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Paulina Golinska-Dawson
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Sustainability in Remanufacturing Operations

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Sustainability in Remanufacturing Operations

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Preface

The present consumption models with short product life cycles result in an increasing number of used products that need to be collected and reused or disposed. Both legal regulations and consumers' concerns regarding these issues have led companies to include reverse material flows in their operations.

Remanufacturing gains recently more popularity among researchers and companies. It is the favourable scenario for the recovery of obsolete of end-of-use products. It allows to capture substantial part of the resources which were used in the primary production at lower cost, providing economic, environmental and social benefits. Remanufacturing is more complex than in traditional manufacturing, primarily because of the inherent uncertainty in the timing, quality and quantity of returns. Many companies face difficulties in organizing resource efficient remanufacturing operations. Small- and medium-size enterprises lack sufficient tools and methods for the monitoring and assessment of their operation with regard to the three dimensions of sustainability.

Implementation of the sustainability concept at a company level might create a chance for long-term economic success and for finding market niche. Remanufacturing companies help to close the material loops in the economy and contribute to the resource conservation.

This book focuses on the sustainability assessment in the remanufacturing operations. The authors in individual chapters present the methods, models and case studies for sustainability improvement in remanufacturing facilities.

This book refers to the studies which were conducted in the framework of the bilateral Polish-German research cooperation for sustainable development project SIRO "Sustainability in Remanufacturing Operations" (grant from National Centre for Research and Development (NCiBR) and German Federal Ministry of Education and Research (BMBF), no WPN/2/2012 and 01RS1204A).

We would like to thank all authors who responded to the call for chapters and submitted manuscripts to this volume. Although not all of the received chapters appear in this book, the efforts spent and the work done for this book are very much appreciated.

The good scientific quality of the chapters was assured by a rigorous blind review process. We would like to thank all reviewers whose names are not listed in the volume due to the confidentiality of the process. Their voluntary service and comments helped the authors to improve the quality of the manuscripts.

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1 Introduction

The scarcity of fossil fuels and raw materials creates a need for new, more resource efficient business models. The sustainable development and the circular economy concept provide a new framework for building up innovative companies strategies. The 12th United Nations Sustainability Goal focuses on ensuring sustainable consumption and production patterns around the globe (UN 2015). That goal encourages use of life cycle perspective and reducing resource consumption and pollution along all products' life phases.

As the EU Action Plan for the circular economy has stated the circular economy is essential "to develop a sustainable, low carbon, resource efficient and competitive economy" (COM 2015/614). The EU circular economy policy put emphasis on improvement of reparability, durability, upgradability of products early from the design phase (COM 2015/614).

Remanufacturing process allows to bring used products to like new conditions and recover a substantial portion of the energy and materials, which were used in primary production at low additional cost, thus reducing the price of product (Ijomah et al. 2004). Remanufacturing allows to close the material loops in the economy and for that reason it contributes to the circular economy implementation in practice. It maintains the value of resources, materials and final products for as long as possible and minimizes the generation of waste.

The literature provides many examples on environmental and economic benefits of remanufacturing (Kim et al. 2008; Kim et al. 2009; Gutowski et al. 2011; Sundin and Lee 2012). It is often assumed that remanufacturing process is sustainable without any further investigation.

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The concept of sustainability is not precisely defined in the literature. Thus, it is open to different interpretations. The most cited definition is coming from the Brundtland Commission (1987) and stated that sustainable development "…meets the needs of the present without comprising the ability of future generations to meet their own needs". Since 1987 many more definitions of sustainability have been published but still sustainability problems are not well defined and don't have an obvious solution. They arise in the interaction of social, technological and ecological systems. The complexity of sustainability problems requires new approaches to allocation and distribution of scarce resources, environmental protection and building good relations with many stakeholders.

It is challenging to transfer rather abstract ideas of sustainability into operational practices in a companies. Small and medium sized enterprises struggle how to interpret, measure and operationalize sustainability concept. Companies aim to measure sustainability in order to be able for (Feng et al. 2010):

- Sustainability accounting—monitoring and documenting of resources utilization, waste and emissions generation in industrial processes,
- Impact analyses—measuring the impact of economic activities on natural environment and human well-being.

There is a very limited literature on "sustainability in remanufacturing", therefore this research takes as a benchmark the framework of performance measurement in "sustainable manufacturing". The goal is to define requirements for comprehensive process metrics for sustainable remanufacturing. This chapter is organized, as follows: first the concept of sustainability at a company level is defined. Then the problems of sustainability performance measurement are addressed. Finally the key requirements for measuring remanufacturing process sustainability are defined.

2 Sustainability Assessment at Company Level

Feng et al. (2010) use the term "sustainability in development", which they define as "an organization's ability to advance its economic state without compromising the environment and the social equity that provide the quality of life for all community residents, present or future". This term suits better the purpose of analyzing sustainability concept at an organization level then general definitions of sustainable development (e.g. the one from Brundtland Commission 1987).

Searcy (2014) has defined the concept of sustainable enterprise "as the creation of stakeholder-focused intra- and inter-organizational business systems that address the integrated economic, environmental and social aspects of performance over the short and long term within the limits imposed by society and nature". That definition highlights a border context, as it includes not only company but also a supply chain perspective.

Sustainability assessment can be defined as "a process that guides decision making towards sustainability" (Hacking and Guthrie 2008). Devuyst et al. (2001)

have defined sustainability assessment as “a tool that helps decision and policy makers to decide what actions should follow or not, in an attempt to make society more sustainable”.

An extensive review on the sustainability assessment methods can be found in the paper of Singh et al. (2009; 2012). They provide an overview of various sustainability indices and describe their information requirements, formulation strategy, scaling, normalization and aggregation (Singh et al. 2012). Most of the methods are dedicated to macro (country or region) level sustainability assessment.

The most popular initiatives which allow to measure sustainability performance also at a company level are, as follows:

- Global Reporting Initiative (GRI)—it provides guidelines and standards for sustainability reporting using a broad scope of environmental, economic and social indicators. It is used mainly by the biggest companies in the world.
- Dow Jones Sustainability Index (DJSI)—it measures suitability performance of the largest 2500 companies listed on the Dow Jones Global Total Stock Market Index,
- OECD Sustainable Manufacturing Toolkit (OECD 2011)—it provides a set of 18 indicators to measure sustainability performance of manufacturing facility in terms of materials and processes,
- United Nations Sustainable Development Indicators—it provides set of over 230 indicators divided into 17 thematic sections/goals (so called SDGs).
- IChemE Sustainable Development Progress Metrics recommended for process industries—it provides tool for measuring performance of processes in chemical sector with regard to the three pillars of sustainability: social (divided into society and workplace, which is measured by categories: a) health and safety at work, employment situation; and society); economic (profit, value, tax and additional economic items) and environmental (usage of energy, materials, water, land and emissions divided into aquatic impact and atmospheric impact).

In the automotive industry some of big corporations implement their own sustainability metrics system like for example: General Motors Metrics for Sustainable Manufacturing or Ford Product Sustainability Index. The comprehensive review of sustainability indicators & metrics is presented in work of Feng and Joung (2009).

The suitability indicators are widely used for monitoring purpose. Indicator is defined as “a quantitative or a qualitative measure derived from a series of observed facts that can reveal relative positions” (Nardo et al. 2008). The design of the indicators’ system is tricky, as they need to compromise the conflicting goals of statistics, science, and politics. Moreover, they should present reality in accurate, comprehensive and relevant way, when “reality is complex (…), Extracting from it the essential requires a process of knowledge-finding where the essential is separated from the non-essential and where small descriptive “information atoms” are aggregated in a stepwise process to form larger artefacts, which then can represent more comprehensive sub-systems of reality” (Radermacher 2005).

Most of the sustainability indicators seem to be elaborated in top-down approach. The monitoring systems are overcomplicated and serve mainly political goals. They monitor fulfillment of general strategic goals rather than real actions.

Performance metric is “a standard means of measuring and tracking an indicator” (Feng et al. 2010). Most of the metrics are dedicated for purpose of the external reporting for stakeholders. They don’t aim to provide decision makers information needed to optimize the processes with regards to sustainability goals. The companies need an easy set of metrics in order to conform with restrictive environmental regulations, asses their economic performance and monitor their relations with stakeholders.

The performance metric should provide decision maker with the information:

- What to measure?—It requires a guidelines for a scope of measurement process;
- How to measure it?—It requires a guidelines for a method for measurement process;
- Why to measure it?—It requires a guideline for a measurement purpose.

Performance metric allows using quantitative or qualitative approach. The results of assessment can be presented as an absolute or a relative value, and a normalized or a non-normalized number. Such approach provides a flexible measurement framework and it allows to use both numerical data and expert’s knowledge which is embodied in a company.

The sustainability performance metric system (SPMS) provides a company with information, that helps “in the short and long-term management, controlling, planning, and performance of the economic, environmental, and social activities” which are performed by that company (Searcy 2012).

The existing metrics for sustainability often are not easy to use for products and manufacturing processes sustainability performance assessments.

The industrial companies make efforts to contribute to the sustainability goals mainly by implementing the concept of sustainable manufacturing (in this chapter the terms “sustainable production” and “sustainable manufacturing” are treated, as equal).

The most common definition of sustainable manufacturing is provided by US Department of Commerce (2011). It states that sustainable manufacturing is “the creation of manufactured products that uses processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound”. The sustainable manufacturing aims to provide products (Nasr et al. 2011):

- using fewer resources,
- generating less waste and pollution,
- contributing to social progress and wellbeing.

