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Decision-Making Tool Development for Used Industrial Equipment Life Cycle Evaluation and Improvement

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TTÜ PRESS

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Declaration:
With this, I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at the Tallinn University of Technology, has not been presented for any academic degree.

Viktoria Baškite............................

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VIKTORIA BAŠKITE

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CONTENTS

ABBREVIATIONS AND SYMBOLS

Abbreviations

AFD	Anticipatory Failure Determination
AHP	Analytic Hierarchy Process
ARIZ	Algorithm for Inventive Problem Solving (Russian acronym)
CAIS	Calculate Analyze Innovate Simulate
DFD	Design for Disassembly
DFE	Design for Environment
DFSS	Design for Six Sigma
DMADV	Define Measure Analyze Design Verify
DMAIC	Define Measure Analyze Improve Control
DPE	Directed Product Evolution
DPP	Disassembly Process Planning
ECM	Environment Conscious Manufacturing
EOL	End-of-Life
EPR	Extended Producer Responsibility
GD	Green Design
GE	Green Engineering
GM	Green Manufacturing
Green Matrix	TRIZ Matrix for Green Manufacturing
IFR	Ideal Final Result
ISO	International Standard Organisation
LCA	Life Cycle Analysis
LCC	Life Cycle Cost
LCE	Life Cycle Engineering
MATRIZ	Master of TRIZ
MIT	Massachusetts Institute of Technology
OEE	Overall Equipment Efficiency
OEM	Original Equipment Manufacturer
PDCA	Plan-Do-Check-Act
PLC	Product Life Cycle
PRP	Product Responsibility Provider
PSS	Product Service System
RL	Reverse Logistics
ROI	Return on Investment
R&D	Research and Development
SME	Small and Medium Enterprise
TRIZ	Theory of Inventive Problem Solving (Russian acronym)

Symbols

B	Cumulative environmental burden
B_E	Burden of the end-of-life stage of equipment in year
B_R	Burden of the maintenance during years
B_V	Environmental burden of the modernization of used equipment

B_U	Burden of the equipment use during years
$\boldsymbol{C}$	Economic feasibility index
$\boldsymbol{c_i}$	Quantity of $\boldsymbol{i}^{th}$ fastening devices
$\boldsymbol{E}$	Ecological feasibility index
$\boldsymbol{E_g}$	Energy embodied in the material of part reused
$\boldsymbol{E_m}$	Energy embodied in all materials within the remanufactured tool
$\boldsymbol{E_r}$	Energy for the remanufacturing process
$\boldsymbol{L}$	Quantity of reused parts
$\boldsymbol{L_j}$	Quantity of the parts that must be cleaned
$\boldsymbol{M}$	Quantity of part variety
$\boldsymbol{M_k}$	Quantity of parts after disassembly and cleaning
$\boldsymbol{M_r}$	Total material saving weight
$\boldsymbol{M_t}$	Total weight of remanufactured equipment
$\boldsymbol{N}$	Quantity of several fastening devices
$\boldsymbol{T}$	Technology feasibility index
$\boldsymbol{T_d}$	Standard disassembly time
$\boldsymbol{\theta_j}$	Difficulty value of the j^{th} washing method
$\boldsymbol{\mu_a}$	Feasibility of reassembly
$\boldsymbol{\mu_c}$	Feasibility of cleaning
$\boldsymbol{\mu_d}$	Disassembly feasibility
$\boldsymbol{\mu_e}$	Profitability of remanufactured equipment
$\boldsymbol{\mu_i}$	Feasibility of inspection and sorting
$\boldsymbol{\mu_m}$	Index of material saving
$\boldsymbol{\mu_s}$	Index of energy saving
$\boldsymbol{\mu_r}$	Feasibility of part reconditioning
$\boldsymbol{\xi}$	Intermediate variable
$\boldsymbol{\rho_k}$	Success probability for k^{th} part reconditioning
$\boldsymbol{\rho}$	Price paid by consumer for the remanufactured product
$\boldsymbol{t_i}$	Disassembly time of $\boldsymbol{i}^{th}$ fastening device
$\boldsymbol{\psi_m}$	Material reusing index of equipment remanufacturing
$\boldsymbol{\psi_e}$	Energy saving index of equipment remanufacturing

INTRODUCTION

Foreword

Abundance of environmental diseases across the world in the 19th and 20th century has created a particular demand for saving Earth's environment and atmosphere. Numerous acts have been elaborated and approved by the governments to improve the standard of living. There is a strong need to develop new manufacturing approaches into daily routines counting on nature, resource conservation and safety of workers. Today companies seek progress over perfection in every industry. Manufacturers have to deliver superior quality products on time. However, customers are not interested in investing into resources which can be still used. The approach developed in this research is focused on two essential aspects: simplification of the decision-making process regarding further life cycle of old equipment and quick reaction towards market and company internal needs. Prolonged life cycle will save resources and energy spent on new product manufacturing. The market satisfied will create more demands for used industrial equipment. In 2016, the European Union assigned funds for the initiative of the Horizon 2020 project the ambitious goal of which is to consolidate as many as industries as possible with the case studies in the remanufacturing field at one place under European Remanufacturing Network [22].

The research objective

The purpose of this thesis research is to develop a decision-making tool to evaluate and prolong the life cycle of used machines. Our main idea is to solve environmental, social and economic issues in a single concerted effort by using the proposed tool. This investigation is concentrated on the development of the Green Manufacturing (GM) framework for the evaluation of the actual state of used industrial equipment and development of the calculation algorithm and database structure for its implementation. It is intended to help industrial engineers in the decision-making of expediency of old equipment utilization or remanufacturing. The introduced approach provides continuous control and monitoring of the necessary inventory to companies and its utilization that minimizes costs and environmental impact.

Used methodologies

This research addresses many methodologies. The whole decision-making tool is a set of different methodologies with known methods. Certainly, the End-Of-Life strategies and the remanufacturing process are the centre of attention. It is crucial to reduce the total quantity of labor, energy, heating and materials spent during the manufacturing of the used equipment significantly. To be more precise, The costs have to be almost twice less than the cost of new equipment production. The reason mainly is in reusing existing components and units and having experience in building similar equipment or machinery. Today the machines used are assessed from just one side – financial aspect. Almost all the companies look at the used assets as a matter of the value with the transit of time, in particular, due to wear. The focus of the current thesis research has been on other important aspects, such as technological change, financial benefit, and ecological value. The Chinese researchers' methodology [36] was adapted and deepened during the estimation process. Prediction algorithms are introduced here, and all data required for the calculation are included in the database structure elaborated by using the IDEF1X method.

TRIZ reference was used as an accurate brainstorming toolkit for innovative solutions and options development to systematize and improve the decision-making process in this research. The Green Matrix is based on Lean tools and Green Engineering (GE) principles with elements of innovation by implementing TRIZ concepts without implementation of the most successful tool such as ARIZ. Such unusual combination has provided remarkable results for prolonging industrial equipment life cycle.

Scientific and practical novelty

The proposed framework for decision-making improves SMEs ability to take control over their resources and stay in tune to the minimization of environmental impact.

The research targets the decision-making tool elaboration with Lean and GM tools and EOL scenario consideration. The new innovation-oriented approach CAIS is proposed for SME industrial equipment controllability and utilization on a daily, monthly, or yearly basis.

Used Waste Matrix was derived as an evaluation tool of Lean and GM techniques integration into each other. TRIZ was integrated for the extension of used industrial products life cycle mainly as a brainstorming instrument.

In general, the concept of GM projects implementation will influence the overall direction for sustainable production and help to save finite natural resources through increasing the life cycle of the spent industrial equipment.

The most significant results achieved in this doctoral research include both the scientific and practical novelties. The scientific innovations expand the theoretical background in the field of mechanical engineering and its application, for example, to improve the course of Innovation. The practical importance of the research lies with the companies who are using industrial equipment at their production plants, for instance, all possible machinery enterprises. The decision-making tool elaborated during the Ph.D. research can be taken as an input for an IT program development to assess and control the actual state of the used industrial equipment.

Contribution of the Thesis and Dissemination

The thesis research was carried out during 2009 – 2017 at Tallinn University of Technology in Tallinn, Estonia. The study was part of the following projects: e-Manufacturing Concept for SME (Project ETF7852), Mechatronic and Production Systems Proactivity and Behavioral Models (Project

SF0140113Bs08), and Enhancing Sustainability of Manufacturing Enterprises Through Reliability Engineering (Project ETF9460).

The results of the Ph.D. thesis have been reported at ten international conferences. The author has published ten international scientific papers directly associated with the thesis research. The author's papers are presented in collections indexed by IEEE Explorer, ISI- Thomson Reuters and 21 other international databases. The most relevant publications directly connected to the research topic are listed at the end of the current work.

Work structure

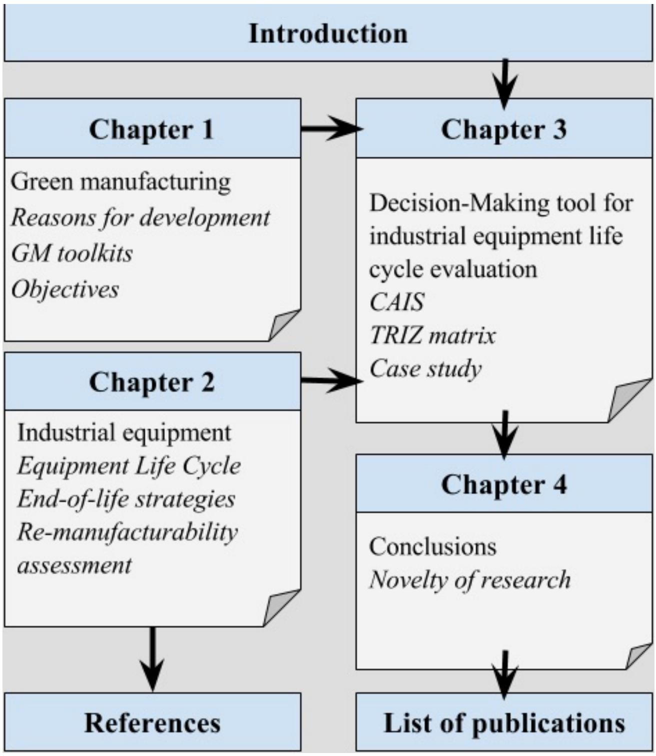

Figure 1. General structure of the thesis

1 GREEN MANUFACTURING

1.1 History of manufacturing systems development

Over the years, the necessity to count on individual consumer demands without compromising quality or price has introduced flexible and mass customization techniques in production (Fig. 1.1).

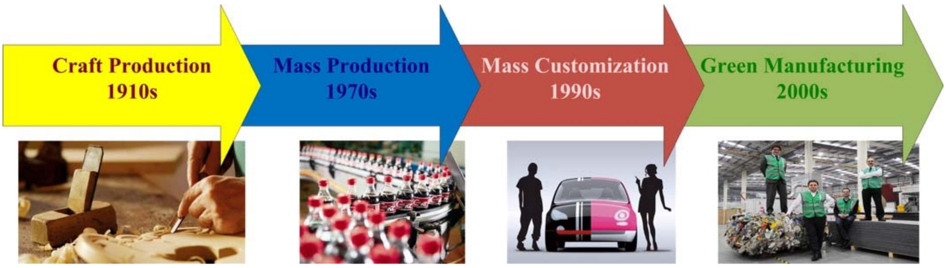

Figure 1.1 Development of manufacturing systems over the last years

The progress of manufacturing concerning productivity, the manufacturing cost per unit, market price, consumption and environmental impact presents the evidence of tremendous changes from the earliest organized in the 1800s up to today [1]. Today's manufacturing results can be viewed with a very simple AS-IS model shown in Figure 1.2. If manufacturers do not implement innovative production techniques towards resource conservation strategy, the growing needs will consume all finite resources, and the environmental impact will increase proportionally.

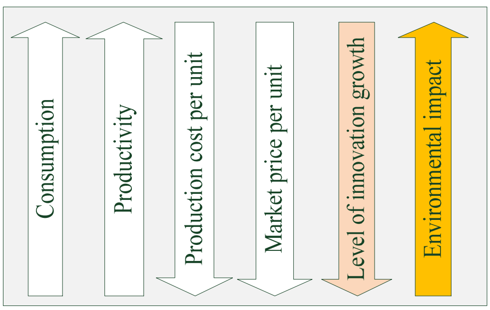

Figure 1.2 Today's manufacturing model AS-IS

The manufacturers seek higher efficiency with a lower cost per unit. As a result, the market price will drop and it will increase the consumption. All these actions will increase the environmental impact.

Tomorrow's TO-BE manufacturing model has to be more or less the same; just the consumption rate cannot influence the growth of the environmental impact (Figure 1.3). It is important to find ways to the "embedded costs" associated with EOL strategies leading closer to sustainable production and the closed loop of product life cycle (PLC).

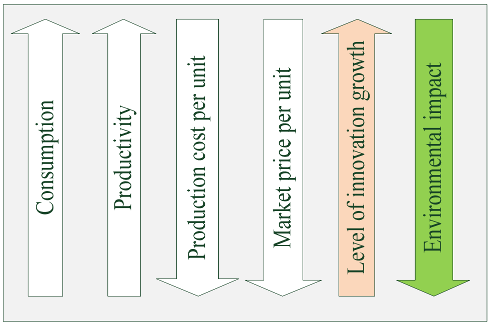

Figure 1.3 Tomorrow's manufacturing model TO-BE

1.2 Reasons for the development of Green Manufacturing

What is Green Manufacturing (GM)? There is no precise meaning of this new approach in the production community. Green manufacturing covers the entire life cycle of an item from design (GD), assembling, maintenance, up to the last disposing of it. By and large, there is no "formula" how to be "green." Each business visionary needs to locate a particular route so as to actualize the GM idea during production.

There are many different definitions of something similar to what GM exactly is. A detailed description is given in the Handbook of Industrial Engineering: Technology and Operation Management, "GM is the new generation production paradigm that is responsible for three aspects: environmental, economic, and social. It is forecast as the initial step toward sustainability " [2]. There are certain rules and principles how companies can become "greener," for example, 10 Golden Rules by Dr. Conrad Luttropp [3]; still, 12 Green Engineering principles [4] were used in this research to elaborate the Green Matrix of an innovation-oriented approach.

Globally, nations fight against the CO_2 increase on a political level. There is the strong support from the European Union (EU) through the largest EU Reseach and Innovation program "Horizon 2020" started in 2014 to make collaboration of different sectors like public and private possible. More importantly, Horizon 2020 program has extended globally. For example, there is an important partnership project with the USA called "Picasso" [5]. It is crucial to connect scientific knowledge and innovation with practical approaches to deliver a "greener" outcome.

The next section reviews different toolkits that cover environmental aspects during the PLC management. The aim is to investigate how user-friendly and how easily implementable they are at SMEs.

1.3 Green Manufacturing toolkits

The focus in the current research is on the GM decision-making tool development for used products such as evaluation and extension of the life cycle of spent industrial equipment. The main idea is to create a GM tool that can help SMEs to estimate the value and make correct decisions about the current situation of their used equipment. For that reason, all the other GM and sustainability toolsets must be reviewed to see the possible advantages and disadvantages.

GM toolkits are developed worldwide by researchers, entrepreneurs, political parties, and manufacturers for various purposes. Most of them include the word "sustainable" in the title as a noun or an adjective in different variations. The concepts of Sustainability and GM in this thesis are used to the environmental impact and non-standard problem-solving by using the concept of innovation; therefore, some of these toolkits are described in this section. Another aspect is connected to PLC extension and assessment possibilities. The tools are widely known, and those mostly suitable for the developed approach in the thesis are as follows:

- The OECD Sustainable Manufacturing Toolkit "Seven Steps to Environmental Excellence." It is one the most powerful tools developed in the last ten years. It provides a starting point for manufacturing companies to improve the efficiency of production processes and products [6].
- Green Renovation Toolkit, which provides for building renovation [7].
- Remanufacturing Opportunity Tool (ReOpT), which is based on the decision-making process such as the nature of the product, customers, markets, resources, and the environment [8].
- Sustainable Manufacturing 101 Module [9].
- EPA Lean Manufacturing and Environment Toolkits, which have developed EPA that shows how manufacturers can use Lean methods [10].
- Institute for Industrial Productivity's Industrial Efficiency Technology Database (IETD) [11].
- Competitive Manufacturing Toolkit, which offers an innovation solution for the manufacturer [12].
- An ERM guide for business is the sustainability toolkit for developed tools and techniques to support business activities [13].
- Green Suppliers Network (GSN), which contributes to identifying process improvements and greater efficiency of materials usage [14].
- Think Green Initiative (TGI), which helps organizations to use environmental GM good practices, reducing costs, improving equipment efficiency [15].
- Sustainability Resource Toolkit. This manual is a very powerful tool for GM toward sustainability development [16].
- Toolkit on environmental sustainability for the ICT sector [17].
- NREL's Renewable Energy Optimization (REopt) Tool, which combines site, resource, cost, incentives, and financial data. The solver identifies minimum cost along with the optimal dispatch strategy [18].

- The Circular Economy Toolkit, which has consolidated all the opportunities and provided information on how a company could start finding benefits [19].
- End-of-Life Design Advisor (ELDA), which helps designers to predict EOL strategies and to assist in decision-making [20].
- Eco-efficiency learning module (WBCSD) for reducing ecological impacts [21].
- European Remanufacturing Network (ERN) is the European Union initiative to connect different industries under one portal to share best practices in the remanufacturing field [22].

