	Waste Reduction	Volume of waste diverted from landfill.	[10],[24]	Supports circular economy and sustainability targets.
	Energy Consumption	Energy used during the EoL process.	[18],[27]	Reduces carbon footprint and energy intensity.
	Process Emissions	Emissions from the EoL process (CO_2, NO_x, particulates).	[27],[28]	Addresses climate change and pollution control.
Social	Hazardous Substances	Operator exposure to hazardous materials.	[29],[30]	Protects health, meets safety regulations.
	Job Creation	Number of jobs created through EoL activities.	[31],[32]	Supports regional economic development and social value.
	Health Impact	Health impact on workers and the public.	[33],[34]	Key to ESG performance and workplace wellbeing.
	Human Rights	Risks of worker exploitation in EoL processes.	[35],[36]	Addresses global supply chain ethics.
	Infrastructure	Impact on local transport, utilities, and logistics.	[37]	Promotes sustainable local development.
	EoL Regulation	Likelihood or effect of relevant regulations.	[38],[39]	Ensures compliance, helps anticipate risks and opportunities.

2.2 EoL Calculator

We used the KPIs described in the previous section as comparison criteria to develop an EoL Calculator for assessing alternative scenarios based on a trade study analysis methodology. A trade study (or trade-off study) is a formal tool that supports decision making selection of the best or most balanced solution among the proposed alternatives [8].

Our calculator is designed to assess the viability and value of various EoL alternatives, making it easier for original equipment manufacturers (OEM) to assess the viability of alternatives to landfill. Results are presented as performance scores against KPIs, enabling users to compare and assess various scenarios effectively.

The steps to use the calculator, once a specific product and EoL alternatives are selected, are shown in Fig. 1.

Compared to tools like SimaPro, GaBi, and openLCA, our EoL Calculator offers specific advantages. It is easier to use and highly customisable—allowing users to add or modify KPIs (including qualitative ones), visualise results, and compare scenarios. It integrates logistics and cost factors (e.g. labour, energy, disposal) often absent from standard LCA tools. The calculator is transparent in the use of information, handles mixed data types (quantitative, qualitative, assumptions), and is suitable for early-stage decision-making, especially where information is scarce and detailed LCA databases are unavailable. While it does not replicate full-scale LCA capabilities, it complements them with practical features, like complete decision-making traceability.

We conducted case studies using the calculator to assess its effectiveness on different products and validate the approach. A relevant example from the aerospace sector is presented in the following section.

Fig. 1. Workflow of the EoL Calculator tool.

2.3 Case Study

Background. This case study develops and validates the EoL Calculator for aircraft seats as an example of its use. The aerospace sector is working towards carbon neutrality by 2050 in response to increasing government pressure to accelerate emissions reductions [40].

Although in-flight emissions have traditionally received the most attention, there are other opportunities within aviation to lower its carbon footprint. Non-operational factors contribute significantly, with tens of thousands of tonnes of material being consumed and discarded as waste each year. The environmental impact is closely linked to the mass of the aircraft cabin [41].

Cabin interiors account for approximately 10% of an aircraft's empty weight and are replaced four to five times over the airframe's lifespan. As a result, they represent a considerable share of an aircraft's environmental footprint [42]. However, applying circularity principles to cabin components is particularly challenging, meaning a significant proportion of aircraft materials end up in landfill or incineration [43].

Since sustainability has historically not been a priority for the industry, there is limited awareness of the environmental impact of cabin interiors beyond their effect on aircraft weight. Consequently, in modern airliners, around 50% of cabin components (by weight) are not currently recycled, with limited reuse within the aerospace sector [44]. Each cabin element presents unique technical and commercial challenges, further complicating efforts to improve sustainability.

Input Data. For this case study we focused on a single element of the aircraft cabin: the aircraft seat. The alternatives compared through the calculator are the following:

- **Landfill (Baseline)**: the product is disposed of in landfill at EoL with no processing.
- **Manual recycling**: the product is recycled by hand for its raw materials.
- **Automatic recycling**: the product is recycled automatically for its raw materials.
- **Manual disassembly for reuse**: the product is disassembled by hand by human operators to recover sub-assemblies and/or components, any remaining parts are recycled.
- **Automatic disassembly for reuse**: the product is disassembled automatically (e.g. using robots) to recover sub-assemblies and/or components, any remaining parts are recycled.

To assess and compare scenarios to support the decision-making process, we developed a Discrete Event Simulation (DES) model in AnyLogic DES software. This analysis was presented in one of our previous papers [45]. In that study, we focused on Western Europe as the geographical area of interest, considering aircraft fleets with varying seat compositions (e.g. number and types of seats) across different countries. We selected Western Europe as the geographical scope of this study due to its strategic relevance to the aerospace sector, the high density of Maintenance, Repair and Overhaul (MRO) facilities, and the availability of detailed fleet and material composition data. The model also incorporated the regular overhauls required for seat components and orders from airlines for new aircraft. Each country's aircraft fleet and corresponding seat configurations (number, type, and size with relative material composition) were incorporated into the model, with data sourced from online databases. This includes the age of the aircraft, reflecting real-life conditions at the start of the model. In the Baseline Scenario no recycled materials were considered. Seat manufacturers receive orders from the aircraft companies and supply new seat components accordingly. We calculated material usage and associated costs over a five-year period. In contrast, the alternative scenarios introduce a hypothetical Seat Recycling Centre, located in the UK. We tested several variations of these scenarios, adjusting parameters such as recycling rates, logistical efficiency, and processing capacity. Further to this, triangular distributions have been used to consider the stochasticity of processing times within the hypothetical recycling centre. After evaluating these variations, we decided to present the most balanced scenario in terms of cost-effectiveness and environmental impact. This balanced scenario offered the most practical and feasible results within the scope of our study.