Remanufacturing meets the sustainable manufacturing goals, as it extends product life cycle, helps closing the loop on material flows, and reducing total materials consumption (Nasr et al. 2011). According to APSRG Report (2014) remanufacturing allows to gain a triple win, as it creates economic, environmental and social opportunities.

Some of the authors treat remanufacturing as an implementation mechanism, for achieving sustainable production metrics (e.g. Nasr et al. 2011) or enabler of sustainable development (Ijomah et al. 2004).

The challenge the companies are facing is to find appropriate comprehensive metrics that would allow them to benchmark their processes against the others in the industry in order to monitor progress toward more sustainable practices.

Liu et al. (2011) have review over 100 scientific publications on sustainability analysis for purpose of greening operations management. They have classified the analyzed previous works, as follows (Liu et al. 2011):

- Methodologies: LCA—Life cycle analysis (including PLC—product life cycle; and OLC—operational life cycle), Multi-Criteria Decision Analysis (MCDA);
- Applications: sustainable product design, sustainable manufacturing, sustainable supply chain management.

Most of researchers focus on assessment of product's sustainability performance, as they treat manufacturing process sustainability just as the sub-elements in product life cycle (Lu et al. 2011). The opinion is prevailing that optimized manufacturing process does not guarantee that product performance is optimal with regard to sustainability. In case of remanufacturing products the assumption can be made that they are positive with regard to sustainability of their performance in the life cycle, as that recovery option has be chosen rather than other recovery scenarios. In order to achieve optimal overall sustainability of product performance the corresponding remanufacturing processes need to be optimized based on some sustainability criteria.

3 Challenges for Assessment of Sustainability of Remanufacturing Process

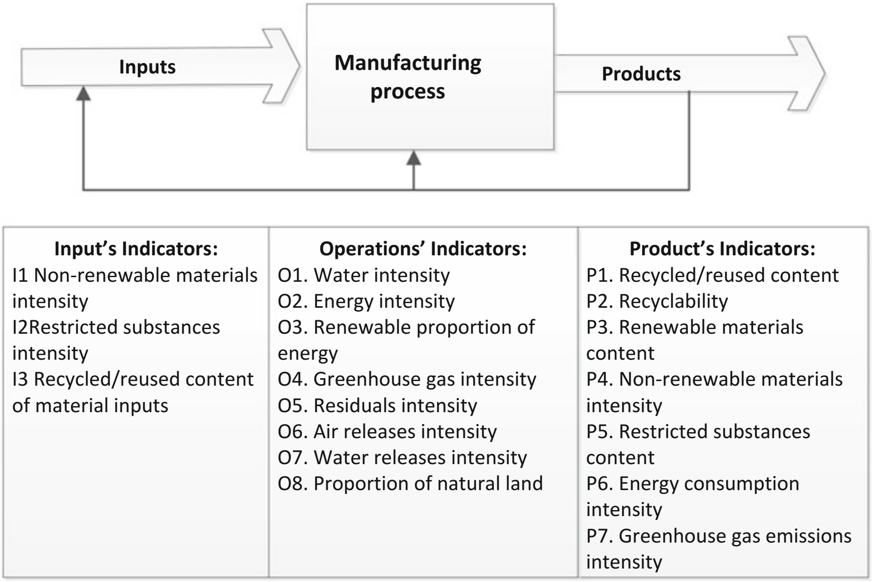
Sustainability in remanufacturing is defined in this chapter, as "remanufacturing process that is economically sound, minimizes negative environmental impacts, saves energy and raw materials and is safe for employees, communities, and consumers". The assessment of remanufacturing processes aims to provide decision-maker with reliable and comprehensive criteria when optimizing process design/organization for higher sustainability level. The sustainability level defines the extent to which those goals are met.

The sustainability assessment might be carried out on the product level, process level or system level (Lu et al. 2011). In this chapter the focus is placed on process level. The supply chain context is excluded in the sustainability assessment and the focus is placed only on focal company remanufacturing process. That simplification results from previous findings of Östlin (2008), Lundmark et al. (2009) and

Barquet et al. (2013), Um et al. (2008) and Oiko et al. (2011), who have confirmed that different supply chain models should be applied in remanufacturing, as it can be performed by different actors (OEM—original equipment remanufacturers, IR—independent remanufactures or CR—contracted remanufacturers). Therefore different supply chain models should be applied in each case. Some authors identify even more types of remanufacturing supply chain models (e.g. Lind et al. 2014) In order to provide some homogenous framework for sustainability assessment the supply chain perspective is excluded.

The focus in this chapter is placed on sustainability process assessment in small and medium sized enterprises (SMEs) in remanufacturing sector, and for this reason the OECD (2011) toolkit is taken into consideration for primary analysis. The OECD sustainable manufacturing framework provides 18 quantitative indicators for evaluation of environmental performance in all types of manufacturing companies (especially SMEs). These indicators aim to assist internal management and decision-making (OECD 2011). Figure 1 presents the summary of OECD indicators. These indicators are designed for measuring performance of a single manufacturing facility but the results might be aggregated to upper levels (all manufacturing facilities). The OECD toolkit provides 7 step performance measurement methodology. That assessment is a cyclic process and it aims to enable innovation and continuous improvement of sustainability in manufacturing facility.

In case of remanufacturing the borderline between operations' and products' indicators (see Fig. 1) is vague, as the recovery processes of materials and components are part of basic operations. Moreover the challenge is also to separate the



Input's Indicators:	Operations' Indicators:	Product's Indicators:
I1 Non-renewable materials intensity I2Restricted substances intensity I3 Recycled/reused content of material inputs	O1. Water intensity O2. Energy intensity O3. Renewable proportion of energy O4. Greenhouse gas intensity O5. Residuals intensity O6. Air releases intensity O7. Water releases intensity O8. Proportion of natural land	P1. Recycled/reused content P2. Recyclability P3. Renewable materials content P4. Non-renewable materials intensity P5. Restricted substances content P6. Energy consumption intensity P7. Greenhouse gas emissions intensity

Fig. 1 OECD sustainable manufacturing indicators (adopted from OECD 2015)

input and output of the remanufacturing process. The products which are output of the process at some point of time should come back as the input to the process.

The other problem with applying OECD toolkit is that it does not include economic and social indicators. In case of remanufacturing sustainability assessment the OECD sustainable manufacturing indicators can be used as guidelines to identify the environmental impact which should be measured. The proposal for adoption of the OECD toolkit to remanufacturing process assessment is presented in Table 1. The codes of OECD sustainable manufacturing indicators correspond with those in Fig. 1.

The indicators presented in Table 1 do not consider economic and social aspects. For that reason the literature research is extended in order to find an alternative framework for sustainability assessment of remanufacturing process in SMEs. Interesting work has been done at the University of Kentucky in developing indicators and metrics for product and process sustainability assessment

Table 1 Adoption of the OECD sustainability

Remanufacturing process indicators	Corresponding OECD sustainable manufacturing indicators
Materials recovery rate (MRR)	I3, P1, P2, P3
Non-renewable materials rate (1-MRR)	I1, P4
Restricted substances intensity	I2, P5,
Energy intensity	O2,
Portion of renewable energy	O3
Air emissions intensity	O4, O6, P7
Water intensity	O1
Land use intensity	O8
Sewage intensity	O7
Waste generation intensity	O5

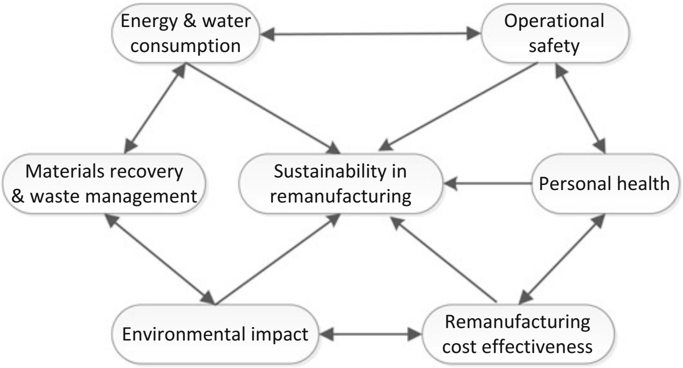


Fig. 2 Key elements of sustainability in remanufacturing processes (adopted from Jawahir and Dillon 2007)

Table 2 Sustainability in remanufacturing processes—metrics and indicators

Sustainability process metrics	Indicator name (unit)	Source in remanufacturing literature
Energy and water consumption	Energy consumption (MJ)	(Kerr and Ryan 2001)
	Life cycle energy consumption/normalized energy unit (MJ/unit product)	(Gutowski et al. 2011)
	Total energy used (MJ)	(Wilson et al. 2014)
	Energy intensity (MJ/kg)	(Sutherland et al. 2008)
	Water consumption (L)	(Kerr and Ryan 2001)
	Reduction in oil consumption (P/L)	(Abdul-Kader and Haque 2011)
Environmental impact	CO_2 equivalents (kg)	(Kerr and Ryan 2001)
	CO_2 consumption (kg)	(Abdul-Kader and Haque 2011)
	Carbon footprint (CO_2 kg equivalent)	(Wilson et al. 2014)
	Total environmental impact	(Ovchinnikov et al. 2014)
	Environmental impact (eco-indicator 99)	(Amaya et al. 2010)
	GHG emissions ($kgC0_2$-eq)	(Kim et al. 2008)
Materials recovery and waste management	Materials consumption (kg)	(Kerr and Ryan 2001)
	Material consumed (kg)	(Kim et al. 2008)
	Volume of scrap (kg)	(Abdul-Kader and Haque 2011)
	Raw material consumption (kg)	(Abdul-Kader and Haque 2011)
	MRR material recovery rate (%)	(Guide and Srivastava 1997)
	Waste generation (kg)	(Kim et al. 2008)
Remanufacturing cost effectiveness	Remanufacturing cost (monetary unit/pcs)	(Östlin et al. 2009)
	Total economic impact (measured by % change in profit)	(Ovchinnikov et al. 2014)
	Life cycle cost LCC (monetary unit)	Schau et al. (2012)
Operational safety	Operator comfort at workplace	Not identified
	Employment opportunities (%)	(Fatimah et al. 2013)
	Innovativeness	Not identified
Personal health	Harmfulness of work conditions	Not identified
	Absenteeism at workplace	Not identified

(e.g. Jawahir and Dillon 2007; Lu et al. 2011). Jawahir and Dillon (2007) have identified a set of sustainability elements for sustainable manufacturing including economic, environmental and social dimension. Their elements are: the manufacturing cost, energy consumption, waste management, environmental impact, personnel health and operational safety (Jawahir and Dillon 2007). Figure 2 presents the adoption of their work to the conditions of remanufacturing process.