The aim of the introduction of all these toolkits is to give an overview of existing tools providing central ideas and direction toward the green and sustainable development of manufacturing systems. Almost all of them are time-consuming because of reading and investigation. The average length of the document is from 50 to 300 pages. The key messages consist of such words as "waste elimination," "innovation," "lean techniques," "resource conservation" and other words. It is clear nowadays that SME management lack time to work the tools through. It is among motivations behind the proposal to provide an easy-to-learn and convenient method to help SMEs take control over used industrial equipment life cycle span by using modern tools and techniques. The developed decision-making framework consists of independent modules and can be integrated separately into the working process. The guidelines of the proposed innovation-oriented approach are presented in Chapter 3.

1.4 Objectives and hypotheses of the research

Continuous growth of wealth and standard in living creates stronger demand for resources. The system of different Green methods developed is a valuable step toward sustainable manufacturing happening shortly in real production facilities. The current study is concentrated on the improvement of the environment impact on nature by using TRIZ theory tools and various EOL strategies. All this is distinguished by combining the remanufacturing process and Green Engineering principles into a GM structured tool for the evaluation and cost of the working industrial equipment. The aim is to develop a systematic approach for their life cycle assessment and prolonging to retain resources and harmonize environment and society. This systematic tool is meant for SME development in the fast developing and competitive environment. TRIZ methodology beauty is in its broad application and can be further used by the company itself. The suggested framework concentrates on the Green Matrix, which is decreased to 19x19 worsening and improving parameters instead of 39x39. The main aim is to simplify the use of the offered decision-making process and help to look at the problem as a challenge and show it from a different angle.

Objectives and Tasks of the Research

The purpose is to improve the environmental impact on nature through systematic decision-making tool creation to value and prolong the life cycle of the machines used. Fewer pieces of old industrial equipment make less waste and generate less demand for the production of new parts. The proposed approach provides a structured analysis of EOL stage selection of industrial equipment and contributes to finding an innovative decision through the TRIZ oriented Green Matrix and standard tools to utilize the resource in the best way to save the environment and company's financial resources.

To approach that aim, the following tasks should be fulfilled:

- To study and analyze different practices that deal with industrial equipment EOL scenarios and successful practices of GM project implementation.
- To integrate TRIZ theory into the decision tool as an innovation mechanism with the consideration of GE principles.
- To elaborate the decision tool for the estimation and extension of the used industrial equipment life cycle:
    - The combination of Lean manufacturing tools and the approach of the re-manufacturability assessment of used equipment from three different aspects, such as technological change, financial benefit, and ecological value.
    - Description of important factors influences the Green Matrix elaboration based on the traditional TRIZ Contradiction Matrix 39x39 and Green Engineering 12 principles.
- To verify the the suggested approach on the case study.

Scope of the Research

The scope and object of the research: to offer the owners of used industrial equipment a straightforward and easy to use decision-making tool for daily operations. Underused industrial equipment is considered as supportive production goods that assist in the manufacturing process, such as fixed equipment and machinery, instruments, jigs, tools.

Hypothesis of the Research

- Green Manufacturing principles integration into the daily SMEs life by making the business model more flexible and competitive thanks to sparing natural assets for further generations by augmentation of used equipment life cycle.
- Advancement of an organized cycle CAIS for current state appraisal of used items for the organization's stock control administration to limit natural effect through asset utilization amid the whole product life cycle.
- New challenges and tasks encourage young and already experienced engineers to look for out-of-the-box solutions, which contributes to establishing new jobs in the production industry.

2 LIFE CYCLE OF INDUSTRIAL EQUIPMENT

2.1 Concept of Life Cycle

Ordinarily, the time range begins with product introduction and ends with its obsolescence and substitution with a new product. The form of the life cycle is rather standard; it is passing the next basic stages: development stage, growth stage, maturity stage and it ends with a decline [19]. It is common for companies to start the R&D for the new product somewhere in the middle of the growth stage of the previous product, as illustrated in Figure 2.1. The red curve represents any 'a' product, the blue curve – any 'b' product, the green curve – 'c' product. Phases: 1 – introduction, 2 – growth, 3 – maturity, 4 – end of maturity and start of the decline, 5 – decline, Q – sales volumes (quantities), and t – time flow [20].

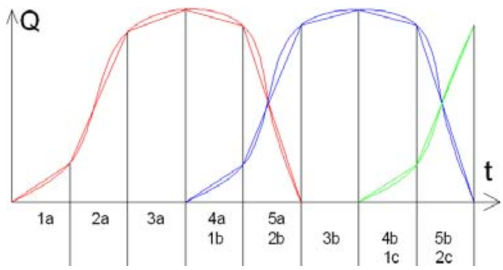

Figure 2.1 Product life cycle curve, product's continuous improvements

Different researchers have covered the behavior of a life cycle of new products. At the same time, many of the solutions provide no support to the second and the next PLC response span. Usually, companies consider the purchase of new tools and machinery without thinking what to do with old and used equipment. Most of the SME managers consider that equipment as waste. If a company maintains a green way, the PLC curve looks as shown in Figure 2.2. The red graph is becoming a "bath" type line. The description seems like the basic one, but the number of stages is increased. The red curve represents any 'a' product, blue curve – any 'b' product, green curve – 'c' product. Phases: 1 – introduction, 2 – growth, 3 – maturity, 4 – end of maturity, 5 – decline, 6 – start of the opening of the next life cycle of the used product, 7 – growth of next life, 8 – start of maturity of next life, 9 – timeline of next life, 10 – end of maturity, 11 – decline of next life, Q – sales volumes (quantities), t – time flow. Certainly, the sales volumes can vary depending on the used product specification. The idea is to keep the cycle as many lives as it is worth it.

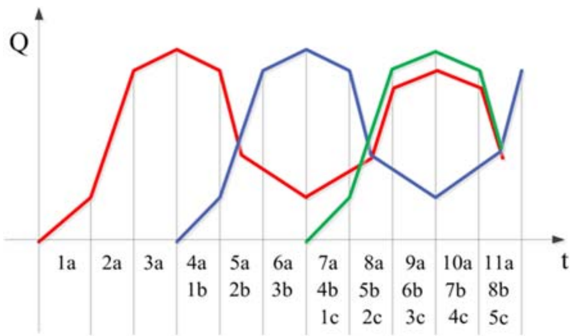

Figure 2.2 Green Product life cycle curve, product's continuous improvements

Other essential requirements are to show the proper moment to start the next life span and what kind of strategy to use.

2.2 Reverse Logistics and End-of-Life strategies

Commonly, original equipment manufacturers (OEM) offer the replacement of old equipment when they reach the end of their life cycle [23]. Most SMEs are not responsible for a take-back process because of no EOL strategies integrated into their daily operations. The take-back process can result in additional costs in an inefficient reverse item stream. Still, there is a need to use the existing assets with the possible highest output. In this case, two ways can be implemented in real practical conditions. The first option is to use known EOL strategies to meet the set goals. Sometimes it is not so easy to fulfill all the needs by using one of the EOL. It will bring the result in one particular case, but will not approach the issue systematically. The second possible way is to unite reverse logistics intention with various EOL strategies. This method is more tactical and promising from the perspective point of view. It is not so natural to actualize, but rather the systematic decision-making tool developed in this research helps to distinguish the desired outcome by closing or extending the loops of the analyzed product life.

The target of different EOL strategies is to find the best option or combination to save about 40-60% of the total cost as compared to new equipment purchase. Different results of studies have been reported [24], [25]. Another major challenge is to reduce the environmental impact by minimizing the waste resulting from the production of new products. It is not simple to show the ecological win-win case studies because of complexity and the vast amount of criteria [26].

According to Gupta and Elgin, there are five commonly used options for a product at its end of life: direct reuse, repair, remanufacturing, recycling, and disposal [27]. More detailed flows with EOL strategies distribution are shown in Figure 2.3.

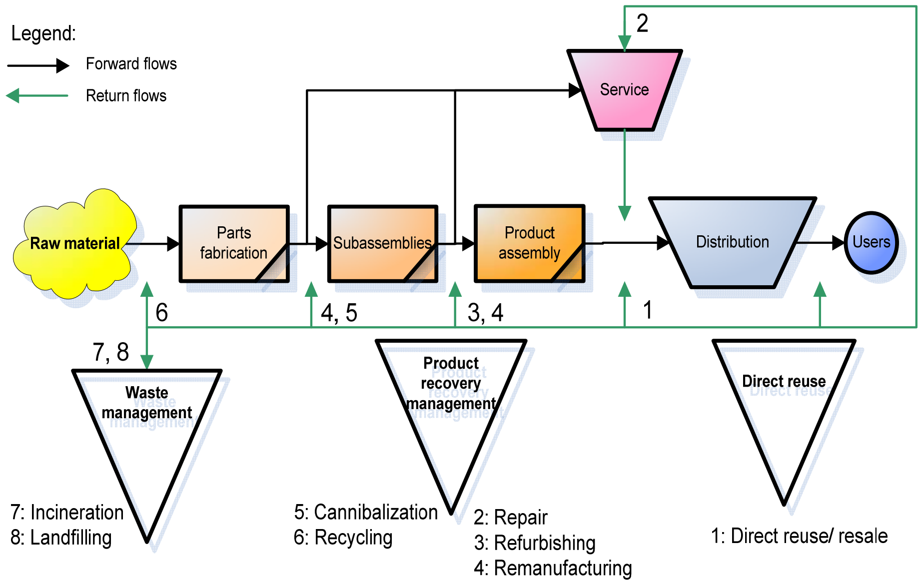

Figure 2.3 Different EOL solutions and loops

In Michaud's opinion, the economic factor is cut up by the lack of research in the field of product end-of-life strategies. Therefore, it is the key factor that will influence any decision or area of strategic concern in which the investigation is provided [28]. According to Gehin et al., "to evaluate the relevance of a strategy, the focus should be on the economic efficiency" [29].

2.3 Influence of End-of-Life strategies

Different approaches are available with regard to "what to do with an old product." The most common methods regarding EOL possibilities are Reusing, Repairing, Reconditioning, Reconfiguration, Recycling, and Remanufacturing. The influence and characteristics of each approach are described in Table 2.1. Also, negative and positive aspects of different end-of-life strategies are presented in this chart.

Table 2.1 EOL strategies and their influences

End-of-Life approach		Positive aspects			Negative aspects		
		Quality level	Life extension	Envir. impact	Energy consumption	Resource consumption	Time taking
1	Product reuse	intermediate	highest	lowest	-	-	-
2	Repair, service	low	high	low	lowest	intermediate	intermediate
3	Reconditioning	intermediate	intermediate	low	low	intermediate	intermediate
4	Remanufacturing, component reuse	highest	high	intermediate	high	intermediate	highest
5	Recycling with disassembly	middle to low	intermediate	low	high	high	high
6	Recycling without disassembly	lowest	intermediate	low	high	high	high
7	Disposal (incineration)	-	-	highest	high	-	intermediate
8	Refurbish or minor repair	intermediate	high	low	lowest	intermediate	lowest

Brazilian researchers have conducted a very relevant investigation; a detailed description of End-of-Life scenarios with references to the experts in this field are shown in Table 2.2 [30].

As not all the products can be reused or serviced after reaching their end-of-use or EOL, there seems to be an option to follow between remanufacturing and recycling, depending on the product's condition. The circuit of the used product under the remanufacturing process is shown in Figure 2.4, presented in Appendix 2. Rose at al. estimated that on average, 40% of the parts are replaced during the remanufacturing of the product, and therefore these parts must be manufactured [31]. While with a repairing option, generally, 10% of the parts need repair, they must be manufactured.

Table 2.2 End of Life strategies (EOL)[32]

EOL	Main characteristics	References
Reuse	The equipment is reused multiple times without prophylactic maintenance or repair. Reuse has no influence on product's quality; it is not new.	Gray and Charter [2006]; Rose [2000]
Repair	The broken parts are replaced, and the equipment can be operated again at full load. The replaced unit has a quality level as new, and the equipment has extended life cycle.	Ijomah et al. [2007]; Gray and Charter [2006]; Ijomah et al. [2004]; Thierry et al. [1995]
Refurbishment / Recondition	The machine's principal objects are repaired to the operational stage again. The quality level depends on the parts' worn-out level, but the life cycle has been extended in any case.	Ijomah et al. [2007]; Gray and Charter [2006]; Ijomah et al. [2004]; King et al. [2006]; Thierry et al. [1995]
Recycle with and without disassembly	Recycle is another possible option to finalize the equipment life cycle. However, it is the high energy, time and material consuming procedure among other options.	King et al. [2006]; Rose [2000]; Thierry et al. [1995]
Remanufacture	The remanufactured industrial equipment has the quality level the same as the new one. Also, the warranty can be provided as long as for the new one or twice less [32].	Gray and Charter [2006]; Hauser and Lund [2003]; Jacobsson [2000]; Steinhilper [1998]
Disposal (incineration)	The disposal scenario is the worst possible option. It has the highest environmental impact and also contributes much energy. Hence, there are initiatives to produce energy during the incineration process, for example, in Denmark where no land is left for landfills.	Hauser and Lund [2003];

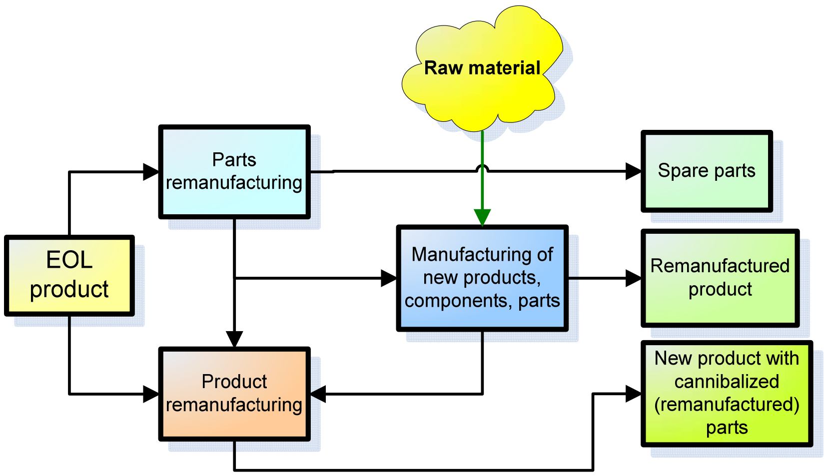

Figure 2.4 Circuit of remanufactured products and components

An MIT team has focused their research on the area of the used product life cycle. Their studies were targeted to the total energy used by 25 various products over the lifetime of the production process. They report that obviously fewer investments, less material and energy is spent for making the product from the recycled material than to start from product design. It is important to mention that almost half of 25 remanufactured products were found of lower energy efficiency due to extra energy consumed over their life cycle. In general, this is the way management makes their decisions. "The decision is always on cost, not energy," Gutowski says [33].

There are many positive aspects of remanufacturing end-of-life itself. First of all, the remanufacturing process does not hinder the innovation; it is possible to make the remanufactured product modern by using new technologies if this one was new. Another factor is connected to the level of warranty of the remanufactured product ensuring its quality. The positive side of the remanufactured product is usually linked to shorter lead times. Of course, the remanufacturing process itself is not standard because quite often it needs the use of non-traditional operations management approaches. It is a broad field of research and an area for the development of new methods to systematize the various operations management issues in remanufacturing [34].

2.4 Re-manufacturability assessment method

It is always a dilemma when exactly the right moment to give the second or next life to used industrial equipment is GM idea is focused on three main ideas: the decision must take into consideration the producer from the economic, ecological, and social point of view, as presented in Figure 2.5 [35].

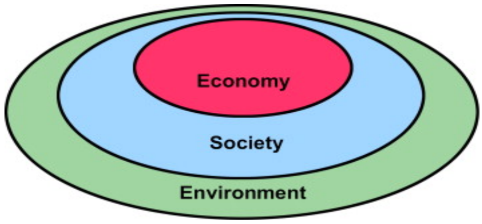

Figure 2.5 Green Manufacturing principles

If there is a deal with used equipment, the social factor must be regarded from the technology standpoint. After remanufacturing, the machine must have the same ergonomic, convenience and easy to handle characteristics as a new one. It is unreasonable to give the next life if the product is not user-friendly and outdated. The possible approach for assessing the re-manufacturability of used assets according to the traditional remanufacturing process is shown in Appendix 2.

Essentially, the used equipment is to be regarded from three most critical aspects: technological change, financial benefit, and environmental impact. Here the Chinese researchers' method, which Du, Y., Cao, H., Liu, F., Li, C., & Chen, X. used to machine small and straightforward tools, can be adapted slightly expanded [36]. First They take the conventional remanufacturing process as the base for the calculation. The economic factor is reviewed from the LCC point of view, remanufacturing costs and spent equipment price versus the new one. The Heinz calculation model [37] and risk analysis was taken as the supportive methodology to achieve better economic results. The green part is covered from the energy and material perspective. For instance, an interesting web-based solution for used cars is available from 2001 where the CO_2 level is taken into consideration [38]. Also, all three indexes of technological change, financial benefit and environmental value assessment are determined by the AHP method [39] and [40]. LCC was calculated according to [41] and [42].

The general workflow adopted and upgraded from Chinese researchers' investigation is shown in

Figure 2.6 [36]. Their treatment carries some degree of expert judgment. During the research it was decided to implement the coefficient of concordance [69] to clarify the results more precisely. As it is known, risks always arise if the case is connected to spent industrial equipment from the economic assessment aspect. It is essential to conduct all the results in Simulate part by an overview of the remanufactured product with the similar new one from ROI and price point of views. Another important deciosion during the investigation was made to use also the Heinz calculation method to estimate a life cycle until failure.

An example of the implementation of the proposed tool with equations and comments is presented in Case study 1 – Used lorry.