We used this previous work as a source of information to validate our EoL Calculator. Product data were entered (***Step 1*** in Fig. 1). This includes the material breakdown for a typical seat and cost value of materials (Table 2). The DES model provided insights for the recycling processes and relative costs (e.g. method of manufacturing, equipment, labour, energy) (***Step 2*** in Fig. 1).

Table 2. Aircraft Seat: material breakdown and costs. All material cost data was originally in USD (as per [45]) and refers to prices as of August 2024. Since the case study focuses on the UK context, values have been converted to British Pounds Sterling (GBP) using the average exchange rate for that month (1 USD = 0.79 GBP) [46].

Material	Composition (%)	Cost
Foam	18.2	£279.87/m^3or £3.10/Kg
Fabric	1.3	£47.24/m^2 or £278.82/Kg
Aluminium	54.7	£3.48/Kg
Plastic	25.8	£1.98/Kg

The calculator allows users to assign relative importance to each KPI (***Step 3*** in Fig. 1). This is used to adjust the performance score assigned to an alternative, adjusting the results depending on KPIs' importance. Importance scores may vary depending on project or company requirements, an investigation with stakeholders is encouraged to properly set the scores at the beginning of any application. For this example, we chose to use a balanced policy for each KPI and consequently set all the importance scores equal.

Alternatives are scored against each KPI (***Step 4*** in Fig. 1). These scores may be of a different nature—quantitative, qualitative, or opinion-based—depending on the data availability. Quantitative and measurable scores (e.g. energy consumption in KWh, energy costs in £) are used where available data or assumptions are possible. These values are normalised on a scale from 1 (very poor performance) to 10 (excellent performance) to facilitate comparison. Scales from 1 to 10 are directly used to score qualitative and opinion-based data through workshop sessions. Justifications and references are recorded to track the decision-making process. For our example, we used open-source data and reasonable assumptions supported by workshop discussions.

Finally, results are presented on a normalised scale from 0 (worst possible performance) and 1 (best possible performance) (***Step 5*** in Fig. 1). Results are visualised through bar charts to facilitate comparison as shown in the following paragraph.

Results. The results of the case study (Fig. 2) showed that 'Manual disassembly for part reuse' scored the highest total when each KPI was weighted equally. This alternative also scored the highest for 'environmental' factors. The lowest scoring alternative was 'Landfill' which received a high score for economic factors (it is the cheapest solution) but received a low score for 'social' and 'environmental' factors.

The results of the case study alternatives were closely matched with only a 3% score difference between the manual and automated for part reuse alternatives. This highlights the influence of subjective data and KPI weighting on outcome variability, in particular, KPIs' importance scoring significantly affects the final rankings of alternatives. For instance, in a scenario where economic factors are prioritised, 'Landfill' alternative has a clear advantage. This finding underscores the importance of lowering the costs related to recycling and reuse options, for example designing products that are easy to disassemble. This also highlights the importance of governance in placing rules and regulations towards obligations towards recyclability routes.

When environmental and social considerations are given greater importance, disassembly options outperform traditional disposal methods. This indicates that companies prioritising sustainability goals may need to adjust their decision frameworks accordingly.

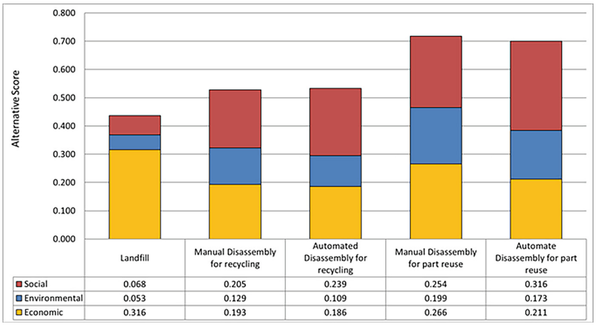

Fig. 2. Results from the EoL Calculator: performance scores across alternatives (normalised).

3 Findings

Our end-of-life (EoL) calculator has been tested across various products and scenarios. The tool has demonstrated value in supporting and informing the decision-making process.

The findings from the case study demonstrate the effectiveness of the decision-support calculator in evaluating EoL options based on economic, environmental, and social factors. The tool provides a structured assessment framework, enabling manufacturers to make data-driven decisions in line with circular economy principles.

The importance of high-quality, real-world data was evident in the analysis. While open-source datasets provided a reasonable baseline, more accurate industry-specific data would further refine the model's reliability and applicability. The case study used data provided by our research centre's aerospace partners. Where specific values were unavailable, we made reasonable assumptions using reputable academic sources, databases, and online data. While some deviations from real-world conditions may exist, the example is not intended to provide definitive answers. Instead, it serves as a proof of concept for the EoL Calculator, to facilitate discussions and offer insights to support the transition towards more sustainable industrial practices. In real-world applications, users will use their own set of data.

4 Conclusions

The calculator's structured approach allows it to be adapted across different sectors and products. Future enhancements, such as integrating real-time market data and automation trends, could improve decision accuracy and broaden its applicability across a wider range of industries. Organisations may adopt the calculator to align their EoL strategies with regulatory frameworks and sustainability targets, potentially gaining economic incentives or mitigating future compliance risks. The methodology also supports policy discussions on waste management and circular economy incentives, providing quantitative evidence to promote reuse over recycling where appropriate. In the long term, the framework will be applied to case studies and projects within our research centre and industrial partners, helping to identify sustainable and profitable solutions, quantify improvements, and provide justification for decisions.

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