Table 2 presents the summary of the findings from literature review with regard to the sustainability process indicators. The key elements of sustainability in remanufacturing processes identified in the Fig. 2 are taken into consideration.

The remanufacturing literature provides many examples of environmental assessment. The works on economic and social aspects are rather limited. The complex performance metrics system that allows assessment of remanufacturing process is needed.

4 Conclusions

The chapter presents the discussion on challenges for the assessment of sustainability in remanufacturing process. There is still lack of sufficient tools and methods which might be used by small and medium size enterprises for the sustainability assessment. Figure 3 presents the proposed classification of the assessment methods.

The limited availability of a numerical data is an important problem in SMEs in remanufacturing sector, and for that reason the qualitative methods might be more attractive for the companies. The methods which are described in the literature focus mainly on the quantitative approach using Life Cycle Assessment software (see for comparison the works cited in Table 2). That approach is not easy to be introduced in SMEs due to the high work effort needed to perform the LCA and the associated additional costs.

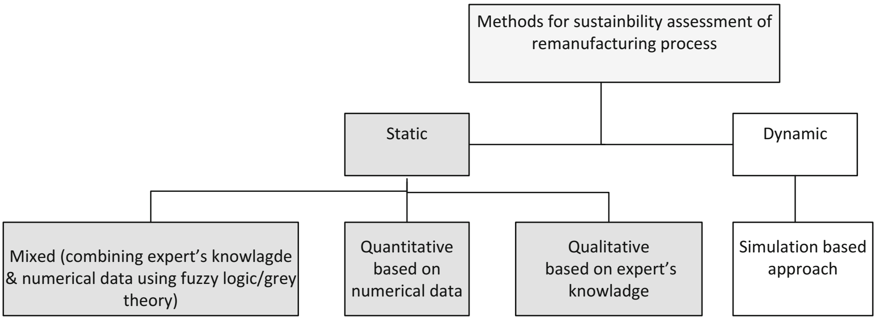


Fig. 3 The classification of the method for sustainability assessment of remanufacturing process

The key requirements for measuring remanufacturing process sustainability are defined, as follows:

- R1: The indicators' set should be limited (less than 20) and be tailored in order to meet the remanufacturing characteristics,
- R2: The indicators should evenly cover the environmental, economic and social aspects,
- R3: The indicators should use existing data (e.g. on energy consumption) and existing expert's knowledge,
- R4: The indicators' aggregation methods should allow to combine qualitative and quantitative assessments.
- R5: The assessments method should provide the decision makers with actionable knowledge on how to improve the sustainability level in the company.

The next chapters in this book present the selected tools and methods for sustainability assessment in the remanufacturing process, which meet the above mentioned criteria.

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The Remanufacturing of the Automotive Components in Poland—Development Prospect

Karolina Werner Lewandowska

1 Introduction

The development of the remanufacturing of the automotive components is in Poland dictated by an the introduction of the EU provisions to the national legislation, particularly regulations of Directive 2000/53/WE of the European Parliament and of the Council of 18 September 2000 on end-of-life vehicles.

Moreover, the awareness of car manufacturers and users in the field of environmental protection is growing. Many car manufacturers offers its customers the automotive components after remanufacturing. For example Toyota concern proposes: complete remanufactured clutches, alternators, steering gears, actuators, motors/heads, the air conditioning compressor.

The objective of this chapter is to present a development prospect of the remanufacturing of the automotive components in Poland considering two aspects:

- the analysis of statistical data on the resources indispensable to execute a remanufacturing process of automotive parts,
- the analysis of statistical data on the volume of the input stream—the number of end-of-life vehicles.

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2 The Development Prospect of the Remanufacturing of the Automotive Components in Poland in Terms of Existing Resources

The remanufacturing of the automotive components is part of recycling and utilization of end-of-life vehicles and their components system that is directly connected with European Union provisions and legislation, especially with regulations of Directive 2000/53/WE of the European Parliament and of the Council of 18 September 2000 on end-of-life vehicles.

The most important elements of Directive with respect to the development of the remanufacturing process are as follows:

- The duty to create by manufacturers and professional car importers the network of collection, treatment and recovery of end-of-life vehicles, cost of building these networks is also borne by them.
- The obligation for producers to take into account already at the stage of design and production of the cars requirements for the dismantling and recycling of end-of-life vehicles and should also label components and materials, in order to facilitate their identification in order to reuse and recycle.
- The achievement of the following indicators of recovery vehicles: No later than 1 January 2015, for all end-of-life vehicles, the reuse and recovery shall be increased to a minimum of 95% by an average weight per vehicle and year. Within the same time limit, the re-use and recycling shall be increased to a minimum of 85% by an average weight per vehicle and year all end of life vehicles will have to be delivered to authorized collectors/dismantlers. The last car owner is responsible for such delivery and he will receive final demolition certificate necessary to de-register the vehicle (Jastrząb 2011, p. 4).

The author evaluates the prospect of the remanufacturing of the automotive components in Poland in terms of existing resources in context of the range of collection network, recycling and recovery of end of life vehicles and the number of cars deregistered in Poland in recent years.

The duty to create by manufacturers and professional car importers a network of collection, treatment and recovery of end-of-life vehicles written in Directive 2000/53/WE of the European Parliament and of the Council of 18 September 2000 on end-of-life vehicles is consistent with the Polish legislation.

In accordance with article 79.1 of the Act of 20 June 1997 the law on road traffic, the vehicle shall be subject to deregistration at the request of its owner in five cases (The Act of 20 June 1997—Law on the road traffic):

- scrapping in Vehicle Dismantling Station,
- vehicle is stolen,
- export to country, its sale and registration in another country,

- random cause when it is necessary to scrapping the car, even if as a result of an accident or fire-raising,
- justification of permanent and complete loss of the vehicle.

The main task of the manager of dismantling station is to ensure that recycling of end-of-life vehicles and arising wastes will be safe for the environment and human health (Golińska 2013, p. 82).

In 2012 in Poland 784 stations of disassembly holding the integrated permit or other decisions functioned in the required waste disposal in relation to running the station of disassembly (so-called official stations of disassembly) and 125 points of collecting vehicles having a business license in collecting waste (Merkisz-Guranowska 2013, p. 4).

Other points of a recycling network of end-of-life vehicles are presented in Table 1.

Since the implementation of the administrative legislation concerning recycling of end-of-life vehicles in Poland, the number of the dismantling and collecting vehicles gradually increased in each subsequent year (Fig. 1), although the pace of growth in recent years has decreased.

Table 1 The size of the end-of-life vehicle recycling network in Poland in 2012

Points of recycling network of end of life vehicles	Amount (2012)
Shredder and processing scrap, equipped with industrial shear	11
Wholesale ferrous scrap collection centers cooperating directly with the ironworks and foundries	163
Collection centres of non-ferrous metals intended for direct recovery	125
Ironworks and large foundries	20
Non-ferrous metal recovery plants	27
Plants for the processing of cullet of glass and headlights	6
Recovery plants of used oils on an industrial scale	11
Recovery plants of brake fluids	3
Recovery plants of coolants	3
Recovery plants of car batteries	2
Tire recycling plants (excluding plants for the retreading of tires) and recovery organizations of waste tire centre providing the reception of tires from anywhere in the country	About 20
Plants for recovery of plastics from vehicles	17
Rubber waste recovery plants on an industrial scale	10
Cement industry leading energy recovery from waste, including waste from vehicles	3
Oil filters recovery facilities	5

Source own study on the basis (Merkisz-Guranowska 2013, p. 4)