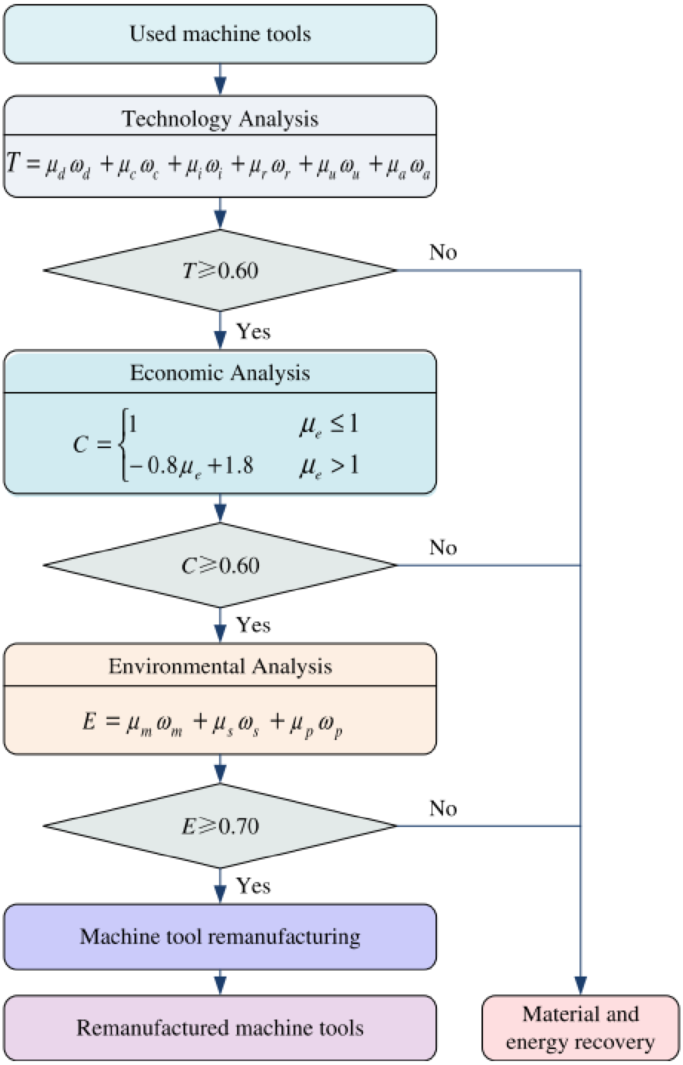

Figure 2.6 Assessment process for re-manufacturability of used machine tools [36]

2.5 Theory of inventive problem solving for equipment life cycle extension

As mentioned above, Green Manufacturing is the production approach that is looking for advancement and new solutions. This test is especially valuable for specialists to discover doors open in the long-term for advancing different production fields. Clearly, there is a serious requirement for creative arrangements. Advancement is not the blazing light in our heads; it is the likelihood to make something new and extraordinary for who and what is to come. The Theory of Inventive Problem-Solving (TRIZ) is one way to address complex tasks and find irregular solutions. TRIZ is a Russian acronym, defined by G. Altshuler, a Russian researcher, in the 1940s [43].

This section describes TRIZ as the primary tool for the development of an innovation-oriented approach.

This theory is not meant merely to understand and use, but rather to provide results that can impress and give unpredictable profits and resolutions. TRIZ is a mental discipline and a methodology that supports systematic problem-solving. It is paramount to provide the opportunity to researchers to forecast the future of industrial system behavior by analyzing the historical development of different products [44].

Several applications of TRIZ in various problem domains are described in more detail below to explain how TRIZ can be applied in original or creative problem solving. Figure 2.7 shows the main flow of particular problem solving using tools along with the principles.

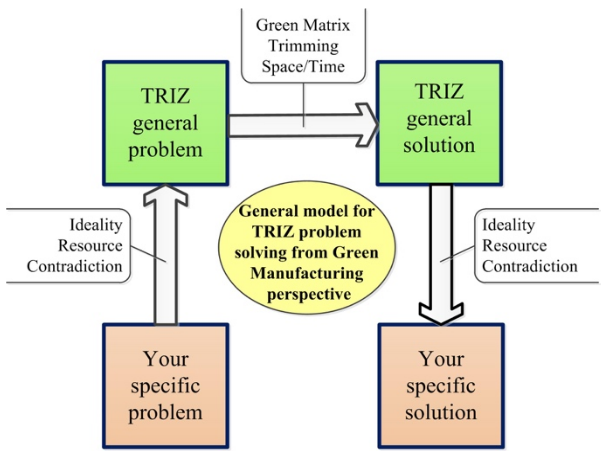

Figure 2.7. Main schema of TRIZ for a proposed decision-making tool

TRIZ addresses different requirements, technical contradictions, and hesitancy towards being creative, psychological inertia problems of the project team through its systematic innovation methods and a wide range of powerful tools. TRIZ had evolved rapidly since the last decade when it reached the west. An algorithm for inventive problem solving (ARIZ), Anticipatory Failure Determination (AFD), Directed Product Evolution (DPE), integration of the Bright process, Ideation TRIZ etc. are its developments, through which TRIZ has evolved from a traditional set of tools to a more comprehensive and efficient methodology [45].

There are certain contradictions between Lean and GM philosophies. Some inconsistencies are described and can be evaluated by using the Lean&Green Waste Matrix developed in this research, as a possible option for end-of-life strategies. TRIZ is not new for the scientific world as well. Mostly, it is globally used as a combination with Lean tools. Also, there are certain use cases which find some Green and Clean opportunities through TRIZ tools. For example, development of environmentally conscious products by combining the Ecodesign and TRIZ [46]. Below is a short overview of a combination of TRIZ with Lean tools, implementation of the theory in the process of new product design in a green or ecologically friendly way to get more creative results.

In fact, TRIZ was mostly used in conjunction with Lean tools also named as Lean Thinking tool [47] and how these two significant methodologies overlap between each other [48]. TRIZ has been tried together with such simple tool like Fishbone 5Why's [49] and also used for Value Stream Mapping (VSM) analysis [50]. The Portuguese researchers reviewed TRIZ for helping the during the integration of continuous improvement in production [51]. Toivonen at al. has utilized TRIZ inventive capabilities with Toyota Kato methodology to simplify the continuous innovation process in the companies [52].

There is an overlapping with the general concept of GM. It is not easy to determine the relations because the GM concept has no certain rules and statements to follow. TRIZ tools are used to solve some environmental issues and as a tool to be implemented cleaner production [53] and eco-innovation projects [54] in manufacturing. More often TRIZ is seen as a toolkit for Eco-design improvements [55]. There is a great research represented by Swedish researchers about green and lean product development through very detailed literature review [56]. Nevertheless, the highest attention was paid to innovative and environmental-friendly product eco-design in the next research works [57], [58], [59], [60], and [61].

Nonetheless, TRIZ is also exercised for EOL strategies analysis. The innovative methodology is applied in Design for Disassembly (DFD) [62]. It is important to mention TRIZ was also used for Design for Manufacturing (DFMA) to maximize the value of the product [63]. Chinese researchers used it to improve the Service Operations Management [64]. An analysis reported shows how to identify which tools and methodologies from TRIZ might be utilized in the Design for Environment (DFE) approaches [65]. Further, the Green Matrix developed during this research is introduced.

2.6 Conclusions of Chapter 2

This chapter reviews the concept of product's life cycle and the implementation of EOL strategies at different types of industrial products. The primary purpose is to find several alternatives from the GM field concerning equipment EOL approaches, to evaluate and create a systematic approach, to apply it further on real examples. It is also important to point out most beneficial solutions for further use.

Another goal of this chapter is to understand which approach is suitable for a particular product in different situations and corporate environments. Furthermore, the best solutions discussed in this section have not always proved suitable for everyday practices and SME environment. Numerous studies of the implementation of EOL strategies have been conducted recently. It is important to mention that combining different EOL solutions gives the best results. The connection of EOL policies can be established through the application of innovative resolutions. The most promising EOL scenario for used industrial equipment is remanufacturing. The Chinese researchers' method was examined and viewed to show the difference and the way it was adapted for the elaboration of the decision-making tool by implementing the innovative theory of TRIZ into the main flow chart of the method.

3 DECISION-MAKING TOOL FOR INDUSTRIAL EQUIPMENT LIFE CYCLE EVALUATION

This section introduces the proposed tool for GM project integration CAIS and compares it with similar well-known techniques. The systematic approach called CAIS is divided into four parts presented in Figure 3.1. The core of this tool evaluates and then prolongs the used equipment life cycle by implementing or combining EOL strategies.

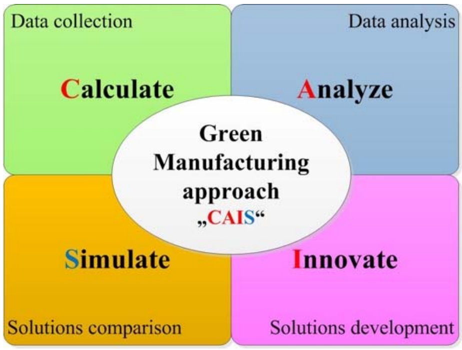

Figure 3.1 General approach for Green Manufacturing project integration

The longest period of industrial product lifespan is in the "use" phase. There are two main decision points: when to remanufacture for the second, third or even fourth time and when the right moment to recycle is. All the moments have to be decided from the environmental, economic and technological viewpoint. As data about used industrial equipment are insufficient, it is necessary to create a more general approach to simplify the decision-making procedure for this specific equipment.

CAIS description & comparison

This decision-making tool can remind of well-known methodologies from Lean Six Sigma, such as Deming cycle or Plan-Do-Check-Act (PDCA), Define-Measure-Analyze-Improve-Control (DMAIC), Design for Six Sigma (DFSS), and Define- Measure-Analyze-Design-Verify (DMADV), but CAIS is a narrowly oriented supportive mechanism for SMEs. It consists of four independent blocks described below in this Section.

The methodologies are compared in Table 3.1. The CAIS approach was developed for everyday usage and has simple logic inside with an integrated innovation module. It is intended to acquire the answers quickly and give the overview of the current used assets condition. It is crucial to stress that CAIS is suggested to overcome fear and find an original resolution to old and inextricable questions and problems. The overall state of the equipment must be assessed according to the proposed approach at least once per year to have an overview of the current situation; therefore, its use is not complicated, enabling easy use in daily operations.

Table 3.1 Comparison of various methodologies

Analyzed Approaches	**PDCA** (Plan Do Check Act)	**DMAIC** (Define Measure Analyze Improve Control)	**DMADV** also known as DFSS (Design For Six Sigma)	**CAIS** (Calculate Analyze Innovate Simulate)
General description	General methodology with a guiding principle	Specific method using statistics to reduce variation (problem- solving tool)	Specific method concentrating on a new process/product development	Specific method using technical data to be used as a problem-solving tool
Short name	Lean Thinking	6 Sigma	6 Sigma	Green Manufacturing
Nr of steps	4 steps	5 steps	4 steps	4 steps
Data type used	Qualitative	Quantitative	Qualitative	Quantitative
Purpose	Process management without innovation	Cycling process improvement by using specific techniques without innovation implementation	Encompasses the entire product development cycle with prepaid step for innovation	Process control & assessment with innovation step
Participants	Allows for the involvement of everybody	A steering committee, tollgates, a champion, and a project sponsor are necessary	DFSS often requires process or product "experts"	Allows for the involvement of everybody, but engineers and operations management are more interested
Results	Daily small improvements. Fast results	Project-based results. Can take a longer time to implement. Too many people involved	New products & process development. Takes time and results can be viewed after implementation	Daily usage. Fast results

The developed CAIS tool has four independent parts that can be used separately and in different stages without going back to the previous one. “C“ means CALCULATE or necessary input data gathering. Next is “A“ that helps us to ANALYZE the collected data. Usually, SME management decisions are made after the first or the second stage, which is incorrect because of many unknown factors. It may cause additional investments, rework or even new analysis. For that reason, it is important not to remove the third stage of the proposed tool and try to find alternative ideas, options, and opportunities by innovative TRIZ tools. The third "I" means INNOVATE. The aim is not to take pleasure in a compromised solution, but to fulfill and truly find the way to Resolute the issue and satisfy the needs. Nowadays, partial solutions and compromises do not suit because of lack of time and a very competitive environment with many start-ups and challenges from customers. It is always good to have one-two unreal and innovative solutions that can be simulated among other standard decisions.

This work is mostly oriented to the first three parts of the proposed approach. The fourth part "Simulate" seeks for superior simulating alternatives. Apparently, it is easier to use computer simulation of EOL scenarios and then choose the best one based on the results of the simulation. The insufficient approach called the trial and error method is still widely used, but from the efficiency point of view, no capacity is available to use that method. The essence of the concept is to take overall control over used industrial equipment and monitor it year-by-year at least on the company level. It is a major challenge for the engineers at the generation of new concepts and solutions. GM EOL solutions, such as remanufacturing, reuse, or recycle, may not satisfy all the needs. Thus, it may be reasonable to think about some new more innovative decisions.

Introduction of the structured tool

The main detailed explanation of the decision-making process is shown in Figure 3.2. In general, it consists of four separate blocks: Calculate, Analyze, Innovate and Simulate. Three first parts are illustrated with flowcharts presented further in this chapter.

The Simulate section is missing because of a simple comparison of all possible options from the ROI point of view. It is evident that the Simulate part always depends on the set target and delta the enterprise is seeking to achieve. However, this thesis research provides all the basic flowcharts and dependencies of database criteria to create the needed module fast enough. The database architecture is shown in Fig. 3.3.

Further, the sections are described more precisely.

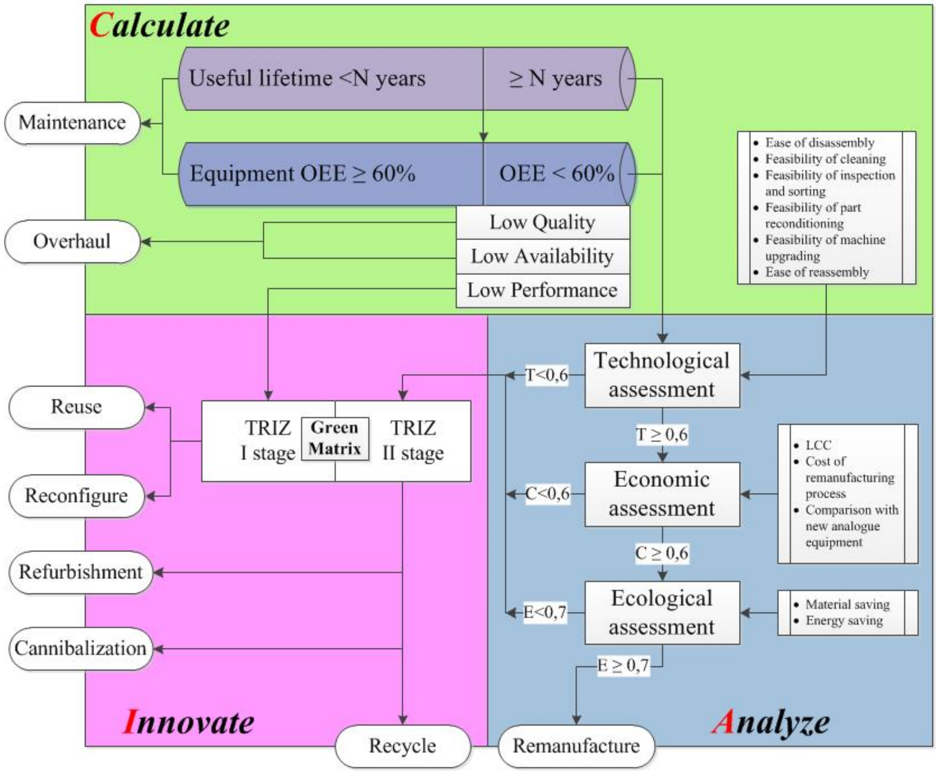

Figure 3.2 Main decision-making framework for used industrial equipment LCA

3.1 Calculate: Definition of equipment state – stage 1

As the first step, the owner of used assets has to decide which industrial equipment to evaluate. It is critical to understand the age of the machines with the complex multi-core case separated into two stages: before and after a useful life. The useful life of the product is shown with value *N* [66]. The age depends on the exploitation conditions; that is why it can differ from a certain inferior limit to the upper one. The equipment ages are specified in Appendix 2. Once the product's age is clarified, the OEE can be calculated in the next stage.

Definition of Overall Equipment Effectiveness and its role in this research

Overall Equipment Effectiveness (OEE) is a known Lean manufacturing tool to monitor and manage the life cycles of the different types of machinery and industrial equipment for already over fifty years. This concept was developed in Japan at the end of the 1960s by the Japanese engineer Seiichi Nakajima but firstly implemented outside the country only at the end of the 1980s.

According to the OEE theory, the value is calculated through the ratio of full production time to the planned operational time. The effectiveness factors used for this purpose are necessary for the context of the current research. These factors: Availability, Performance, and Quality are shown in Figure 3.3. All the equations of the OEE calculation are presented in [67].

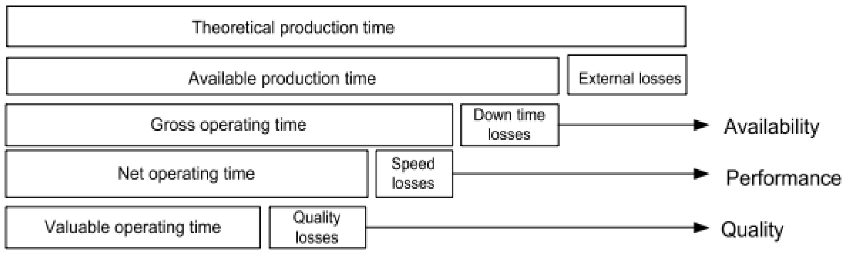

Figure 3.3 OEE effectiveness factors [67]

These factors are important for the total OEE estimation in the technological change analysis section. The performance factor is a critical metric for the used industrial equipment due to its flexibility in the quickly changing environment. Once the product or business flow changes, the narrowly oriented supportive machines or assets can drop out from the main flow. Hence, the performance value has to be considered as the crucial one during the OEE value calculation process.

The OEE top-level is 85%, which is indicated in the World Class OEE Report [68]. In the general scheme, according to overall world practice in manufacturing enterprises, the total OEE rate is 60%, shown in Table 3.2 [67].

Table 3.2 Top-level OEE and total OEE values from different types of industries

Industry	OEE top-level (%)	Total OEE (%)
Manufacturing	85	60
Process	>90	>68
Metallurgy	75	55
Paper	95	>70
Cement	>80	60

The main flowchart of the OEE estimation for used industrial equipment is visualized in Figure 3.4. It is easy to follow and represent it in simple Excel file. No specific software engineering skills are required.

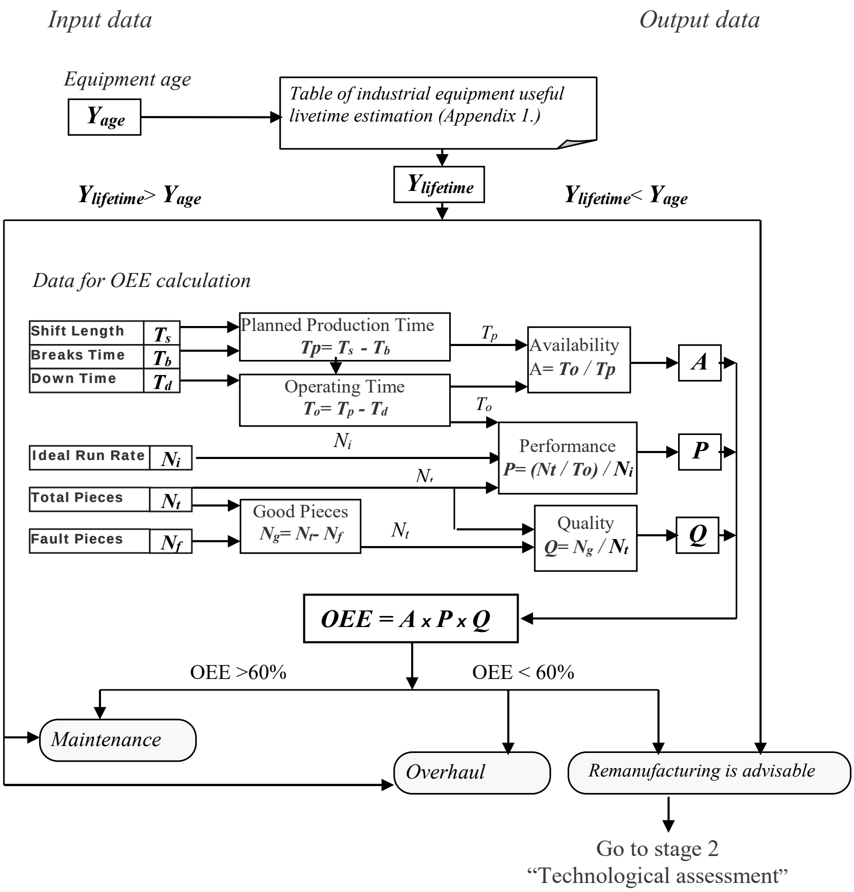

Figure 3.4 Algorithm of industrial equipment age and OEE estimation

Once the useful life age, *N*, and the OEE value are defined, and the object of the investigation is found, the Calculate part of the CAIS tool is finalized. There are two possible scenarios available by following the main scheme of the CAIS tool in Figure 3.2 Main decision-making framework for used industrial equipment LCA.

In the first scenario, the OEE is higher or equal to 60%, the object of study is operating as usual, waiting for the next round of the evaluation process. At the same time, if OEE is less than 60%, the used equipment will follow more precise research seen through the OEE main factors to narrow the scope of further analysis.

The second scenario can develop in two ways. If the Availability and Quality factors have low value, the object of study has to be forwarded to the exact repairing procedure, for instance, to the overhaul. The Performance criteria have an individual approach; thus, they can include various factors not necessarily associated with poor productivity. There is always a reason why the Performance is low or not good enough. As it was mentioned before that at times a SME is forced to change the line or product of the business model. Occasionally, narrowly oriented equipment can fall out from the business process, resulting in minimum effectiveness. It is required to find the cause and not to try to hide the bad Performance under trickery. The best part of CAIS is kept in the third part of the suggested approach, which is associated directly with creative solution finding even for scrapped and useless assets. TRIZ tools can give a certain idea and direction of further research. Naturally, it is a complicated process of the alternative purpose search for some specific tools or machines. Furthermore, all the solutions and ideas must be evaluated. This procedure must involve management members as the main driver towards successful decisions.

In the second scenario, all three values are under 60%. It means that the equipment needs more attention and the most important question here is if it is possible to remanufacture or not. It is the moment when the second part of the CAIS approach plays the main role to identify if the object of the study can be remanufactured or not.

3.2 Analyze: Remanufacturing advisability – stage 2

This stage of the CAIS approach is dedicated to the possible re-manufacturability of the object of research. As it was referenced previously, there are various ways to find out the main challenges and opportunities. This thesis analysis focused on the consideration of creative ideas during the end-of-life strategies selection towards GM development. The re-manufacturability is considered not only from the financial aspect, but also from the aspects of technological changes and environmental impact (see Fig. 3.5).

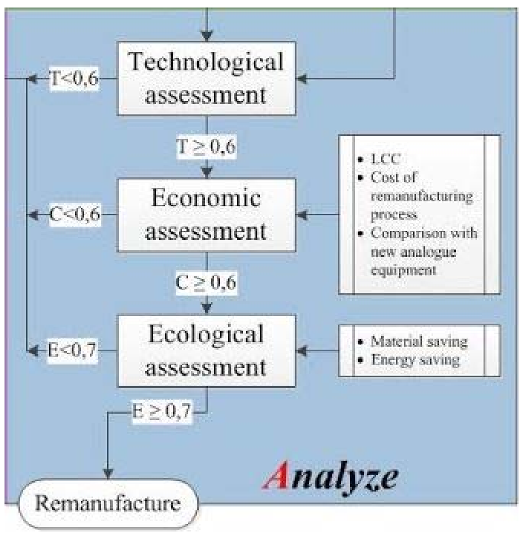

Figure 3.5 Flow chart of used machinery assessment with innovative integrated approach

There is one crucial factor that can influence the re-manufacturability opportunities. The used equipment can be exploited in very different ways, so the level of worn units and parts can be very different. Not every company can afford the service and maintenance on time and because of the business particularity, the working conditions lead to a shorter life cycle. Only this risk has to drive the investigative party to evaluate the used asset from all points of view.

The main algorithm of the “Analyze” part is based on the Chinese researchers’ remanufacturing process flow of used machine tools introduced in [36]. Because the used industrial equipment is a multi-core product, it is required to expand the Chinese researchers’ approach and add the TRIZ tools during the re-manufacturability assessment stage. It is usually worth considering the alternative before scrapping valuable multi-core used material by giving it another chance for the next life. As one of the possible outcomes, the object can be remanufactured and then the cycle is finished. In this case, the used equipment follows the conventional remanufacturing process. If it is not remanufacturable, the spent industrial equipment will be reviewed from the TRIZ perspective. Usually, there is an opportunity to extend the life cycle of the studied subject by applying one of the possible end-of-life strategies. Section 3.3 describes the options available here.

Technological assessment

As the first step of the “Analyze“ part, it is the most important and critical part from the costing point of view. The whole remanufacturing process must be reviewed according to Appendix 2. Usually, the remanufacturing procedure is made up of disassembly, cleaning, checking and sorting reconditioning, partially or wholly upgrading of parts or main bodies, and reassembly.

The algorithm for technological feasibility calculation is introduced in

Figure 3.6. to establish weights for the technological criteria, the Analytic Hierarchy Process (AHP) method in [39] and [40] is suitable, but other methods can also be used. However, it is an easier way. Since we have five parameters (ω_d, ω_c, ω_i, ω_r, ω_a.), by default parameters importance is uniformly divided and equal 1/5 = 0.2. Based on the assertion that the sum of all priorities is equal to 1, it is possible to change priorities for each parameter within this meaning.

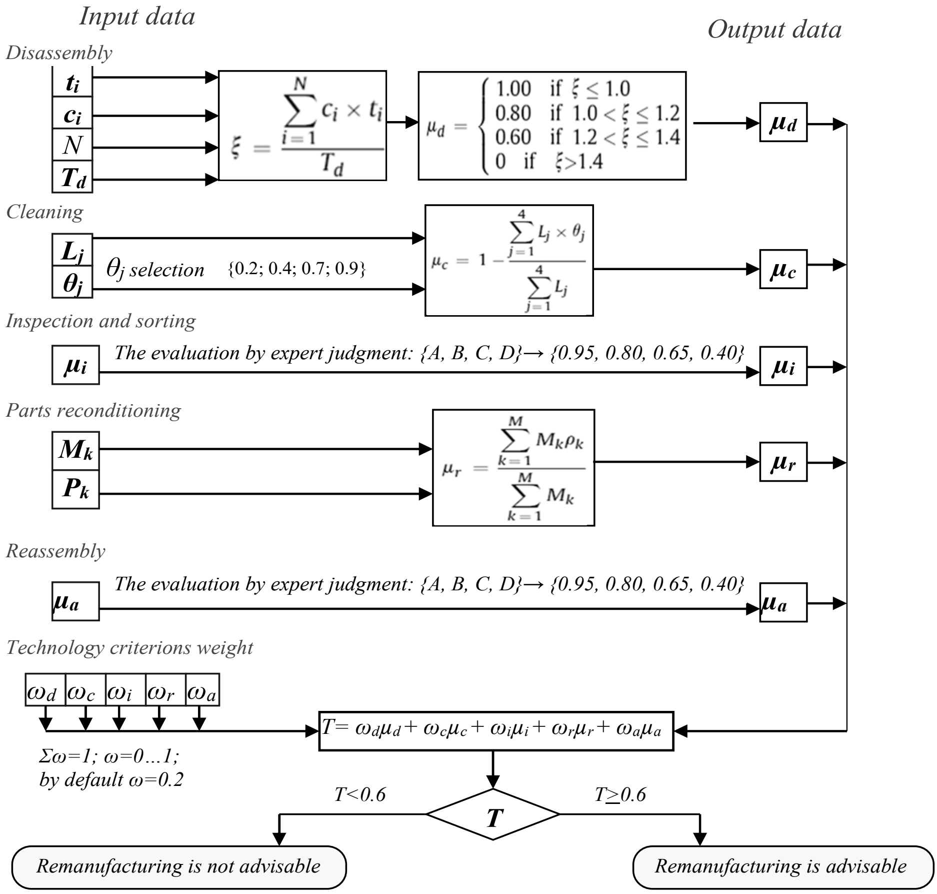

Figure 3.6 The algorithm of technological feasibility calculation

Economic assessment

This part of the "Analyze" stage focuses on the financial benefits of the possible remanufacturing process. It comes as the second step of the technological evaluation process. The industrial equipment units and parts are considered as very costly; therefore, it is critical to find the best solution during the assessment process. To start the analysis of the financial aspect, firstly, the LCC definition is addressed from the point of view of the Capital Cost, the Operating Cost and the Cost of Deferred or Delayed Production (C_1). Then the remanufacturing (C_2) cost plays a significant role in the Labour Cost calculation, and the Cost of newly acquired units and parts and the Cost of the possible real consumption perspective [36]. The overhead cost (C_3), such as paid taxes, management and marketing fees, and some other items are also considered, including all possible administrative costs to conduct the final price of the economic assessment process.

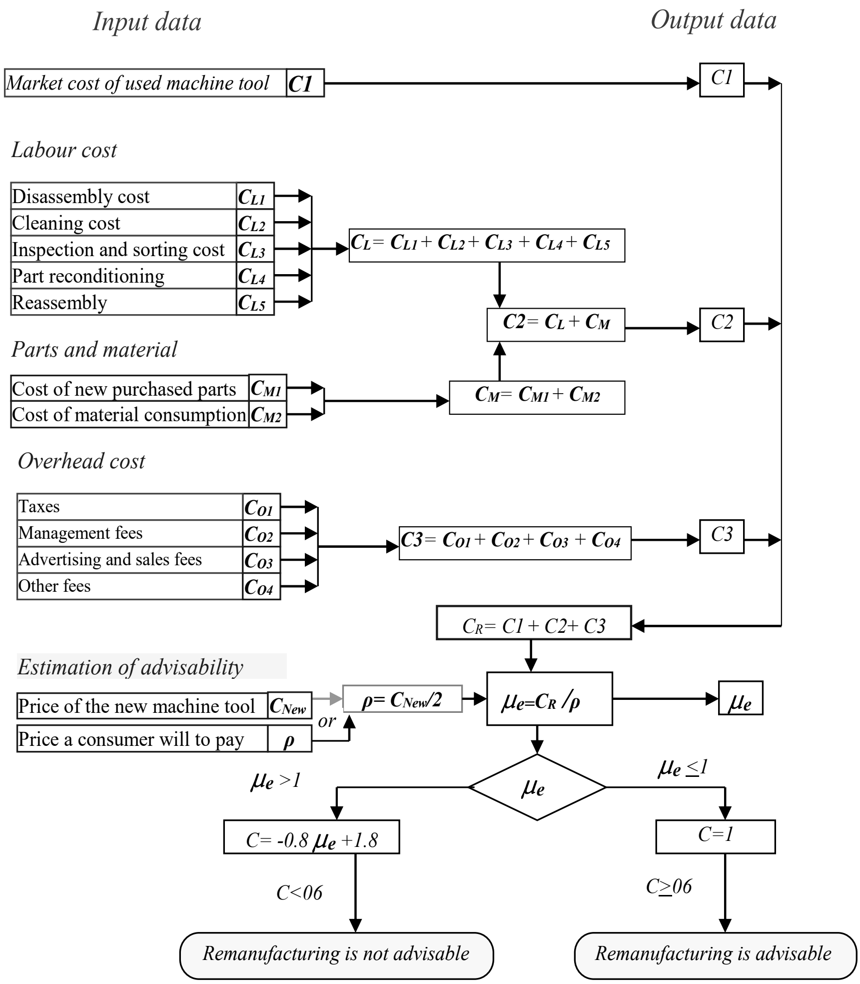

Figure 3.7 Algorithm of economic feasibility calculation

The algorithm of economic viability calculation is shown in Figure 3.7, where:

ρ - the market price of the remanufactured equipment (should be about 50% of the new one);

μ_e - the remanufactured equipment profitability;

C - economic index.

To specify a possible weight scheme for the re-manufacturability of the subject of study, the AHP method [39] and [40] can be employed.

The comparison procedure of the new analog equipment with the old one is separated into two steps:

- the first step is focused on the price estimation for the new and remanufactured (C_R) equipment;

- the second step concentrates on the risks evaluation. It is decided to use a very simple Heinz's calculation method to calculate the MTBF (the mean-time-between-failure) and the future fuel consumption as the other critical factor.

Heinz's main equation is expressed as follows [37]:

$$MTBF = \frac{1}{\left[\left(\frac{1}{L_1}\right)^2 + \left(\frac{1}{L_2}\right)^2 + \left(\frac{1}{L_3}\right)^2 + \left(\frac{1}{L_4}\right)^2\right]^{0.5}}, \qquad (3.1)$$

where L_N is the forecasted life frame of the unit under subject in years. It is crucial to mention that the units must be defined and their possible lifetimes have to be estimated. The major machinery components and units, such as engines, pumps, hydraulic units, gear mechanism, are considered here.

In the estimation process of possible prices of new and remanufactured equipment, the factor of the future fuel consumption has to be taken into consideration during this stage. Usually, it is required to review if the type of the engine is replaced after the remanufacturing process. To be more precise, here is a potential scenario associated with this example. To illustrate here, the remanufactured object used to operate with gasoline/petrol as the type of fuel and then it changed to CNG (compressed natural gas). It is easy to calculate the ROI by using an estimated price for the further 5, 10 or 15 years. There are different scenarios that can occur in this case: the hybrid engine instead of the diesel or the petrol version, semi-electric to fully electrical type. This thesis case study does not examine the evaluation of fuel consumption because the truck reviewed has a diesel engine and operates it further approximately in the same range.

Environmental benefits

Various tools can examine the environmental impact, covering different aspects. One option is to use the Life Cycle Assessment model to compare the environmental impact between used and remanufactured equipment regarding waste programs. Below, results of a valuable study are shown, where *B1−B3* represent the ultimate environmental burden for the four policies in Figure 3.8:

a. If the company operates the machinery throughout the time *N*, the environmental burden (*B*) increases and will result in *B1*.
b. If the company decides to change the first machine with a new one at the certain point of time *Ta* and start to operate the new equipment until *N*, the environmental burden (*B*) increases and will result in *B2*.
c. If the company decides to change the used equipment with the new one at the certain point of time at *Ta* and changes this other one again at this point of time *Tb*, the environmental burden (*B*) increases and will result in *B3*.

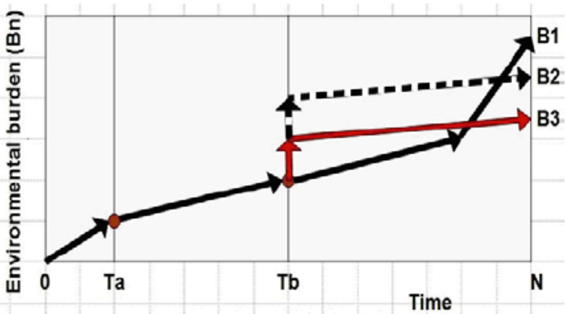

Figure 3.8 Schematic example of the LCA model to determine the influence of the environmental burden

The actual investigation reviews the upgrade of the object of study, not the possible replacement. Nevertheless, it is critical to mention that the burden of the manufacturing materials of the equipment is not taken into account in this specific mathematical model. The new criteria of the environmental burden of the modernization $B_V(i,k)$, are considered. The offered model has to pay more attention to the selection of potential end-of-life strategies from the environmental perspective. Cumulative environmental burden B can be expressed by equation (3.2) [32]:

$$B = B_E(i,k) + \sum_{k=1}^{j} (B_U(i,k) + B_R(i,k) + B_V(i,k) \quad (3.2)$$

where

$B_V(i,k)$ - environmental burden of the modernization of used equipment;
$B_U(i,k)$ - burden of the equipment use during years i, k and it service;
$B_R(i,k)$ - burden of the maintenance during years i, k;
$B_E(i,k)$ - burden of the end-of-life stage of equipment in year k.