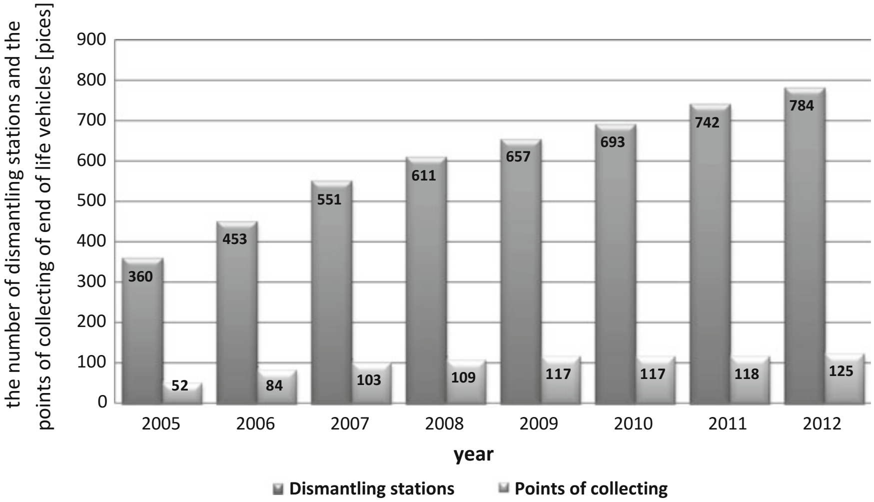

Fig. 1 Dismantling stations and the points of collecting of end-of-life vehicles in Poland in the years 2005–2012. *Source* Own study on the base: (Golińska 2012, pp. 46–49)

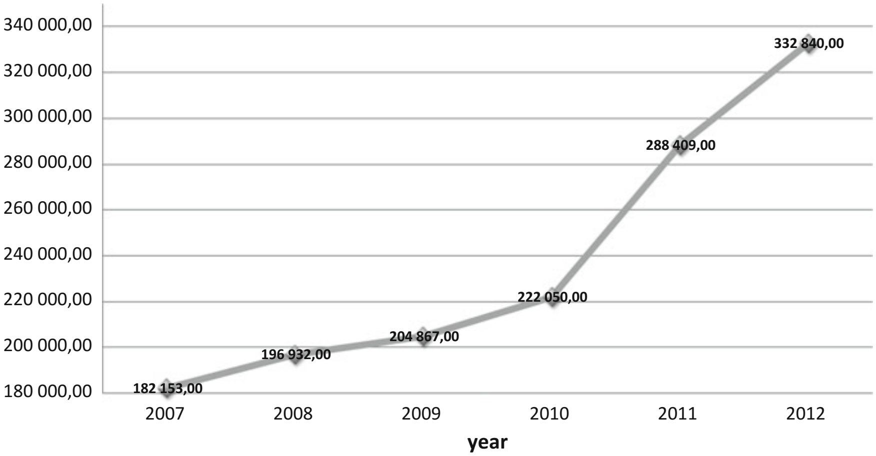

Fig. 2 The number of deregistered vehicles in Poland in years 2007–2012. *Source* own study on the basis (http://www.cepik.gov.pl (12.06.2013r.))

The largest waste stream to further planning is generated by end-of-life vehicles. In accordance with article 4. 79.1 of the Act of 20 June 1997 the law on road traffic, the vehicle shall be subject to deregistration at the request of its owner, inter alia, in the case of scrapping in vehicles dismantling station.

The total number of deregistered cars in Poland in the years 2007–2012 is gradually increasing (Fig. 2).

3 The Development Prospect of the Remanufacturing of the Automotive Components in Poland in Terms of Volume of Input Stream

The development prospect of the remanufacturing of the automotive components in Poland in terms of the volume of the input stream has been assessed by the author in terms of age structure of passenger car park spaces in recent years.

As it results from the annual reports of the Main Statistical Office (GUS) entitled “Transport in numbers” for the vehicles in Poland since 2004, maintains a growing trend with a varying growth (Fig. 3).

The Main Statistical Office data indicate that in 2012 the number of passenger cars in Poland amounted to 18,744,412 units. Approximately 30% of this amount were vehicles over the age of 20 years, only 10% of the Polish car park constituted cars below 5 years, and over 61% of cars in Poland were vehicles aged 6–20 years (Fig. 4).

On this basis, it can be concluded that, in the age structure of passenger cars in Poland favors the development of remanufacturing in the automotive industry.

The existing theoretical and empirical research in the area of remanufacturing of automotive parts indicate that cars between 6 and 15 years old represent the input stream to the process of remanufacturing of automotive components.

As show statistics over the years 2004–2012 share of this age group in the Polish car park has averaged 46% (Fig. 5).

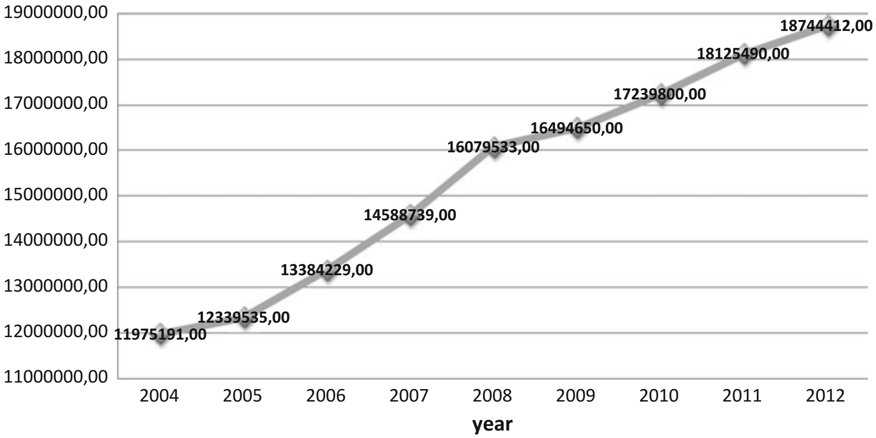

Fig. 3 The number of registered passenger cars in Poland in the years 2004–2012. *Source* own study on the basis: (GUS, “*Transport—wyniki działalności*”, Warszawa, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013)

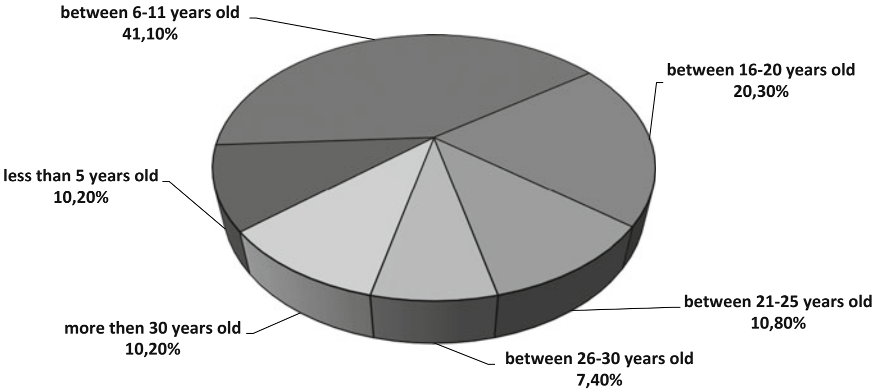

Fig. 4 Age structure of passenger cars in Poland in 2012. *Source* own study on the basis: (GUS, "Transport—wyniki działalności", Warszawa, 2013)

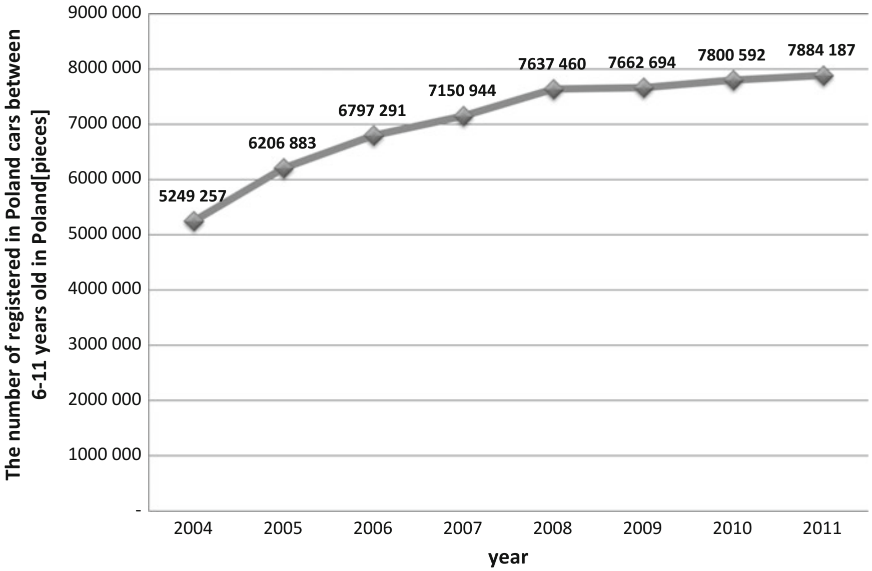

Fig. 5 The number of registered in Poland cars between 6 and 15 years old in Poland. *Source* own study on the basis: (GUS, "*Transport—wyniki działalności*", Warszawa, 2004–2013)

4 The Development Prospect of the Remanufacturing of the Automotive Components in Poland in Terms of Forecasts of the Volume of the Input Stream

On the basis of the data from car park in Poland in the years 2004–2012 and the number of passenger cars between 6 and 15 years old carried out econometric calculations designed to indicate the number of cars in the country, including cars more between 6 and 15 years old in 2020.

To build the prediction of the number of passenger cars in Poland by the year 2020 model used a simple linear regression (*regression methods*).

Method of simple linear regression to predict values for the data with trend characteristics.

Method uses a linear trend Eq. (1):

$$p_{t+1} = a \cdot n + b \tag{1}$$

where

- a—the value of the variable over the period
- b—the value of increase or decrease of dependent variable
- n—the sequence number of analysed and forecast period.