Based on the Chinese researchers' approach used for the calculation of the environmental benefits [36], a calculation algorithm for ecological feasibility was elaborated to keep the simplicity and uniformity of the proposed tool.

The algorithm introduced in Fig. 3.9 contains the following:

M_r - total material saving;
μ_m - index of material saving;
μ_s - index of energy conservation;
ψ_e - energy saving index of equipment remanufacturing;
ψ_m - material reusing index of equipment remanufacturing.

Energy saving parameters may be taken from Inventory of Carbon & Energy (ICE) standard, Version 2.0 Sustainable Energy Research Team (SERT), and

Department of Mechanical Engineering University of Bath, UK. Excel File ICE V2.0.xlc is connected Use only Sheet "Summary table.“

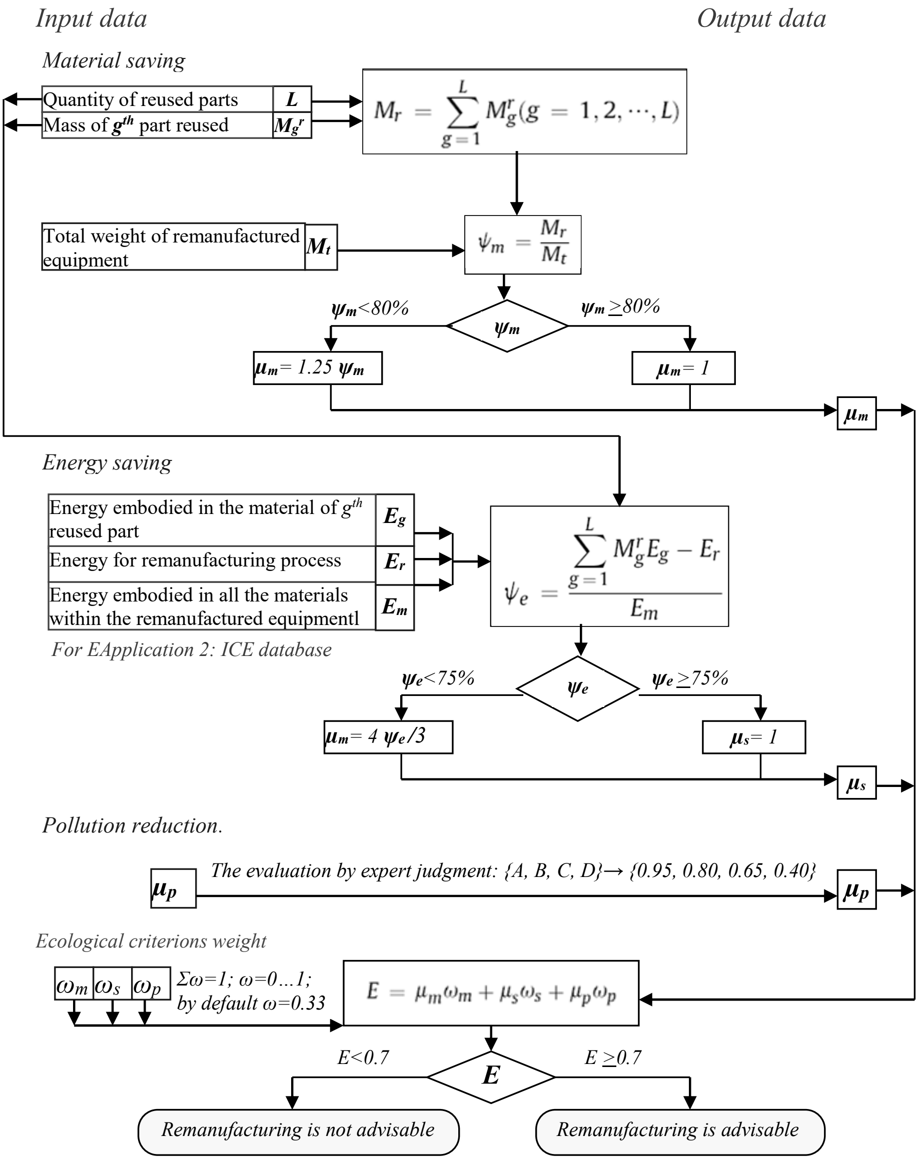

Figure 3.9 Algorithm of ecological feasibility calculation

Only after the implementation of the "Innovative" module, the bad cores with low re-manufacturability can be recycled. The old industrial equipment is usually a multi-core machine. Utilizing all the resources is important even if it is possible to do it partially.

All the flowcharts and parameters listed in the previous sections can be summarized in one database for further software or online web service development on IT level.

As it follows, the calculated data are marked with one asterisk * and selected data with two asterisks, like "**" in Fig. 3.10.

Figure 3.10 Framework of database architecture

3.3 Innovate: Innovative solution search – stage 3

When the "Analyze" part of the CAIS decision-making tool is performed, there are two options left. If the re-manufacturability indexes are all positive, the used equipment is worth of the next life cycle by implementing the remanufacturing end-of-life strategy. However, if one of the indexes is below the norm, there is still no decision what to do with it. The used equipment cores are expensive, and it is essential to be sure that the resource is utilized to the limit. There are no simple decisions, and it is evident that innovative solutions can provide unpredictably good results. Hence, an innovative module must be explored to find the best possible solution for the cores with low re-manufacturability. The TRIZ methodology with its tools is used to provide the decision out-of-the-box.

In the CAIS approach, the "Innovate" part is divided into two stages. The first stage is designed to find the best potential solution for the used equipment with low performance presented in section 3.1 partly and in the case studies reported in the author's publications more specifically. Normally, it is not an old product, but it has lost the needed performance and main duties in this specific manufacturing area. The second stage of the "Innovate" module analyzes the cores with low re-manufacturability.

The second stage of the TRIZ studies the cores and units that cannot be remanufactured after being evaluated from the technological, economic and ecological perspectives. There is always a possibility to implement another EOL scenario to utilize the core entirely. No studies in the literature explain how to use the TRIZ regarding the execution of various EOL approaches. It is important to investigate every case individually, but there are certain systematic ways to run the innovation. One of the ways proposed by MATRIZ Darell Mann is implemented in [45]. Another option is developed by MATRIZ Ellen Domb and H.William Dettmer in [70]. A general TRIZ problem-solving flow chart shows almost all TRIZ tools. Both analysis routines can be used to address innovative issues connected to the selection of the EOL strategy.

The second stage of TRIZ in the proposed decision-making tool is vital because it is responsible for the right EOL strategy choice or combination of different EOL scenario suggestions for this specific equipment. The case studies show the possible outputs.

3.4 Simulate: Comparison of different solutions – stage 4

This stage is complicated from the execution point of view. There are two directions in this juncture. The first and simplest way to give a rating to solutions found during "Innovate" stage is by using ROI metric. Today's world is based on cost and profit. If there is no positive ROI, it is pointless to invest money into that specific project.

Another option is to develop the "Simulate" part as the supportive tool for the "Innovate" stage for different EOL strategies combination, which is giving the most positive ROI after all. It will be possible only when sufficient primary data of different EOL implementation are analyzed and conducted under one project. It is evident that it involves substantial work that can be handled as separate research. Unfortunately, initial data about used industrial equipment in the win-win case studies are insufficient in the electronic view. The Green TRIZ Matrix was developed to provide one simple tool for decision-making by using the TRIZ Contradiction Matrix. The next section describes the matrix in more detail.

3.5 Green TRIZ Matrix elaboration

TRIZ Contradiction Matrix is a complex and powerful tool. The main aim of this thesis research is to turn voluminous toolkits into fast and usable ones. A difficult task was to find a relevant way for solving environmental contradictions. It is not easy to overcome psychological inertia with ecological problems. It was decided to connect TRIZ 40 Principles illustrated in Appendix 3 by GE principles presented in Appendix 4 to create the Green TRIZ Matrix. The idea came during the Lean&Green Waste Matrix development in the early stage of this research; it is shown in Figure 3.11.

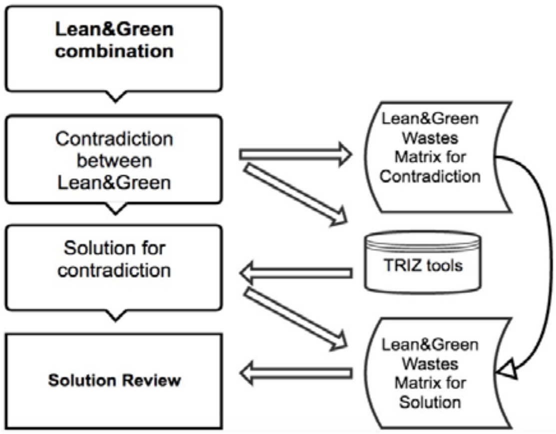

Figure 3.11 General scheme of the Lean&Green Waste Matrix

It is necessary to define the part of the Contradiction Matrix that can be used to investigate GM issues. The Original TRIZ Contradiction Matrix was designed to solve mostly technical (mechanical) contradictions [71]. However, the present tendency is to address environmental questions. Importantly, TRIZ is used to make engineers think out-of-the-box. The main problem was to connect it with GE principles that describe the whole GM concept. The goal matches GM direction perfectly. After some investigation, GE 12 principles were combined with TRIZ Principles, and with possible Lean tools if applicable, and the TRIZ Matrix was elaborated, as presented in Figure 3.12.

Improving \ Worsening	21: Power	22: Loss of energy	23: Loss of substance	24: Loss of Information	25: Loss of time	26: Quantity of substance	27: Reliability	28: Measurement accuracy	29: Manufacturing precision	30: Object-affected harmful	31: Object-generated harmful	32: Ease of manufacture	33: Ease of operation	34: Ease of repair	35: Adaptability or versatility	36: Device complexity	37: Difficulty of detecting	38: Extent of automation	39: Productivity
21: Power	X	10, 35,38	18, 27, 28, 38	10, 19	6, 10, 20, 35	4, 19, 34	19, 24, 26, 31	2, 15, 22	2, 32	2, 19, 22, 31	2, 35, 18	10, 26, 34	10, 26, 35	2, 10, 34, 35	17, 19, 34	19, 20, 30, 34	16, 19, 35	2, 17, 28	28, 34, 35
22: Loss of energy	3, 38	X	2, 27, 35, 37	10, 19	7, 10, 18, 32	7, 18, 25	10, 11, 35	32	-	2, 21, 22, 35	2, 21, 22, 35	-	1, 32, 35	2, 19	-	7, 23	3, 15, 23, 35	2	10, 28, 29, 35
23: Loss of substance	18, 27, 28, 38	2, 27, 31, 35	X	-	10, 15, 18, 35	3, 6, 10, 24	10, 29, 35, 39	16, 28, 31, 34	10, 24, 31, 35	22, 30, 33, 40	1, 10, 29, 34	15, 33, 34	2, 24, 28, 32	2, 27, 34, 35	2, 10, 15	10, 24, 28, 35	10, 13, 18, 35	10, 18, 35	10, 23, 28, 35
24: Loss of Information	10, 19	10, 19	-	X	24, 26, 28, 32	24, 28, 35	10, 23, 28	-	-	1, 10, 22	10, 21, 22	32	22, 27	-	-	-	33, 35	35	13, 15, 23
25: Loss of time	6, 10, 20, 35	5, 10, 18, 32	10, 18, 35, 39	24, 26, 28, 32	X	16, 18, 35, 38	4, 10, 30	24, 28, 32, 34	18, 24, 26, 28	18, 34, 35	18, 22, 35, 39	4, 28, 34, 35	4, 10, 28, 34	1, 10, 32	28, 35	6, 29	10, 18, 28, 32	24, 28, 30, 35	-
26: Quantity of substance/the	35	7, 18, 25	3, 6, 10, 24	24, 28, 35	16, 18, 35, 38	X	3, 18, 28, 40	2, 13, 28	30, 33	29, 31, 33, 35	3, 35, 39, 40	1, 27, 29, 35	10, 25, 29, 35	2, 10, 25, 32	3, 15, 29	3, 10, 13, 27	3, 18, 27, 29	8, 35	3, 13, 27, 29
27: Reliability	11, 21, 26, 31	10, 11, 35	10, 29, 35, 39	10, 28	4, 10, 30	3, 21, 28, 40	X	3, 11, 23, 32	1, 11, 32	2, 27, 35, 40	2, 26, 35, 40	-	17, 27, 40	1, 11	8, 13, 24, 35	1, 13, 35	27, 28, 40	11, 13, 27	1, 29, 35, 38
28: Measurement accuracy	3, 6, 32	26, 27, 32	10, 16, 28, 31	-	24, 28, 32, 34	2, 6, 32	1, 5, 11, 23	X	-	22, 24, 26, 28	3, 10, 33, 39	6, 18, 25, 35	1, 13, 17, 34	1, 11, 13, 32	2, 13, 35	10, 27, 34, 35	24, 26, 28, 32	2, 10, 28, 34	10, 28, 32, 34
29: Manufacturing precision	2, 32	2, 13, 32	10, 24, 31, 35	-	18, 26, 28, 32	30, 32	1, 11, 32	-	X	10, 26, 28, 36	4, 17, 26, 34	-	1, 23, 32, 35	10, 25	-	2, 18, 26	-	18, 23, 26, 28	10, 18, 32, 39
30: Object-affected harmful	2, 19, 22, 31	2, 21, 22, 35	19, 22, 33, 40	2, 10, 22	18, 34, 35	29, 31, 33, 35	2, 24, 27, 40	23, 26, 28, 33	10, 18, 26, 28	X	-	2, 24, 35	2, 25, 28, 39	2, 10, 35	11, 22, 31, 35	19, 22, 29, 40	19, 22, 29, 40	3, 33, 34	13, 22, 24, 35
31: Object-generated harmful	2, 18, 35	2, 21, 22, 35	1, 10, 34	10, 21, 29	1, 22	1, 3, 24, 39	2, 24, 39, 40	3, 26, 33	4, 17, 26, 34	-	X	-	-	-	-	1, 19, 31	1, 2, 21, 27	2	18, 22, 35, 39
32: Ease of manufacture	1, 12, 24, 27	19, 35	15, 33, 34	16, 18, 24, 32	4, 28, 34, 35	1, 23, 24, 35	-	1, 12, 18, 35	-	2, 24	-	X	2, 5, 13, 16	1, 9, 11, 35	2, 13, 15	1, 26, 27	1, 6, 11, 28	1, 8, 28	1, 10, 28, 35
33: Ease of operation	2, 10, 34, 35	2, 13, 19	2, 24, 28, 32	4, 10, 22, 27	4, 10, 28, 34	12, 35	8, 17, 27, 40	2, 13, 25, 34	1, 23, 32, 35	2, 25, 28, 39	-	2, 5, 12	X	1, 12, 26, 32	1, 15, 16, 34	12, 17, 26, 32	-	1, 3, 12, 34	1, 15, 28
34: Ease of repair	2, 10, 15, 32	1, 15, 19, 32	2, 27, 34, 35	-	1, 10, 25, 32	2, 10, 25, 28	1, 10, 11, 16	2, 10, 13	10, 25	2, 10, 16, 35	-	1, 10, 11, 35	1, 12, 15, 26	X	1, 4, 7, 16	1, 11, 13, 35	-	7, 13, 34, 35	1, 10, 32
35: Adaptability or versatility	1, 19, 29	1, 15, 18	2, 10, 13, 15	-	28, 35	3, 15, 35	8, 13, 24, 35	1, 5, 10, 35	-	11, 31, 32, 35	-	1, 13, 31	1, 15, 16, 34	1, 4, 7, 16	X	15, 28, 29, 37	1	27, 34, 35	6, 28, 35, 37
36: Device complexity	19, 20, 30, 34	2, 10, 13, 35	10, 28, 29, 35	-	6, 29	3, 10, 13, 27	1, 13, 35	2, 10, 26, 34	24, 26, 32	19, 22, 29, 40	1, 19	1, 13, 26, 27	9, 24, 26, 27	1, 13	15, 28, 29, 37	X	10, 15, 28, 37	1, 15, 24	12, 17, 28
37: Difficulty of detecting	1, 10, 16, 18	3, 15, 19, 35	1, 10, 18, 24	22, 27, 33, 35	9, 18, 28, 32	3, 18, 27, 29	8, 27, 28, 40	24, 26, 28, 32	-	19, 22, 28, 29	2, 21	5, 11, 28, 29	2, 5	12, 26	1, 15	10, 15, 28, 37	X	21, 34	18, 35
38: Extent of automation	2, 27, 28	23, 28	5, 10, 18, 35	33, 35	24, 28, 30, 35	13, 35	11, 27, 32	10, 26, 28, 34	18, 23, 26, 28	2, 33	2	1, 13, 26	1, 3, 12, 34	1, 13, 35	1, 4, 27, 35	10, 15, 24	25, 27, 34	X	5, 12, 26, 35
39: Productivity	10, 20, 35	10, 28, 29, 35	10, 23, 28, 35	13, 15, 23	-	35, 38	1, 10, 35, 38	1, 10, 28, 34	1, 10, 18, 32	13, 22, 24, 35	18, 22, 35, 39	2, 24, 28, 35	1, 7, 10, 28	1, 10, 25, 32	1, 28, 35, 37	12, 17, 24, 28	2, 18, 27, 35	5, 12, 26, 35	X

Figure 3.12 TRIZ Matrix for Green Manufacturing

Table 3.3 below provides a better understanding of how GE 12 principles connect Green Matrix and EOL strategies.

Table 3.3 Combination of Green Matrix, Green Engineering Principles and EOL strategies in one table

GE principles	TRIZ solutions with possible Lean tools and examples	EOL strategy & Lean tools
Principle 1 - Inherent rather than circumstantial	**20. Continuity of useful action**	EOL: reduce, reuse, resale Lean: SMED
	Ensure the work is in-progress without significant pauses, all the time and at full capacity [72]. SMED (Single-Minute Exchange of Dies) can be used to reduce the changeover time during the process.	
	21. Skipping	EOL: reduce, reuse, resale Lean: SMED
	All possible harmful or hazardous operations have to be conducted as fast as possible. Do not be afraid of trying new approaches. For example, take out more parts if there is no direct need for them and replace with combined units. Next time it will be easier to repair or maintain the machine.	
	22. "Turn Lemons into Lemonade."	EOL: refurbishing, recondition, cannibalization, remanufacturing Lean: 5S, 8 Wastes, Work Balancing
	Use negative input to achieve a positive feedback. The lean 5S technique can be implemented here. At first, there are certain non-value adding activities (negative input), and then by its elimination, the process takes less time and has a positive output.	
	Another good example is the motivation of the employees to detect the potential defects by increasing the attention due to improved salary conditions [73].	
	38. Strong oxidants (can be liquids, gasses)	EOL: refurbishing, recondition, cannibalization, remanufacturing
	Replace diesel engine with LPG (liquid petroleum gas).	
	Replace fuel engine with CNG (compressed natural gas).	
Principle 2 - Prevention instead of treatment	**9. Preliminary anti-action**	EOL: refurbishing, recondition, cannibalization Lean: Kaizen event
	Arrange the certain stresses beforehand to make the afterward working processes simpler or even stress-free. For example, train people hard to make their real job tasks much easier.	
	Pre-stressed small parts like bolts, nuts.	

Table 3.3 continuation

GE principles	TRIZ solutions with possible Lean tools and examples	EOL strategy & Lean tools
Principle 2 - Prevention instead of treatment	**10. Preliminary action**	EOL: refurbishing, recondition, cannibalization
	Process before it is needed. For example, prepare all the tools before starting the possible EOL process.	
	Pre-arrange objects in such way that they can come into action from the most convenient place and without losing time for their delivery. It is an excellent opportunity for a Lean tool such as 5S.	Lean: 5S, Workplace organization
	11. Beforehand cushioning	EOL: refurbishing, recondition, cannibalization
	All possible known solutions to backup the system from collapsing should be considered. For instance, the touchdown ball-bearing system designed to back the mechanical one for high-speed rotary machines.	
	24. 'Intermediary'	EOL: refurbishing, recondition, cannibalization
	Use a transitional object to improve the output of the process. As a possible example, the catalysts implementation for CO_2 index improvement for diesel engines.	
	Combine two or more spare parts or units to simplify further repair or reuse processes.	
Principle 3 - Design for Separation	**1. Segmentation**	EOL: cannibalization, remanufacturing
	Divide an object or part into free ones [72].	
	For example, increase the level of illumination only in the critical areas not in the whole shop floor [73].	
	2. Extraction	EOL: refurbishing, recondition
	Take out the disturbing part from the machine and use it separately from the main machine body.	
Principle 4 - Maximize efficiency - Maximize mass, energy, space, and time efficiency	**3. Local quality**	EOL: repair
	Change the operators' working environment by redesigning the clothes and shoes and reviewing the working time slots to reduce the fatigue [73].	
	First, make all the workplaces function perfectly only then consider the whole line and then factory	
	4. Asymmetry	EOL: repair, refurbishing, recondition, cannibalization,
	Make the parts, units or cores asymmetrical instead of symmetrical.	
	If a unit or part is already asymmetrical, increase its degree of asymmetry.	

Table 3.3 continuation

Principle 4 continuation	**5. Merging**	EOL: repair, refurbishing, recondition, cannibalization. Lean: SMED, Takt time
	Unite the same or equal units or parts, and try making identical parts perform parallel operations.	
	Replace the operations with alternative or similar ones; bring them together in time.	
	13. Inversion	EOL: repair, refurbishing, recondition, cannibalization
	Transpose the steps used. For example, instead of increasing the speed of the object, try to slow it down.	
	For example, try to change the sequence of actions performed to solve the issue.	
	Turn the process “upside down.”	
	Create the process map of AS-IS situation, then analyze all the steps from the other interested party point of view and try to find possible ways to improve the potential TO-BE model just by looking at the process from both sides.	Lean tools: Process mapping
	15. Dynamization	EOL: repair, refurbishing, recondition, cannibalization
	Allow a process to change to be optimal or find a different working environment. Instead of using static working tables and letting employees sit the whole day, just give them the opportunity to stand at their desk by implementing manual lifting mechanism.	
	For example, the smart nuts design change by using a different material to avoid the self-disassemble when the temperature gets above the glass transition one [74].	Lean tools: 8 Wastes Workplace standardization
	Adapt the continuous procedure of employees’ development to reduce the potential Waste of Intellect by just challenging workers with the new projects and tasks out of their usual scope of the job. Possible “Do Good” projects.	
	17. Another dimension	EOL: repair, refurbishing, recondition, cannibalization
	Move an object in different level dimensional space, for example 3D, 4D, 5D movies.	
	Use a multi-story arrangement of objects instead of a single-story agreement.	
	Use an inside side of the outside area and vice versa.	
	18. Mechanical vibration	EOL:repair, refurbishing, recondition, cannibalization
	Increase the number of meals per day by decreasing the portion itself to minimize the burden to digesting system.	

Table 3.3 continuation

GE principles	TRIZ solutions with possible Lean tools and examples	EOL strategy & Lean tools
Principle 4 continuation	Use mobile phone vibration option instead of loud sound to minimize the level of noise in open office space.	
	Make the public transportation free of charge for the local people to decrease the degree of pollution and amount of cars in the city.	
	27. Cheap short-living objects	EOL: reuse Lean tools: Poka-Yoke
	Replace the employees with the permanent agreement with the rented ones for short-term projects to avoid additional costs once the project is finished and no resource is needed anymore.	
	29. Pneumatics and hydraulics	EOL: refurbishing, recondition, cannibalization
	Use virtual environments to manage the team globally all over the world. For example, instead of inviting the company representative technician ask him to guide through the video call.	
	32. Color changes	EOL: repair, refurbishing, recondition, cannibalization
	Use specific chemical indicators to detect the potential defects where it is critical to quality [73].	
	35. Parameter changes	EOL: repair, refurbishing, recondition, cannibalization Lean tools: Kanban
	Play around with an object's or product's orders by decreasing or increasing the quantity to meet the today's demand and free up the needed space.	
	Once the remanufactured equipment is ready for exploitation, put it under all possible tests by applying multiple parameters at a time.	
	36. Phase transitions	EOL: repair, refurbishing, recondition, cannibalization Lean tools: Visualization
	Closely follow-up all the end-of-life projects by creating the memos between the project phases to have a better understanding in the future cases [72].	
	Switching from one fuel engine or another one. It is crucial to closely monitor the changes in other units of the machine or equipment.	
	37. Thermal expansion	EOL: repair, refurbishing, recondition, cannibalization
	Give employees the opportunity to take a day off whatever time they need without tracking this activity.	
	Set straightforward KPIs, so the organization can expand and meet the goals.	
	39. Inert atmosphere	EOL: repair, refurbishing, recondition, cannibalization
	Give the opportunity to work from home if it is possible.	

Table 3.3 continuation

GE principles	TRIZ solutions with possible Lean tools and examples	EOL strategy & Lean tools
Principle 5 - Output-Pulled versus Input-Pushed	**12. Equipotentiality**	EOL: repair, refurbishing, recondition, cannibalization Lean: One-piece flow assembly line
	In a potential field, limit position changes (e.g. change operating conditions to eliminate the need to raise or lower objects in a gravity field) [72].	
	For example, deliver the pre-assembled units to the line by skipping this action during the main assembly process	
Principle 6 - Conserve complexity	**7. Nested doll**	EOL: repair, refurbishing, recondition, cannibalization
	Create certain environments for specific actions on the same shop floor. For example, make different environments for various versions of the tool that will be used for separate projects but in one machine.	
	8. Anti-weight	EOL: repair, refurbishing, recondition, cannibalization
	Involve the customer as much as possible into the process to compensate all possible unpredictable situations once the product is delivered.	
	Continuously ask for the feedback.	
Principle 7 - Durability rather than Immortality	**25. Self-service**	EOL: recondition, cannibalization
	The unit has to become independent of maintenance; it has to serve itself. For example, self-lubricating bearings.	
	Let the engineer work directly with the customer to simplify the information flow.	
Principle 8 - Meet need, minimize excess	**6. Universality**	EOL: recondition, cannibalization
	Organize the cross-functional training to make all possible positions replaceable by each other.	
	16. Partial or excessive actions	EOL: repair, refurbishing, recondition, cannibalization, remanufacturing
	Always do a little bit more to meet and amplify the customer's expectations.	
	19. Periodic action	EOL: reduce, reuse Lean: Heijunka, Kanban
	If an action is already periodic, change the periodic magnitude or frequency [72].	
	Use pauses between impulses to perform a different action [72].	
Principle 9 - Minimize material diversity	**31. Porous materials**	EOL: recondition, cannibalization
	Make the small teams work on projects and immediately split if they get too big to simplify the communication and deliver results faster by concentrating on one task/project at a time.	

Table 3.3 continuation

GE principles	TRIZ solutions with possible Lean tools and examples	EOL strategy & Lean tools
	33. Homogeneity	EOL: recondition, cannibalization Lean tools: Standardization Poka-Yoke
	Know your team's psychological features and combine them by implementing this knowledge.	
	Implement techniques or tools to manufacture all the time the same way to deliver excellent quality.	
Principle 10 - Integrate material and energy flows	**23. Feedback**	EOL: recondition, cannibalization
	Use the machine monitoring software to have the continuous feedback from the machine itself: number of produced pieces, OEE. For example, the dashboard of the car signals when it is time to go to service.	
	28. Mechanics substitution	EOL: refurbishing, recondition, cannibalization
	Instead of fighting the fires all the time, the customers provide their long-term forecast with minimum and maximum stocks of high runners, so it will be easier to keep the needed quantities in stock all the time and not overproduce.	
	Change the manual loading-unloading operations into the automatic ones [73].	Lean tools: JIT Min-max stock
Principle 11 - Design for commercial "Afterlife."	**34. Discarding and recovering**	EOL: recycle, recondition
	All the employees have to take at least two weeks in a row vacation time to avoid possible burn out.	
	The best example of end-of-life strategy - reconditioning.	
	40. Composite materials	EOL: recycle, recondition
	If there is no chance to remanufacture, it is always possible to consider the recycle or cannibalization of potentially useful units.	
	Consider having a technician with the various skill set. If the employees are good in technical questions, also make them learn best practices talking to the customers and be partly sales people.	
Principle 12 - Renewable rather than depleting	**26. Copying**	EOL: recycle
	Try to simulate all critical decisions by using mock-ups or simulators. Never change anything without reasonable check.	
	Virtual reality is possible without smartphones.	
	Consume own products instead of buying ones.	

3.6 Case study – Used lorry

Product life-prolonging activity does not only increase the useful life of the product but also in pair with product upgrading can result in entirely new purpose equipment. By remanufacturing an existing product, a business can save resources, money and time. This final case study is made to show an example of how to apply the proposed decision-making framework efficiently to an EOL approach together with the upgrading of used industrial equipment. The result of this project is a manufactured special purpose truck-based mixing plant.

"Calculate"

The object of study is a used lorry truck with a grab crane and high mileage. The truck had the following technical specifications:

- Weight – 26 t;
- Manufacturer – IVECO;
- Year of manufacturing – 2001;
- Condition – content;
- Estimated value – 23,800.00 EUR;
- Comment – the lorry was used to load and transport free-flowing soil.

The useful lifetime of such machines is eight years. This information is taken from Appendix 3. The current state of the OEE was less than 60%. The truck was in the working condition, but last year the OEE dropped to 56%. It was necessary to handle the query for re-manufacturability by using the second stage of the proposed tool "Analyze."

"Analyze"

It is important to mention that during this estimation mixer blades were not considered even though they are the fastest wearing out parts. They are replaced according to specific requirements, taking into account how frequently a mixer is used and what sort of soil or rubble is mixed. Also, it is obligatory to investigate the used product from all points of view. The main results are presented in Table 3.4.

The estimated lifetime for the IVECO lorry with minor repairs is N_1 = 5 years. An estimated lifetime for EB50 also with minor repairs, appropriate care, and the full working load is N_2 = 10 years. An estimated lifetime before failure for electric motors used in this mixing plant is considered N_3 = 4 years. A summary MTBF will be three years. Thus, it is crucial to supply a customer with appropriate technical help and maintenance to avoid previous failures happening.

Table 3.4 Experimental results of the used lorry case study with flowcharts

Criteria	Index	μ, feasibility		ω, weight	
Technological assessment	Ease of disassembly	μ_d	0.6	ω_d	0.27
	Feasibility of cleaning	μ_c	0.55	ω_c	0.05
	Feasibility of inspection and sorting	μ_i	0.8	ω_i	0.05
	Feasibility of part reconditioning	μ_r	0.5	ω_r	0.27
	Feasibility of machine upgrading	μ_u	0.8	ω_u	0.27
	Ease of reassembly	μ_a	0.7	ω_a	0.11
	Total technological assessment *T* = *0.6445*				
Economic assessment	Life Cycle Cost (LCC)	C_1	23 800€		
	Cost of remanufacturing process	C_2	5 000€		
	Overhead cost of machine tool remanufacturing	C_3	8 980€		
	Total cost of equipment remanufacturing C_R	μ_e	0.4		
	Comparison with new analog equipment	*Price*	33980€ versus 88900€	Less than 50%	
	Useful lifetime forecast	*MTBF*	3 years	Warranty is 2 years	
	Total economic assessment *C* = *1*				
Environmental assessment	Material saving	μ_m	1	ω_m	0.5
	Energy saving	μ_s	1	ω_s	0.3
	Pollution reduction	μ_p	0.95	ω_p	0.3
	Total environmental assessment *E* = *1*				

"Innovate" and "Simulate"

Evidently, the lorry can be remanufactured to "like-new" condition. The only risk is connected to the technological assessment part. The coefficient is too near to the limit. The general purpose of the used lorry was to transport materials from one point to another. The mileage is high, and it is good to check the other opportunities this lorry can have. All the characteristics are excellent; just the technological indicator is critical regarding regular lorry life cycle. It is the opportunity for the engineers to develop new non-standard options by using TRIZ tools in the "Innovate" part. It is important to consider all possible resources the lorry has to offer in case of some new interesting challenges.

This time, the systematized TRIZ module was chosen to define the problem, then to select the correct TRIZ tool in order to solve the defined problem and to evaluate it.

A. Define

The lorry has high mileage, meaning that it has spent almost ¾ of its resource as a truck. The ideal final result for this lorry is not to travel, but the condition is still too safe for disposal. The re-manufacturability analysis has proved that this lorry can be remanufactured from every aspect.

B. Select

Several tools can be used in the current case study. The selection is concentrated on the Green Matrix and resources.

C. Solve

The following contradiction has taken place: the lorry cannot travel, but the productivity must be high. According to the Green Matrix, this means that there is a need to improve versatility without worsening productivity.

Improving 35: Adaptability or versatility without damaging 39: Productivity

Solutions can be as follows:

35. Parameter changes
28. Mechanics substitution
6. Universality
37. Thermal expansion

More precise explanation of all options is given in the complete table in Appendix 4.

D. Evaluate

Principle 6 was chosen. Thus, the used IVECO truck with a grab crane can be modified into a truck-based mixing plant. The best solution for the current specific problem is the construction of the mixing unit by this lorry truck by manufacturing the special purpose platform on the chassis of the truck. The used truck will not travel much and will also be extremely productive.

3.7 Conclusions of Chapter 3

This chapter presented the experimental results of the proposed systematic approach. A tool for the innovation-oriented decision-making mechanism was developed to show how daily used tools can be integrated into one environment. CAIS is the routine tool with different sections that can be used in one cycle or separately. It is always complicated to make the right quick decision about EOL scenario choice without having proper analysis and initial data. Therefore, this work is targeted to the development of the decision-making tool based on Lean and GM principles and consideration of the most favorable EOL scenario.

In the structured decision-making framework for assessing the condition of the equipment, much attention is paid to the remanufacturing process. It is critical that the total quantity of labor, energy, heating and materials spent during the manufacturing of the used equipment should be significantly smaller than that of the new equipment. That is mainly because of reusing existing components and units and having experience in building similar equipment. The cost savings from applying this project are significant. It is estimated that to produce almost the same equipment, 2.6 times less money would be spent in the case of remanufacturing from the perspective of production costs.

The TRIZ methodology appears most promising for overcoming the psychological inertia during different decision-making procedures. It helps a user regarding to technical and psychological aspects. It is a systematic approach based on certain results and historical facts.

The combination of Lean fundamentals with TRIZ tools and GE principles resulted in the new Lean&Green Waste Matrix for several solution evaluations and the Green Matrix for solving environmental contradictions.