In order to determine a and b parameters it is necessary to solve the two Eq. (2):

$$\begin{cases} a\sum_1^n t_i^2 + b\sum_1^n t_i = \sum_1^n t_i \cdot y_i \\ a\sum_1^n t_i + b \cdot n = \sum_1^n y_i \end{cases} \tag{2}$$

where

- t_i—the period sequence number (t= 1,2,3, …), that is a value of independent time variable
- y_i—dependent variable,
- a—the value of the variable over the period
- b—the value of increase or decrease of dependent variable,
- n—the sequence number of analysed and forecast period.

To verify the model of simple linear regression uses a coefficient of determination R^2, which determines the degree of fit of the model to the empirical data. The coefficient of determination R^2 is a descriptive measure of the strength of the linear relationship between the variables, which is a measure of the fit of the regression line to data (Aczel 2000, p. 490).

The coefficient of determination is in the range <0, 1>. When the value of the coefficient is closer to 1, this means that the estimated model explains in nearly 100% of the variability of the dependent variable. It proves that the model is well fitted to empirical data. If R^2 is close to 0, it means that the model is poorly matched to the empirical data.

The trend Eq. (3) for the analyzed data takes the form:

$$y = 900\,863.37\,x - 1793\,492\,353.74 \tag{3}$$

a *coefficient of determination* $R^2 = 0.98$, what indicates a good match of regression line with a primary data (Fig. 6).

On the basis of the trend equation a forecast of the number of registered passenger cars in Poland up to 2020 has been estimated as 27,028,646 pcs (Fig. 7).

In the same way the forecast calculations has been made for the number of passenger cars between 6 and 15 years old in Poland in 2020.

As shown findings of econometric calculations this number will be formed at the level of 12,224,851 pcs, which will constitute 45% of all vehicles registered in Poland in 2020. Assuming that the age structure of Polish passenger car park will not significantly change until 2020, it can be assumed that almost half of cars respectable numbers in Poland will be a vehicle between 6 and 15 years old, which from the point of view of the remanufacturing is a positive.

The volume of the input streams determine the development of this process in Poland, the stream will be greater the demand for remanufacturing services will grow.

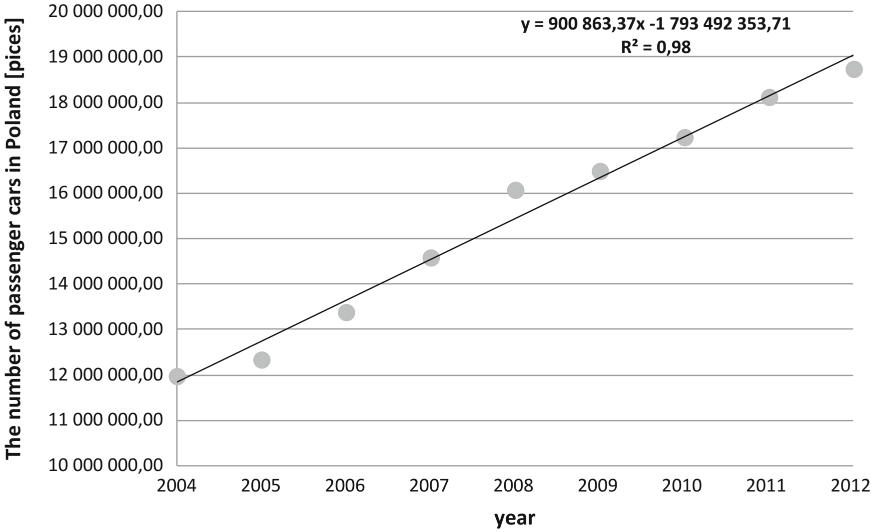

Fig. 6 Trend line and R^2 of number of passenger cars in Poland in years 2004–2012. *Source* own study on the basis: (GUS, "*Transport—wyniki działalności*", Warszawa, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013)

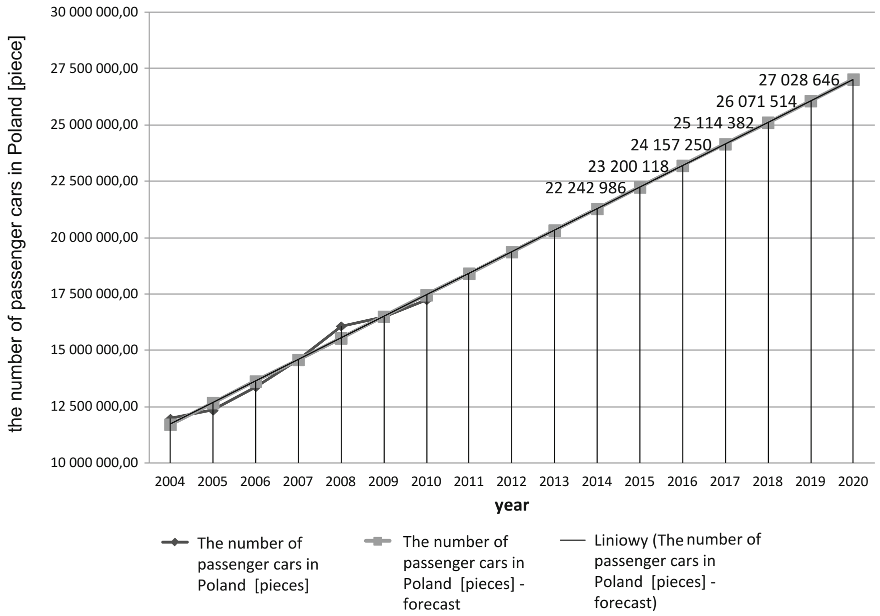

Fig. 7 The forecast of the number of passenger cars in Poland in 2020. *Source* own study on the basis: (GUS, "*Transport—wyniki działalności*", Warszawa, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013)

5 Remuneration, as a Determinant of the Development of Automotive Components Remanufacturing in Poland

Age structure of passenger car park may be derived from the wealth of the country residents.

Therefore, in examining the prospects for the development of remanufacturing process in terms of the volume of the input stream relevant seems to explore the relationship between the level of the average monthly income per person in the household and the age structure of registered passenger cars in Poland.

For that purpose the author proposes the use of analysis of the interdependence of phenomena whose objective shall be to predict the direction and pace of development of examined variables and to define the strength and the shape of relations between the variables.

Correlation which was used in the study, is a special case of the stochastic dependency.

Set the values of one variable correspond to specific mean values of the other variable. One can determine how changes, on average, the value of the dependent variable (Y) depending on the independent variable X. Numerical confirmation of interdependence of phenomena does not always mean the existence of cause-effect between examinees phenomena. The analysis identifies only the existence of the relationship, however, you cannot establish a causal link which is the base of these relationships.

Correlation analysis enables to detect and describe the quantified only interact with the variables. Granting these connections cause and effect character requires a deeper substantive analysis (Wyrwicka and Wener 2010, p. 218).

Pearson coefficient of the correlation is used for variables quantitative in nature. It is used to determine the direction and strength of occurring dependencies.

The value of the coefficient of correlation is calculated from the Eq. (4):

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i \bar{y})^2}} \tag{4}$$

where

- x_i, y_i—values of variables appropriately X, Y for observation $i(i = 1, 2, 3, \ldots, n)$,
- n—the number of observations,
- $\bar{x}, \bar{y}$—values of arithmetic mean for X, Y variables.

The coefficients of correlation with values range from −1.00 to +1.00. The value of −1.00 represents a perfect negative correlation, and a value of +1.00 perfect correlation positive. A value of 0.00 is the lack of correlation (Pedersen et al. 2010, p. 158).

Pearson coefficient of correlation calculated (Table 2) for the relationship between the level of the average monthly income per person in the household and the numerical structure of registered passenger cars in Poland is 0.996043 for the total number of registered cars in Poland, 0.161335 for the number of registered passenger cars newer than 5 years, 0.875392 for cars at the age of 6–15 years, 0.995641 for cars at the age of 16–20 years registered in Poland and 0.985492 for cars at the age of 16–20 years.

The analysis shows that there is positive correlation between average income of household in Poland and the number of registered cars in Poland at the age of

Table 2 The value of correlation coefficient for examined variables

Correlations. Given coefficient of correlation are significant with $p < 0.05000$ N = 9 (the no data was being removed with cases)

	Registered vehicles number (pcs)	The number of registered passenger cars			
		Younger than 5 years (pcs)	At the age of 6–15 years (pcs)	At the age of 16–20 years (pcs)	Of more than 20 years (pcs)
AMGR[1] (PLN)	0.996043	0.161335	0.875392	0.995641	0.985492

Source own elaboration (on the basis on GUS data)

[1] *AMGR* average monthly gross remuneration

6–15 years. This means that the average Pole earns more, the number of cars at the age of 6–15 years in Poland is increasing. This is quite an interesting phenomenon, because it would seem that if the average income per person in the household increases, is the standard of living raised and sold are tangible goods of higher quality.

As the results of correlation analysis, the dependence between the average level of income on people in Poland in the household and the number of registered vehicles not older than 5 years is quite poor.

It means that the number of registered passenger cars newer than 5 years, to a little extent depends on the rise in the monthly income of the average Polish man.

This may be due to factors such as rising inflation, the Poles seem to not treat a newer car, as a manifestation of the improvement of the comfort of life. For an average person, car between 6 and 15 years old, is still good enough and an increased income is not translated into purchase of a car newer than 6–15 years.

From the prospect of the development of remanufacturing of automotive components in Poland depending on the above are positive and suggest that the volume of the input stream to the factory recovery remains on the satisfactory level.

6 Conclusions

Provisions of the directive 2000/53/WE being in force in Poland from 18 September 2000 on end-of-life vehicles is contributing to the development remanufacturing of automotive components in the country.

Described analyses of statistical data concerning prospects of the development remanufacturing of car park in Poland, show the upturn in this respect.

The age structure of the Polish park of passenger cars is pointing, that large volume of the input stream in the prospect of 2020, will be conditioning the development of dismantle stations of end-of-life vehicles.

Both objects of described analysis—resources and the input stream are demonstrating the increasing trend. According to the author it provides the potential in Poland for the development of the remanufacturing process of the automotive components.

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Automotive Parts Remanufacturing—Processes, Problems and Challenges. Case Study on a Polish Remanufacturing Company

Monika Kosacka

1 Introduction

Remanufacturing is an industrial process, which allows to bring back the obsolete or worn out products to the condition "*like a new*" (Golińska 2014). The key term is "*like a new*". From the producers' point of view, this represents the remanufacturers' intent. From the customers' perspective, that statement represents the customers' expectation for the product sold as remanufactured, that remanufactured product is as good as new one, sometimes even better. It may also include some improvements in relation to the product was originally made (Hauser and Lund 2008).

Hauser and Lund (2010) have divided remanufacturing companies into three categories, as follows:

1. **Conventional firms** which purchase cores (the units that are remanufactured), remanufacture them and sell them to new owners directly, through distributors, or through retailers (including retail chains),
2. **Contract firms**, which agree with the owner of a product to remanufacture it and return it to the owner. They provide products to individual owners or customers with fleets, such as trucking companies (tires), airlines (engines),
3. **Original Equipment Manufacturers (OEM)** are manufacturers of a product who also remanufacture their product for resale, typically with the use of through their dealer networks.

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According to TRI[1] any product that can be manufactured can also be remanufactured. Robert Lund identified 75 categories of remanufacturable products and developed reference criteria including (Lund 1985):

- durability of the product;
- functionality failure;
- standardized type of product, consisted of interchangeable parts;
- high level of the added value at end of life stage;
- lower cost of obtaining the core than the remaining intrinsic value;
- stability of the product's technology over a period of time that exceeds the single lifecycle;
- customers' awareness about remanufactured products availability on the market;
- technology providing removing parts from products without damaging them and restoring the product.

The list of the products which are generally remanufactured includes:

- Motor Vehicle Parts;
- Office Furniture;
- Compressors;
- Photo Copiers;
- Laser Toner Cartridges;
- Data Communication Equipment;
- Aircraft Parts;
- Musical Instruments.

At the first place there are motor vehicle parts which become the most significant remanufactured products' group from the perspective of the quantity, frequency and variety of parts.

Remanufacturing business depends on the cores sourcing. In the case of remanufacturing car parts the policy of End of Life Vehicles (ELV) is essential. In different countries there are some national legislation which are related to that issues. Polish law has been adapted to The Directive 2000/53/WE of EU. Although the law regulation, growing awareness of car manufacturers and users in the field of environmental protection (e.g. factory car parts' regeneration by the Toyota company) has an impact on remanufacturing in automotive industry in Poland.

In Poland the biggest group in remanufacturing sector are SME's companies from the automotive sector (car parts).

In that chapter there will be analyzed a representative of the remanufacturing business sector in Poland.

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[1] The Remanufacturing Institute (TRI) is a global non-profit organization providing support for the marketing efforts of the aftermarket remanufactured products community (http://www.reman.org/).

2 Remanufacturing Process Characteristic

2.1 Remanufacturing Process in the Activities' Structure of the Remanufacturing Company

In the remanufacturing business there were determined 5 phases (Fig. 1).

The most important issue for remanufacturing company is sourcing. Without cores company will not have work to do. Cores are delivered by individual suppliers or institutional including car repairs, dismantling stations, etc. Before core will be accepted, it has to meet the requirements determined in Cores Acceptance Conditions (CAC), presented in the Table 1.

It is a good practice to define conditions for accepting delivered cores. Company has defined, so called catalogue of damages, which includes information about types of damages which make remanufacturing impossible. Analyzed company defines the following catalogue of damages, including:

(a) **For starters**: excessive corrosion, damaged rotor shaft, broken fixing holes or broken head;

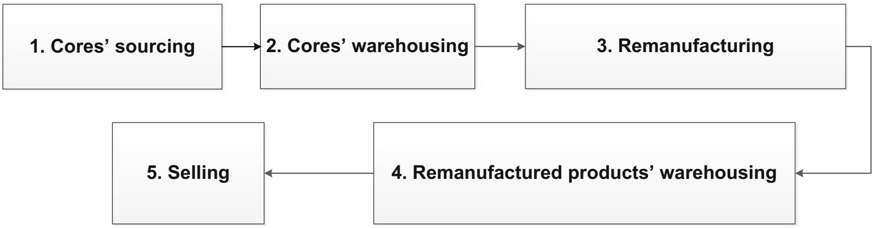

Fig. 1 Phases in the remanufacturing business

Table 1 Cores acceptance conditions (own elaboration based on company materials)

Requirement	Description
Safety	The core is properly packed in order to prevent the negative effects on the environment. The core should have removed all the working fluids, which may negatively affect the environment (e.g. Pump)
Tracebility	Due to the large variety of products, the core should have a manufacturer's number (identification number), allowing recognition of the model, type, parameters (e.g. manufacturer stickers)
Undamaged	Core must not have mechanical defects. All damages should result from their normal use
Completeness	The core must not be decomposed into constituent components—it should be delivered integrally Delivery in parts is accepted, when the core is delivered without normal and: standardized details that require always replacement during the remanufacturing

(b) **For alternators**: mechanical damage of a cover no pump (for parts originally equipped with a pump), minted fixing holes.

The most common cause which make remanufacturing impossible is **excessive corrosion**.

Each core delivered to the company is verified using CAC by visual inspection. In case of any doubts regarding to the completeness of the product, some extended inspection takes place to check internal structure of core.

After positive verification, cores are transported to the warehouse. According to the remanufacturing plan they are collected from the warehouse to feed-in the process.

2.2 Remanufacturing Process Structure

The remanufacturing process consists of many operations. In the literature there can be found different classification of remanufacturing operations (see Hammond and Bras 1996; Steinhilper 1998; Sundin 2004; Ostlin 2008; Golinska 2013). The transformation of the input into output through remanufacturing process can be presented using IDEF0 diagram—level A0 (Fig. 2). IDEF0 method was well described in IDEF0 1993

The IDEF0 diagram on the level 0 presents Input (I), Output (O), Mechanism (M) and Control (C). The inputs are cores and new parts which are used to replace non remanufacturable parts. The process is executed according to control elements such as: legal requirements, internal procedures established by company (e.g. CAC, Warranty terms), industry's standards, knowledge and skills of employees.

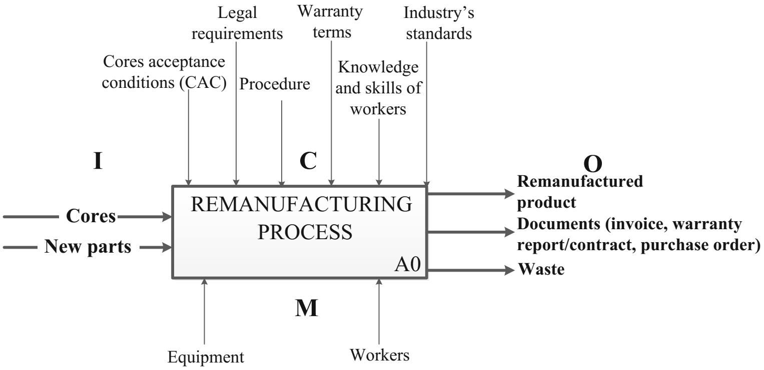

Fig. 2 Remanufacturing process—diagram A0

The process cannot be performed without adequate equipment (such as machines and tools) and people who service them. It is relevant in that business to have good staff and equipment.

The remanufacturing process results in outputs including remanufactured products, waste produced during the process and some documents (e.g. warranty contract or report, purchase order and invoice).

The remanufacturing process can be divided into 8 main activities, as presented in the Fig. 3.

The first phase of the process is disassembling, where parts are separated from the core. During that stage precision and precautions are crucial to provide parts without any damages.

Disassembled parts are verified according to the procedure valid in a company. In the result there are three sets:

1. **Parts for exchange**, which are designed for disposal (they are waste for the company);
2. **Parts in a good condition**, which can be use after cleaning without any further reprocessing;
3. **Parts which require remanufacturing** process to restore them to use.

Parts and components that have successfully passed the first test, are cleaned with appropriate chemicals. Step includes the surface preparation in appropriate way. There are made operations of sandblasting, shot blasting and grinding. It can be performed manually or automatically. It allows to clean up the item from the remnants of old paint, raids etc. The technology depends on the material of remanufactured part and part's features.

Then reprocessing of components takes place. The operations in this phase depend on the type of the components and usually includes welding, rewiring, painting, substituting some parts, etc. That stage is made only for parts which are remanufacturable.