4 CONCLUSIONS

The goal of this work was to find ways for minimizing the impact on the environment by reduction of the number of old pieces using the untraditional TRIZ theory in the correct EOL strategy search. Development of the cyclic tool for systematic analysis of the highest utilization of various used industrial products owned by SME companies at the end of its life helps to solve the issue. The proposed CAIS approach is compared with the existing well-known techniques. The main idea was to generate a narrow-targeted solution for SMEs to keep their resources under yearly, monthly or even daily control.

The new innovation-oriented systematic approach CAIS for the life cycle extension and monitoring of the used industrial equipment is based on the assumption that resource conservation is a major direction of GM development, which is directed by laws for environment protection all over the world and principles of GE through innovation-oriented TRIZ. The target was to develop the decision-making process for the proposed CAIS tool and guidelines towards the maximum utilization of existing industrial equipment resources in the EOL stage.

In the framework of the doctoral thesis, the following results were achieved:

1. The traditional approaches to forecasting the EOL scenario for spent industrial equipment like an LCA tool are implemented in Section 3.2. Likewise, different RL concepts are considered for prolonging used products life cycle. The results are presented in the author's papers and in Section 3.6. The remanufacturing strategy is the most promising end-of-strategy today and must be a part of assessing the decision-making tool from the GM perspective. Different ready-to-use GM toolkits are explored and considered as possible candidates for daily use in SMEs for the evaluation and extension of the special state of the existing industrial equipment. All these tools are significant and have clear core inside; in fact, almost all of them are too complicated or too voluminous for integration into daily life in SMEs.

2. TRIZ philosophy was used as an accurate brainstorming toolkit for innovative solutions and options development to systematize and improve the decision-making process in this research. The Green Matrix from the general TRIZ Contradiction Matrix was elaborated to resolve environmental conflicts by using GE principles. The innovation part was solved by using various TRIZ tools regarding the implementation perspective of the GM projects. The Green Matrix can be utilized in the context of the general decision-making process as is proposed in this thesis and also as the free tool to resolve environmental contradictions.

3. The developed tool CAIS makes environmental friendly thinking more easy to approach by extending the used equipment life cycle prolonging based on GM principles. The mixed method for assessing the re-manufacturability of spent assets from technology, economy and ecology perspective was applied and improved.

It is important to mention that the CAIS tool consists of four independent modules and it is a significant achievement of this thesis research. Another strong side of the developed decision-making tool is the ability to operate with standard and innovative options through the system.

4. The experimental results are distinguished by analyzing the possibility to remanufacture the used lorry with high mileage and the implementation of non-standard solutions for large quantities of old machinery. As a result, the decision-making tool can be used for the assessment of standard and non-standard used equipment and EOL scenario choice.

Novelty of research

Scientific Novelty

- The decision-making GM tool was developed to evaluate the current state of the used industrial equipment, and the most suitable EOL strategy is proposed.
    - Lean technique implementation for current technical state analysis of used industrial products.
    - Adaptation of the re-manufacturability module by improving the economic assessment part with the Heinz calculation module and risk analysis.
    - Independent Green Matrix derivation from the general TRIZ Contradiction Matrix to resolve environmental contradictions by using GE 12 principles. The Green Matrix can be utilized under the CAIS approach and also as the free tool to address environmental issues.
- The new innovation-oriented approach CAIS is proposed for SME industrial equipment controllability and utilization on a daily, monthly or yearly basis.
- Used Waste Matrix was derived as an evaluation tool of Lean and GM techniques integration into each other.
- TRIZ was implemented for the extension of used industrial products life cycle.

Practical Importance

- A well-ordered evaluation process was developed for the state analysis of the used industrial equipment based on a yearly assessment procedure through the CAIS regular cycle.
- The proposed decision-making green tool on the machinery faults analysis was investigated experimentally and an innovative solution to prolong its useful life cycle was developed.
- Design guidelines for the proposed CAIS innovation-oriented approach for “Calculate,“ “Analyze,“ and “Innovate“ stages were developed. The flowcharts were created for future software development and described.

Future work

The future work would be concentrated on the ”Simulate” part development. It is not easy to build the code to compare the innovative solutions found by combining various EOL strategies. At the moment, initial data analyzed are insufficient to create valuable and trustful software. The acquired knowledge and experience could be used in the field of industrial equipment to evaluate the current situation. The idea is to realize the entire concept of the decision-making process of the used industrial equipment in the software mode. There are certain software programs in this field like Creax Innovations, but they do not offer a sophisticated solution that is so important for an SME with a lack of resources and time. Approval of the hypotheses formulated in the beginning and other results of the research could be articulated in the following form:

1. The proposed GM tool for decision-making improves SMEs ability to take control over their resources and stay in tune to the minimization of the environmental impact. This approach reduces the material consumption through the entire PLC.
2. The integration of the decision-making module with the TRIZ concept inside encourages engineers to improve their personal knowledge in different research areas and also create new jobs in the manufacturing sector.
3. In general, the idea of GM projects implementation has to influence the overall direction for sustainable production and help to save finite natural resources through increasing the life cycle of the spent industrial equipment.

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LIST OF AUTHOR'S PUBLICATION

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ABSTRACT

Decision-Making Tool Development for Used Industrial Equipment Life Cycle Evaluation and Improvement

Decision-making is a major challenge in the industry. Therefore, this thesis research is focused on the decision-making framework development with Lean and GM tools and EOL scenario consideration.

A precise mechanism was developed for used industrial equipment life cycle extension to save money, nature, and society. The proposed decision tool encourages businesses to raise their benefits by including a creative approach of utilizing the TRIZ complex, which would enable more general and straightforward implementation of the widest variety of used industrial items. To achieve this aim, the Green Matrix was elaborated from the TRIZ Contradiction Matrix and 12 GE principles.

Much attention was paid to the remanufacturing procedure in the decision-making tool to consider the condition of equipment. An integrated method for evaluating the re-manufacturability of the used industrial equipment is proposed, in which the technological, economic and ecological assessment of spent industrial products is analyzed regarding remanufacturing.

Advancement of a conventional decision tool for the evaluation of utilized industrial items enhances organization stock controllability and usage that thus limits natural effect and asset utilization amid the whole cycle.

KOKKUVÕTE

Otsustustehnoloogia arendamine kasutatud tööstusseadmete elutsükli hindamiseks ja parendamiseks

Rohelise tootmise põhimõtete arendus on tänapäeval mikro-, väike- ja keskmise suurusega ettevõtetes Euroopas ja mujal maailmas väga aktuaalne teema. Erinevad Euroopa Liidu direktiivid ja uued keskkonnanormid suunavad tootmisettevõtteid rohelisemalt mõtlema ja arendama oma rohelist lähenemist. Rohetootmine pole ainult üleminek taastuvenergiale, vaid ka oma ressursside juhtimine. Paljud masinatööstuse ettevõtted on avastanus, et oma ressursside pidev kontroll ja taastamine annab võimaluse maksimaalselt ja optimaalselt seda ära kasutada ja vähendada keskkonnamõju taaskasutamisel olemasolevaid ressursse. Väga oluline on leida õige moment olemasolevate vahendite väljavahetamiseks, esimeseks taastamiseks, järgmiseks taastamiseks, hoolduseks ja müümiseks. Otsustuse tegemine on alati problemaatiline aspekt igas ettevõttes, kuna juhtkonna liikmed kuigi ka tavalised töölised ja spetsialistid kipuvad otsuseid edasi lükkama.

Käesolev doktoritöö "Otsustamise tehnoloogia arendamine kasutatud tööstusseadmete elutsükli hindamiseks ja parendamiseks" põhineb avaldatud artiklitel, mis on lisatud tööle. Uurimistöö viidi läbi viie aasta vältel tihedas koostöös erinevate tööstusfirmadega ja Tallinna Tehnikaülikooli projektide raames.

Uurimistöö uudsus seisneb järgnevas:

- Välja pakuti uudne otsustamise tehnoloogia, mis põhineb erinevate tööstusseadmete elutsüklite lõppstrateegiate uuringul.
- Töötati välja uus innovatsioonile orienteeritud tööriist CAIS, mis on mõeldud mikro-, väike- ja keskmise suurusega ettevõtetele, et võimaldada neil teostada kasutatud tehnika igapäevast kontrolli.
- Loova probleemilahenduse teooria TRIZ arendus võimaldab uute instrumentide kasutamist ja nende juurutamist tööstusseadmete elutsükli pikendamiseks. TRIZ arendusena valmis keskkonna vastuolude lahendamiseks kohandatav rohemaatriks.
- Väljatöötatud otsustamise tööriist kombineeriti säästliku ja rohelise tootmise põhimõtteid selleks, et analüüsi abil hinnata tehnika hetkeseisu. Kõik loodud metoodika kolm meetodit (moodulit) on iseseisvad instrumendid, mida on võimalik kasutada ka üksteisest eraldi.
- Uudne jäätmekasutusmaatriksi väljapakkumine andis võimaluse hinnata keskkonnamõju prügitekitamise seisukohalt (jäätmete liigid kulusäästlikus tootmises).

Käesoleva töö põhieesmärgiks oli välja töötada otsustamise roheraamistik ja lähenemisviis kasutatud tööstusseadmete elutsükli pikendamiseks selle lõppetapil, mis võimaldab ettevõtetel maksimaalselt rakendada oma ressursse ja saavutada pikaajalises perspektiivis jätkusuutlikkus vähendades keskkonnamõju.

Antud doktoritöö koosneb neljast peatükist. Esimeses peatükis on kirjeldatud üldisi olulisi põhjuseid tootmissüsteemide arendamiseks keskkonnasäästlikus suunas ja selleks läbitud etappe. Ajaloolised faktid näitavad, kuidas tehnoloogiline revolutsioon on hävitanud loodust ja inimeste tervist. Seda kõike on võimalik seletada TRIZ teooria baasil, kasutades tehnilise süsteemi arenguseadusi.

Teises peatükis on põhjalikult kirjeldatud toote elutsükli kontseptsiooni tööstusseadmete näitel. Uurimistöö raames katsetati ja analüüsiti erinevaid meetodeid. Enim levinud ja kasulikum on tööstusettevõttele olnud taastamine uude olekusse. Lõppetapi stsenaariumide, nagu remondi, taaskasutamise, ümberkonfigureerimise, varuosadeks lammutamise ja täieliku taastamise vahelised omapärad on esile toodud. Samuti on kirjeldatud rohetoote elutsükli olemust. Väga oluliseks osutus lahendada küsimus: mitu korda on võimalik tööstusseadet taastada ja millistel ajavahemikel, kui sellel on juba teine, kolmas või isegi neljas elutsükkel. Samuti on iseloomustatud mõju tööstustoodete elutsüklitele lõppstrateegiate täitmisel.

Kolmandas peatükis on selgitatud ja kirjeldatud TRIZ teooria põhimõtteid ja instrumente rohelise tootmise seisukohalt. On oluline mainida, kuidas ja mil viisil kasutati TRIZi eelnevalt roheprojektide arendamiseks ja elluviimiseks.

Neljandas peatükis on kirjeldatud väljatöötatud lähenemismetoodikat koos uudse otsustamise raamistikuga. Samm-sammult on seletatud kõiki CAIS lähenemisviisi etappe ja erinevate instrumentide käsitlemist otsustusraamistiku raames. Üks kasutusjuht on adapteeritud Hiina teadlaste uurimistööst ja sobis väga hästi arendatud otsustusmehhanismi puhul. Veel on näidatud ühe kasutatud veoki peal väljatöötatud metodoloogia rakendamist.

Töö tulemused:

1. Teadustöö peamise eesmärgi täitmiseks uuriti suurt hulka erinevaid riigiasutuste ja praktikute poolt väljapakutud lähenemisi, tehnikaid ja raamistikke. Mitmed traditsioonilised lähenemisviisid eksisteerivad selleks, et prognoosida kasutatud tööstusseadmete elutsükli lõppfaasi, nagu LCA instrument, mida edukalt kasutati peatükis 3.2, samuti pakuti välja ka mitmeid tagastuslogistika võimalusi kasutatud tehnika elutsükli pikendamiseks. Uurimistöö käigus selgitati, et taastaastamine on tänapäeval rohetehnoloogia arenduse seisukohalt kõige paljulubavam elutsükli lõppstrateegia. Uuriti ja käsitleti erinevaid olemasolevaid rohetootmise tööriistakomplekte kasutamiseks väikese ja keskmise suurusega tööstusfirmades kasutatud tööstusseadmete tehnilise seisukorra hindamiseks ja kontrolliks. Kindlasti on kõik need vahendid olulised ja tähtsad, kuid peaaegu kõik need on väikeettevõtetes juurutamiseks liiga keerulised või mahukad.
2. Üks oluline saavutus selle töö raames on seotud rohemaatriksi arendusega rohetehnoloogia vastuolude lahendamiseks TRIZ vastuolude maatriksi baasil ja

Rohelise Tehnika 12 printsiibi kasutamisel. TRIZ on võimas ja keeruline metoodika uuenduslike realisatsioonide otsimiseks. See teooria pole piiratud ühe uurimisvaldkonnaga. Oluline on mainida ka seda, et pole progressi seal, kus puudub innovatiivne mõtlemine ja julgete ideede tekkimine. TRIZi mõte seisneb selles, et ületada psühholoogilist inertsi ja aktiveerida loovat mõtlemist.

3. Antud töös kasutatud tööstusseadmete elutsükli lõppstrateegia valik põhineb innovatiivsete lahenduste otsimisel. CAIS on kitsalt koondatud lähenemisviis ärakulunud tehnika hindamiseks ja selle elutsükli pikendamiseks, kasutades rohetootmise põhimõtteid. Oluline on ka fakt, et väljatöötatud lähenemisviis tugineb otsustamise raamistikul, mis annab võimaluse otsida nii standardseid kui ka tulemuslikke lahendusi ja juhtida innovatsiooni, mitte ainult jälgida neid parimate näidiste järgi. Rakendades uuenduslikke lahendusi, saab teha väikese äri tulusamaks ja konkurentsivõimelisemaks.

Selle töö eesmärgiks oli välja töötada mehhanism, mis on orienteeritud innovatiivsete ja ebastandardsetele lahenduste leidmiseks selleks, et kasutatud tööstusseadmete tehnilist seisu hinnata ja otsustada, mida nendega edasi teha. See meetod annab võimaluse kombineerida igapäevaselt kasutatud tööriistu ühtses raamistikus. Kõik kolm moodulit on iseseisvad tööriistad ja neid saab kasutada ja juurutada eraldi.

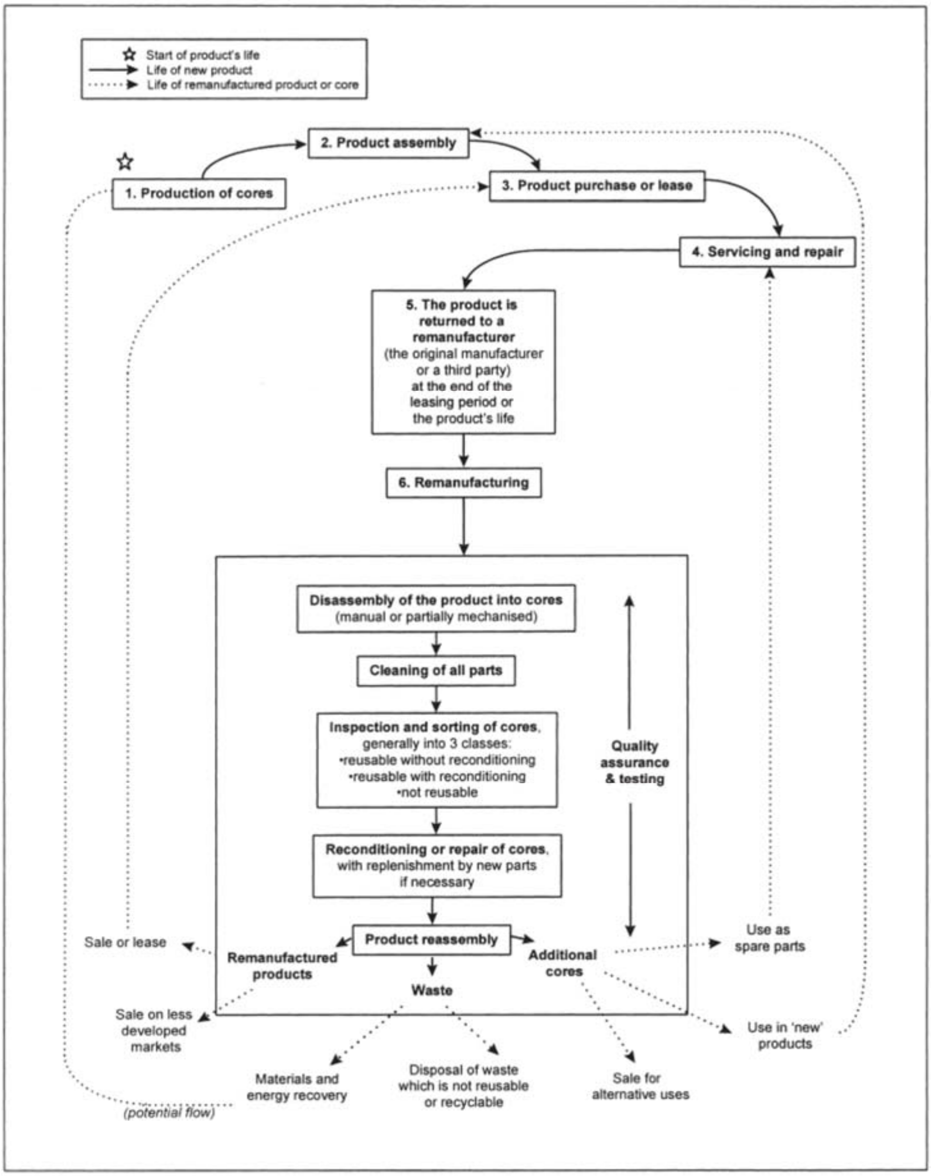
Eksperemendi tulemused näitasid, et CAISi on võimalik kasutada, mis on välja toodud peatükis 3.6 uuritud kasutusjuhus.