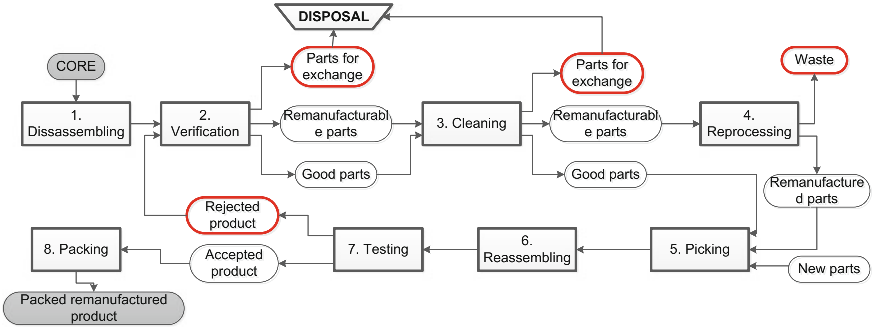

Fig. 3 Remanufacturing process

In the next stage, all parts are picked: new one (very often they are at that moment ordered), as well as remanufactured one (from the previous stages of the process).

During picking operation, it is relevant to assign each part to the product of the same type. This stage is characterized by high variability of the Material Recovery Rate, which is different for each product. The missing parts must be completed in accordance with the predefined structure of the regenerated product (DBOM—Disassembly Bill of Materials). Sometimes parts are ordered at that moment.

The last step is to insert into the process parts, which are always exchanged for new ones—consumable parts (e.g. seal), with 0 percent of the MRR. After the picking, workers can re-assembly all parts into remanufactured product.

In the next stage, assembling products are tested. The accepted products which meet the quality requirements are packed and ready for selling. If the product failed, it should be taken back to the previous step of the remanufacturing process, namely verification.

2.3 Remanufacturing Process Realization in Company Under Study

The analyzed company is remanufacturing starters and alternators. Developed machine park helped to expand business on a larger scale and resulted in the expansion of the offer and cooperation with many companies in the market of automotive, electronics, home appliances and others. In the offer there can be found: new and remanufactured alternators and starters available in several types depending on the destination:

- Vehicles;
- Tractors and machinery for agriculture;
- Trucks.

The company processed more than 700 types of alternators and starters for most cars and machines available on the market. The remanufacturing process is realized according to the procedure presented in the Fig. 3., in the Sect. 2.2.

The remanufacturing process of the alternators and starters was the subject research conducted in the company. In the Table 2, there is presented the analysis for the alternator remanufacturing process with the use of the IDEF0 notification. The remanufacturing process of the alternator consists of 21 different actions. Each action was analyzed from the perspective of the materials, documents and information on the input and output; machines, tools, workstations and workers making mechanism and procedures, regulations creating control. The table is prepared to make the IDEF0 diagrams. The order of the activities is determined by the ID number. Relationships between activities including material and information flow is determined by the activities sequence (ID Previous, ID next).

Table 2 ICOM table for the alternator

ID	Action	I—input	C—control	O—output	M—mechanism	ID previous	ID next	Time (min)
A10	Warehouse release	Cores' source	Plan product	Cores' batch	Cores' warehouse, worker, forklift	–	A20	
A20	Disassembly	Cores' batch	Standards, operation sheets	Parts for cleaning, scrap	Disassembly workstations, hand tools, press, worker	A10	A30, A90, A100, A120	0.21
A30	Cleaning	Parts for cleaning	Standards, operation sheets	Cleaned parts, waste	Washer, worker	A20	A40, A50, A45	7/cycle
A40	Sandblasting	Cleaned parts	Standards, operation sheets	Sandblasted parts, sand	Sandblaster, abrasive, worker	A30	A55, A60	
A45	Electric parts drying	Cleaned wet electric parts	Standards, operation sheets, time of the day	Cleaned dry electric parts, waste	Dryer, worker	A30	A60	240
A50	Shot blasting	Cleaned parts	Standards, operation sheets	Parts after shot blasting	Shot blasting machine, worker	A30	A55, A60	
A55	Galvanizing (cooperation)	Sandblasted parts	Standards, operation sheets	Galvanized parts		A40, A50	A60	
A60	Verification	Parts after cleaning, drying, sandblasting and galvanizing	Standards, operation sheets, stock level	Parts for reprocessing, list of parts for ordering, waste	Verification workstation, rotor winding measuring device, worker	A40, A50, A45, A55	A70, A80, A82, A90, A100, A110, A120	
A70	Ordering new parts	List of parts for ordering	Stock level	Purchase order (new parts)	Computer, programme, internet, worker	A60	A130	
A80	Rectifier reprocessing	Dried rectifiers	Standards, operation sheets	Reprocessed rectifiers	Testers, worker	A60	A130	0.12

(continued)

Table 2 (continued)

ID	Action	I—input	C—control	O—output	M—mechanism	ID previous	ID next	Time (min)
A82	Controller reprocessing	Dried Controllers	Standards, operation sheets	Reprocessed Controllers, waste	Testers, drill, grinder, worker	A60	A130	0.12
A90	Pump reprocessing	Pumps for reprocessing	Standards, operation sheets	Reprocessed pumps, waste	Test instrument, grinder, worker	A60	A130	0.2
A100	Rotor reprocessing	Rotors for reprocessing	Standards, operation sheets	Reprocessed rotors, waste	Slip rings exchange workstation, press, tables, drill, grinder, racks, lathe, worker	A60	A130	0.16
A110	Stator reprocessing	Stators for reprocessing	Standards, operation sheets	Reprocessed stators, waste	Cleaning device, tester, Soldering pots, worker	A60	A130	0.11
A120	Pulley wheel and fan reprocessing	Pulley wheel and fan for reprocessing	Standards, operation sheets	reprocessed pulley wheel and fan, waste	Reprocessing workstation, worker	A60	A130	0.1
A130	Picking and parts ordering	All reprocessed parts (unsorted)	BOM of reprocessed products, stock level.	All reprocessed parts (sorted), purchase order (missing parts)	Table, worker	A70, A80, A82, A90, A100, A110, A120	A140	
A140	Final reassembly	All reprocessed parts (sorted), Delivered missing parts, packages	Standards, operation sheets.	Reassembled products, waste (packages)	Reassembly workstations, grinder, computer, worker	A130	A150	0.38
A150	Coating/painting	Reassembled products, paint, varnish	Standards, operation sheets, customer's requirements	Painted products,	Spray booth	A140	A160	

(continued)

Table 2 (continued)

ID	Action	I—input	C—control	O—output	M—mechanism	ID previous	ID next	Time (min)
A160	Final testing	Painted products	Standards, operation sheets, new products parameters	Tested products, reports from tests	Tester, intermediate storage tables, computer, worker	A150	A170	
A170	Packing	Tested products, packages	Standards, customer requirements	Packed products	Worker, tables	A160	A180	
A180	Transfer to the final products warehouse	Packed products	Disposition of packing in overpacks	Information about remanufactured product ready to receive	Foklift, worker	A170	–	

Considering data included into Table 2, it may be perceived that the remanufacturing process is very complex and it requires involvement of many material, information and human resources. The whole process is controlled by the operations sheets. There is one operation—galvanization which is made in the cooperation. Rest of the activities are made, in the analyzed company, with the use of the resources, of which the company is the owner.

3 Remanufacturing Problems

3.1 The Characteristics of Remanufacturing

The remanufacturing business is a difficult activity. In many papers there is presented the comparison of remanufacturing and manufacturing where the objective is to emphasize the complication of the remanufacturing (e.g. Golinska and Kawa 2011; Sutherland et al. 2008).

The complicating characteristics of remanufacturing is created by a few areas, including:

1. Product characteristic;
2. Market issues;
3. Technical issues;
4. Management issues.

3.1.1 Product Characteristic

Many authors have pointed as a key complication of remanufacturing the product differentiation (Cheng-Hu et al. 2015; Hammond et al. 1996; Wei et al. 2015; Guide 2000).

Manufacturers are practicing of making many variations of the same product with one or two minor differences, what results in increasing diversity of products, what is a challenge for remanufacturers. In reality there is not only high volume of cores but also various types, series and versions (Cheng-Hu et al. 2015). The remanufacturer in contrast to the manufacturer has to deal with small batches encompassing a range of product variants and generations, what makes tool-changing, disassembly, and assembly processes complicated (Seitz and Peattie 2004).

Moreover acquired cores are characterized by various quality level (Cheng-Hu et al. 2015). It should be noticed that in the reality, the quality of each acquirable core may be different and unknown before acquisition (Teunter and Flapper 2011). It is common for remanufacturing companies to remanufacture cores without quality analysis. In the result there are remanufactured cores with a poor quality (Cheng-Hu et al. 2015).

The high level of the variability of cores according to the number and quality, results in small production size, high level of inventory (against uncertainty), long inventory cycle and variable process lead times (Golinska and Kawa 2011).

3.1.2 Market Issues

From the perspective of the market issues there can be distinguished the following areas:

- Competition with the manufacturers of new parts;
- Legislation restrictions for remanufacturing companies;
- Uncertainty in timing and quantity of supplies;
- Customers of remanufactured products.

The remanufacturing companies have a problem with balancing returns and demand (Guide 2000). There is a problem with obtaining cores (returns), while at the same time it is still common that remanufacturing is unfamiliar concept among the customers (Wei et al. 2015).

According to the research conducted by (Abdulrahman et al. 2015) consumers consider remanufactured products as essentially inferior products which can only be purchased at a giveaway price in comparison to similar new products. What is more, there is greater competition between companies offering new parts and those offering remanufacturing products. The biggest competitor for the manufacturer is a China producer of products of low quality but also low level of the price. It is relevant especially in the context of lack of confidence in remanufactured parts among potential customers. Moreover, remanufacturing companies have to deal with competitors offering low—priced new products, while costs of running business are increasing, and there are observed greater requirements according to legislation restrictions (Wei et al. 2015).