Edasistes uuringute tuleks keskenduda simulatsiooniosa arendamisele. Pole lihtne arendada head programmikoodi, et leida ja võrrelda innovatiivseid lahendusi. Töös toodud oskusteavet ja metoodikat saab kasutada tööstusseadmete valdkonnas hetkeseisu tehnilise olukorra hindamiseks. Oluline on edasi arendada kogu CAIS kontseptsiooni kasutatud tööstusseadmete kontrollimiseks ja hindamiseks programmilisel kujul. Hetkel on turul teatud programmid innovatiivsete lahenduste leidmiseks, nagu Creax Innovations, aga pole veel komplekset pakkumist väikese ja keskmise suurusega ettevõtetele, et saaks aja ja ressursside puudumisel otsust kiiresti ja teaduslikult põhjendatult vastu võtta. Töös püstitatud hüpoteesi tõestust ja uurimistöö muid tulemusi saab edasi arendada ja kasutada järgmisel kujul:

1. Arendatud otsustusraamistiku metoodika annab võimalust kontrollida ettevõtte ressursse ja minimiseerida mõju keskkonnale. Selline lähenemisviis vähendab uute materjalide kasutamist toote kogu elutsükli raames.
2. Otsustusraamistiku integreerimine TRIZ metoodikaga ergutab insenere arendama ja parandama oma teadmisi erinevates uurimisvaldkondades.
3. Üldiselt mõjutab rohetootmise projektide rakendamine tootmisettevõtete suunda säästvale tootmisele ja säästab piiratud loodusvarusid tänu kasutatud tööstusseadmete elutsükli pikendamisele.

APPENDICES

Appendix 1. A generic remanufacturing process



Appendix 2. Table of estimated useful lives (industrial equipment)

P R O P E R T Y	YEARS
I. Motor and Other Vehicles	
Automobiles	
Owner Driver	10
Passengers	5
Salesman	3
Motor Cycle	4
Trucks/Pick-ups:	
Field/Rural/Provincial use -	
Diesel & Gasoline	
Light	8
Medium	8
Heavy	6
City/Urban use -	
Light	10
Medium	10
Heavy	8
Check Writers	8
Cleaners electric vacuum	6
III. Major Heavy Equipment	
Batching Plant, Concrete	7
Compressor, Air	6
Crane	9
Crane, Truck Mounted	11
Crane, Amphibious	8
CS & W Plant Aggregate	7
Excavator, Crawler Backhoe	10
Excavator, Crawler Gradall	7
Jeep Trailer	10
Generator Set	6
Grader, Road	7
Jeep Trailer	6
Loader, Crawler with Backhoe	7
Loader, Crawler	7
Loader, Wheel with Backhoe	7
Loader, Wheel	7
Mixer Concrete	10
Pump, Centrifugal	6
Rig, Drilling	6
Roller, Static	10

Roller, Sheepfoot	15
Scraper, Wheel Tractor	4
Tractor, Crawler	6
Tractor, Farm	7
Truck, Mixer	8
Truck-Tractor with Trailer	8
Vibratory, Concrete	4
Dredging Machine	10
Compactor, Spreader	6
Scraper, Dozer	8
Service Rig	9
IV. Minor Heavy Equipment	
Air Drill Machine	5
Boat, Speed	4
Chain Saw	3
Compactor, Tamping	4
Drilling Machine/Fadrig	6
Forklift	8
Motor bicycles	5
Pavement Breaker/Jackhammer	9
Pile hammer	14
Power Tiller	8
Pump, Booster/SU/Test/Turbine/Air	6
Pump, Grout	13
Pump, High Pressure	5
Pump, Propeller	6
Pump, Monitor	5
Pump, Triplex, Duplex	15
Rock Drill	9
Tanker, Fuel	8
Tanker, Water	8
Tanker-Trailer, Water	10
Truck Lubricating	9
Truck, Repair Shop Mobile	9
Truck, Bridge	8
Truck, Oil Field with Boom	8
Weed Cutter	3
Welding Machine	4
Gate Machine	10
Desander	11
Amphibian Truck	8

Rice Tresher	6
Mech. Rice Drier	6
Trailer, Towed Type	10
Fire Truck	8
Compressor, Gasoline	6
Portable Rice Mill	10
V. Other Assets	
Air-conditioning Unit	10
Photographic Machine	26
Plumbing	20
Power Plant	20
Power Transmission Line	10-15
Railroads:	
Rails	20
Ties	8
Refrigerator	10
Sawmill	20
Sewing Machine	10
Steamship freight:	
Ocean going	20
Closing Machine, can	15
Cutters, paper	15
Gluing Machine, box or carton	20
Boiler	30
Crusher	25
Pulverizer (cement)	25
Truck (quarry)	15
Automobile tank car	10
Railroad tank car	25
Water tower, cooling	15
Foundries	25

Sources:

1) *US Treasury Dept. Bulletin F Income Tax Useful Lives and Depreciation Rates*
2) *National Irrigation Administration*
3) *Department of Public Works & Highways*
4) *Technical Services Office, This Commission*

Appendix 3. TRIZ 40 Principles

Altshuller's 40 Principles of TRIZ

1. Segmentation	15. Dynamics	28. Mechanics substitution
2. Taking out	16. Partial or excessive actions	29. Pneumatics and hydraulics
3. Local Quality	17. Another dimension	30. Flexible shells and thin films
4. Asymmetry	18. Mechanical vibration	31. Porous materials
5. Merging	19. Periodic action	32. Color changes
6. Universality	20. Continuity of useful action	33. Homogeneity
7. "Nested doll"	21. Skipping	34. Discarding and recovering
8. Anti-weight	22 "Blessing in disguise"	35. Parameter changes
9. Preliminary anti-action	23. Feedback	36. Phase transitions
10. Preliminary action	24. 'Intermediary'	37. Thermal expansion
11. Beforehand cushioning	25. Self-service	38. Strong oxidants
12. Equipotentiality	26. Copying	39. Inert atmosphere
13. The other way around	27. Cheap short-living	40. Composite material films
14. Spheroidality		

Source: http://www.umich.edu/~scps/html/07chap/html/summary.htm

Interactive Contradiction Matrix: The 40 TRIZ Principles are brought to you by TRIZ40

Appendix 4. 12 Principles of Green Engineering

CENTER FOR GREEN CHEMISTRY & GREEN ENGINEERING AT YALE

The 12 Principles of Green Engineering

1. **Inherent Rather Than Circumstantial**
   Designers need to strive to ensure that all materials and energy inputs and outputs are as inherently nonhazardous as possible.

2. **Prevention Instead of Treatment**
   It is better to prevent waste than to treat or clean up waste after it is formed.

3. **Design for Separation**
   Separation and purification operations should be designed to minimize energy consumption and materials use.

4. **Maximize Efficiency**
   Products, processes, and systems should be designed to maximize mass, energy, space, and time efficiency.

5. **Output-Pulled Versus Input-Pushed**
   Products, processes, and systems should be "output pulled" rather than "input pushed" through the use of energy and materials.

6. **Conserve Complexity**
   Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse, or beneficial disposition.

7. **Durability Rather Than Immortality**
   Targeted durability, not immortality, should be a design goal.

8. **Meet Need, Minimize Excess**
   Design for unnecessary capacity or capability (e.g., "one size fits all") solutions should be considered a design flaw.

9. **Minimize Material Diversity**
   Material diversity in multicomponent products should be minimized to promote disassembly and value retention.

10. **Integrate Material and Energy Flows**
    Design of products, processes, and systems must include integration and interconnectivity with available energy and materials flows.

11. **Design for Commercial "Afterlife"**
    Products, processes, and systems should be designed for performance in a commercial "afterlife."

12. **Renewable Rather Than Depleting**
    Material and energy inputs should be renewable rather than depleting.

Anastas, P.T., and Zimmerman, J.B., "Design through the Twelve Principles of Green Engineering", Env. Sci. Tech. 2003, 37(5), 94A-101A.

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3. Education

Educational institution	Graduation year	Education (field of study/degree)
Tallinn University of Technology	2009 - ….	Mechanical Engineering, Doctoral studies
Tallinn University of Technology	2008	Product Development and Production Engineering, Master of Science
Tallinn University of Technology	2006	Product Development and Production Engineering, Bachelor of Science
Lasnamäe Russian School	2003	Secondary education

4. Language competence/skills (fluent; average, basic skills)

Language	Level
Russian	Fluent
Estonian	Fluent
English	Fluent
Finnish	Intermediate

5. Special Courses

Period	Educational or other organization
2009–2012	Tallinn University of Technology, different courses at Doctoral School of Energy and Geotechnology II
2012	1st DAAAM International Doctoral School University of Zadar, Croatia
2014–2015	Green Belt, 6Sigma training
2015	Kaizen Institute training, Kaizen coach

6. Professional Employment

Period	Organisation	Position
2016	Twilio Estonia OÜ	Product Operations Specialist
2016	Hilding Anders Baltic AS	Process Engineer
2015	ABB AS	Process Engineer
2012	Universidade Nova de Lisboa	Researcher
2011	Tere AS	Manager of Production Planning Department
2010	Greiner Packaging AS	Production Planner
2006	Alimper OÜ	Sales Manager of lifting equipment
2004	Toyota Material Handling Eesti AS (BT Eesti AS)	Service and Sales Support

7. Scientific work in projects

Publications:

- Karaulova T.; Bashkite V., Tool Development for Strategy Selection for Used Industrial Equipment, *Proceedings of the 22nd International Conference "MECHANIKA 2017",* Kaunas*,* 2017 (accepted for publication)
- Karaulova T.; Bashkite V., Decision-making Framework for Used Industrial Equipment, *Engineering Economics*, 2016, 27 (1), 23−31, 10.5755/j01.ee.27.1.8618.
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- Bashkite V.; Durmanenko D.; Karaulova T., Life Cycle Extension for Used Vehicles and Their Environmental Impact. *Proceedings of the 8th International Conference on DAAAM Baltic Industrial Engineering*, TUT Press, 2012, 401 - 406.
- Zahharov R.; Bashkite V.; Karaulova T.; Miina, A. Industrial building life cycle extension through the concept of modular construction. *Proceedings of the 21st DAAAM World Symposium*, 2011, 805 – 806.
- Gulevitš J.; Bashkite V.; Problemy kachestvennogo proizvodstva stroitel'nogo materiala dlja stroitel'stva dorozhnogo pokrytija s vysokoj chastotoj dvizhenija. *Problemy Nedropol'zovanija. Sankt-Peterburgskij Gosudarstvennyj Gornyj* Ins, 2010, 189, 108 – 110.
- Jõgi G.; Bashkite V.; Karaulova T.; Analysis of first waste-to-energy plant production line at Kunda Nordic Cement AS. *Proceedings of 7th International Conference of DAAAM Baltic Industrial Engineering*, Tallinn, TUT Press, 2010, 358−363.
- Moseichuk V.; Bashkite V.; Karaulova T.; Lifecycle extension for industrial equipment. *Proceedings of 7th International Conference of DAAAM Baltic Industrial Engineering*, Tallinn, 2010. TUT Press, 364−369.

Other projects:

- e-Manufacturing Concept for SME (ETF7852).
- Enhancing Sustainability of Manufacturing Enterprises through reliability engineering (ETF9460).
- Optimal design of composite and functional material structures, products, and manufacturing processes (SF0140035s12).

8. Defended theses

Master of Science thesis: Improvement of Lifting Equipment Sales Process by the Introduction of New Information Module, 2008, Supervisor: Ph.D. Tatjana Karaulova (Tallinn University of Technology).

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3. Hariduskäik

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Tallinn Tehnikaülikool	2009…	Tootearendus ja tootmistehnika, doktorantuur
Tallinn Tehnikaülikool	2008	Tootearendus ja tootmistehnika, tehnikateaduse magistri kraad
Tallinn Tehnikaülikool	2006	Tootearendus ja tootmistehnika, tehnikateaduste bakalaureuse kraad
Lasnamäe Vene Gümnaasium	2003	Keskharidus

4. Keelteoskus (alg-, kesk- või kõrgtase)

Keel	Tase
Vene keel	Kõrgtase
Eesti keel	Kõrgtase
Inglise keel	Kõrgtase
Soome keel	Kesktase

5. Täiendusõpe

Õppimise aeg	Täiendusõppe läbiviija nimetus
2009–2013	Tallinna Tehnikaülikool, erinevad kursused Energia- ja geotehnika doktorikooli II raames
2012	Esimene DAAAM'i rahvusvaheline doktorikool University of Zadar, Horvaatia
2014–2015	Green Belt, 6Sigma koolitus
2015	Kaizen Instituudi koolitus, Kaizen treener

6. Teenistuskäik

Töötamise aeg	Tööandja nimetus	Ametikoht
2017	Twilio Estonia OÜ	Toote opereerimise spetsialist
2016	Hilding Anders Baltic AS	Protsessiinsener
2015	ABB AS	Protsessiinsener
2012	Universidade Nova de Lisboa	Teadur
2011	Tere AS	Planeerimise osakonna juhataja
2010	Greiner Packaging AS	Tootmise planeerija
2006	Alimper OÜ	Tõste- ja laotehnika müügijuht
2004	Toyota Material Handling Eesti AS (BT Eesti AS)	Tehnilise- ja müügiosakondade assisteerimine

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Publikatsioonid:

- Karaulova T.; Bashkite V., Tool Development for Strategy Selection for Used Industrial Equipment, *Proceedings of the 22th International Conference "MECHANIKA 2017",* Kaunas*,* 2017 (accepted to publication)
- Karaulova T.; Bashkite V., Decision-making Framework for Used Industrial Equipment, *Engineering Economics*, 2016, 27 (1), 23−31, 10.5755/j01.ee.27.1.8618.
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- Gulevitš J.; Bashkite V.; Problemy kachestvennogo proizvodstva stroitel'nogo materiala dlja stroitel'stva dorozhnogo pokrytija s vysokoj chastotoj dvizhenija. *Problemy Nedropol'zovanija. Sankt-Peterburgskij Gosudarstvennyj Gornyj* Ins, 2010, 189, 108 – 110.
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- Moseichuk V.; Bashkite V.; Karaulova T.; Lifecycle extension for industrial equipment. *Proceedings of 7th International Conference of DAAAM Baltic Industrial Engineering*, Tallinn, 2010. TUT Press, 364–369.

Teised projektid:

- E-tootmise kontseptsioon väike- ja keskmise suurusega ettevõtetele (ETF7852).
- Tootmisettevõtete jätkusuutlikkuse parendamine töökindla tehnoloogia abil (ETF9460).
- Komposiit- ja funktsionaalsetest materjalidest konstruktsioonide, toodete ja tootmisprotsesside optimaalne projekteerimine (SF0140035s12).

8. Kaitstud lõputööd

Magistritöö: Tõste- ja laotehnika realiseerimisprotsessi täiustus uue infomooduli rakendamisega, 2008. a. Juhendaja: Ph.D Tatjana Karaulova (Tallinna Tehnikaülikool).

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25. **Dmitri Neshumayev**. Experimental and Numerical Investigation of Combined Heat Transfer Enhancement Technique in Gas-Heated Channels. 2005.

26. **Renno Veinthal**. Characterization and Modelling of Erosion Wear of Powder Composite Materials and Coatings. 2005.

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28. **Tauno Otto**. Models for Monitoring of Technological Processes and Production Systems. 2006.

29. **Maksim Antonov**. Assessment of Cermets Performance in Aggressive Media. 2006.

30. **Tatjana Barashkova**. Research of the Effect of Correlation at the Measurement of Alternating Voltage. 2006.

31. **Jaan Kers**. Recycling of Composite Plastics. 2006.

32. **Raivo Sell**. Model Based Mechatronic Systems Modeling Methodology in Conceptual Design Stage. 2007.

33. **Hans Rämmal**. Experimental Methods for Sound Propagation Studies in Automotive Duct Systems. 2007.

34. **Meelis Pohlak**. Rapid Prototyping of Sheet Metal Components with Incremental Sheet Forming Technology. 2007.

35. **Priidu Peetsalu**. Microstructural Aspects of Thermal Sprayed WC-Co Coatings and Ni-Cr Coated Steels. 2007.

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42. **Mart Saarna**. Fatigue Characteristics of PM Steels. 2008.

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50. **Igor Krupenski**. Numerical Simulation of Two-Phase Turbulent Flows in Ash Circulating Fluidized Bed. 2010.

51. **Aleksandr Hlebnikov**. The Analysis of Efficiency and Optimization of District Heating Networks in Estonia. 2010.

52. **Andres Petritšenko**. Vibration of Ladder Frames. 2010.

53. **Renee Joost**. Novel Methods for Hardmetal Production and Recycling. 2010.

54. **Andre Gregor**. Hard PVD Coatings for Tooling. 2010.

55. **Tõnu Roosaar**. Wear Performance of WC- and TiC-Based Ceramic-Metallic Composites. 2010.

56. **Alina Sivitski**. Sliding Wear of PVD Hard Coatings: Fatigue and Measurement Aspects. 2010.

57. **Sergei Kramanenko**. Fractal Approach for Multiple Project Management in Manufacturing Enterprises. 2010.

58. **Eduard Latõsov**. Model for the Analysis of Combined Heat and Power Production. 2011.

59. **Jürgen Riim**. Calibration Methods of Coating Thickness Standards. 2011.

60. **Andrei Surzhenkov**. Duplex Treatment of Steel Surface. 2011.

61. **Steffen Dahms**. Diffusion Welding of Different Materials. 2011.

62. **Birthe Matsi**. Research of Innovation Capasity Monitoring Methodology for Engineering Industry. 2011.

63. **Peeter Ross**. Data Sharing and Shared Workflow in Medical Imaging. 2011.

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