Abdulrahman et al. (2015) have noticed that there is a problem in the case of companies, which offer new product and the remanufactured one, because of the possible brand damage they may face. The next barrier to engage in remanufacturing is possible cannibalization of a new product market by remanufactured products following low prices.

There is a high uncertainty level in the timing and the quantity of returns in the case of cores supplies (Guide 2000). According to research conducted by Guide (2000) over half—61.5% of the firms report that they have no control over the timing or quantity of returns, what will be affected inventories, the level of machines utilization, process lead time, etc.

3.1.3 Technical Issues

Technical issues in remanufacturing are complicated, they require significant modifications to traditional production planning and control systems (Guide 2000).

In the effect of the remanufacturing process there is obtained a remanufactured product "*as good as a new one*", sometimes better.

In order to fulfill those high requirements, company needs appropriate material resources—machines and tools. There are technology constraints in remanufacturing—use of old machines, lack of specialized technology for remanufacturing are the major problems (Wei et al. 2015).

Moreover, there are problems with the design of the product, which makes the product not intended to remanufacturing. Product design influences the disassembly and possibilities of reprocessing parts of the remanufactured product (Abdulrahman et al. 2015).

Another issue is material matching (Abdulrahman et al. 2015; Ferrer and Whybark 2001). It is a problem at a disassembly stage, where both unique and common parts in the cores, are disassembled (Ferrer and Whybark 2001). Sometimes customers require cores and assembled components matching, what will require the change of the disassembly schedule (Ferrer and Whybark 2001).

3.1.4 Management Issues

Many authors have pointed as a key complication of remanufacturing business, lack of the organizational integration (Abdulrahman et al. 2015; Tibben-Lembke and Rogers 2002; Hammond et al. 1998). The problem statement is related to the following issues, including (Hammond et al. 1998):

- location of take-back centers,
- product return incentives,
- transportation methods,
- decisions on constructing reverse logistics channels.

What is more, the management issues include problem with availability of the skilled workforce (Abdulrahman et al. 2015; Guide and Van Wassenhove 2001). The availability of a skilled workforce is critical aspect as remanufacturing is inherently labor intensive, due to the fact that major operations are made manually, with no automated techniques (Guide and Van Wassenhove 2001). In the result, it was stated, that experience and technical skills of Employees are relevant for the remanufacturing process correctness.

It was assumed, that remanufacturing company must be able to manage complex tasks, different from tasks in a traditional manufacturing environment.

3.2 Remanufacturing Process Defects and Problems—Case Study

Running a remanufacturing company is related to the problems which are resulting from remanufacturing process characteristics. Typical problems related to the activities realized during remanufacturing process were defined in the Table 3 according to conducted Process Failure Mode and Effects Analysis (PFMEA).

Table 3 Typical problems in remanufacturing process

No	Activity category		Examples of defects and problems
1	Disassembling	1.1	Parts' damages
		1.2	Incorrect assessment of the suitability of reuse option for a part
		1.3	High time required for disassembling
		1.4	Inseparable connections between components (e.g. glued)
		1.5	Product not designed for disassembling
2	Verification	2.1	Incorrect assessment of the part (e.g. good part verified as a waste)
		2.2	Parts' damages
		2.3	Impossible verification (e.g. dirty part, lack of model and parameters description)
3	Cleaning	3.1	Inaccurate cleaning (part remains dirty)
		3.2	Parts' damages (e.g. inappropriate cleaning parameters)
4	Reprocessing	4.1	Improper performance of the operation
		4.2	Parts' damages
		4.3	Inappropriate processing parameters (e.g. used tools)
		4.4	Machines/tools damages
5	Picking	5.1	Parts assigned to wrong transport containers
		5.2	Delivery/order errors of new parts which are always replaced (e.g. delay, inadequate number or quality)
		5.3	Delivery/order errors of parts exchanged due to the impossible reprocessing (e.g. delay, inadequate number or quality)
		5.4	Downtimes (source: lack of parts)
6	Reassembling	6.1	Incorrectness in matching parts (parts not from the same product)
		6.2	Measurement inaccuracy during assembling
		6.3	Parts' damages
		6.4	Delays in the operation execution (e.g. lack of parts, busy machines)
7	Testing	7.1	Product's damage during testing
		7.2	Acceptation for product which does not meet the quality requirements
8	Packing	8.1	Products' damages
		8.2	Packing error (noncompliance of a product with the markings on the packaging)
		8.3	Delays in order fulfilment
		8.4	Lack/inadequate security of the remanufactured product

Source Own elaboration on the basis of research in analyzed company

Considering data presented in the Table 3, it was noticed, that the most common and serious problem is part's damage. When remanufacturable or good part is broken, there is noticed a loss in a process. Instead of the profit for the company (lower cost of the remanufacturing of the old part than buying new one) and lower environmental burden, new components have to be involved. It results in less sustainable remanufacturing process. The problem is related not only to the workers as the result of their carelessness, but the major cause is poor condition of the acquired cores mostly, because of that, there are reprocessed cores which are not susceptible to remanufacturing.

In order to identify problems and to determine some preventive measures it was recommended to make PFMEA.

3.3 Problems in Remanufacturing—Sustainable Perspective

Sustainable development issues become a platform to discuss problems in the remanufacturing from the perspective of three dimensions:

- social;
- economic;
- ecologic.

There was used Ishikawa diagrams in order to identify potential factors causing an overall effect (problem) related to each sustainability dimension. In the Ishikawa diagrams, causes of the problem are usually grouped into major categories to identify sources of variation (Ishikawa 1976).

The first examined sustainability dimension was "*Social*". It was considered from the point of view of Employees. Due to the nature of the work associated with the remanufacturing process, workers are exposed to conditions detrimental to health. The major social problem was "*Threats to health of workers*" (Fig. 4).

In the analyzed company there were identified 5 main categories of problem sources including: Employee, Remanufacturing process (organization), Machines,

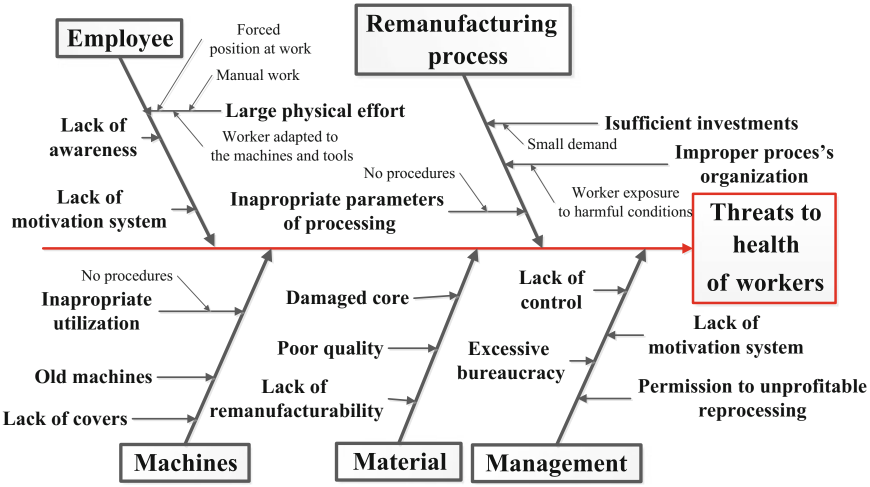

Fig. 4 Ishikawa diagram for a problem of threats to health and life of employees in remanufacturing company

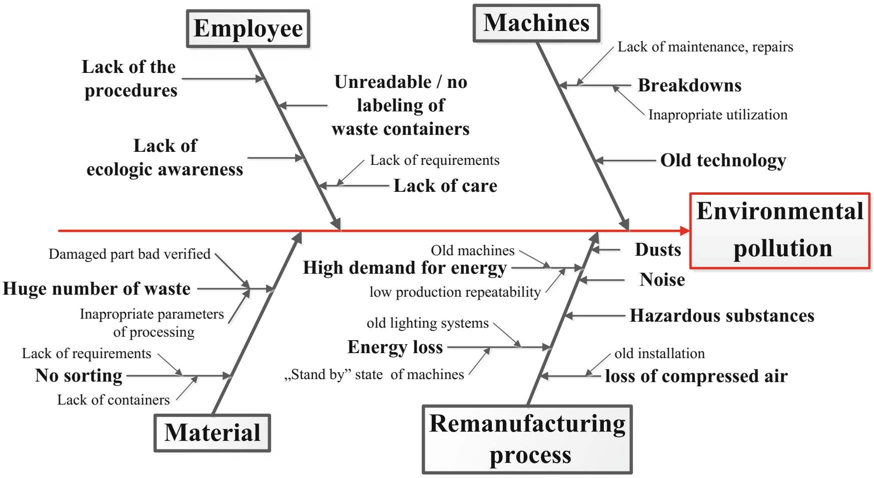

Fig. 5 Ishikawa diagram for a problem of environment pollution in remanufacturing company

Material (Cores) and Management. It was noticed that threats to health are not only caused by workers. There is a potential in building their awareness and motivate them, because when the worker is hurt or sick, there will be a problem with finding somebody for replacement. What is more, workers should be unburdened with the heavy physical effort. Sometimes machines, tools and material which have some defects are the basic source of threats for workers.

The second examined sustainability dimension was "*Environment*". It is relevant from the perspective of conducting a business, especially which has an impact on the Environment, to identify consequences related to the business. During the remanufacturing process, particularly dangerous for the environment are waste and emissions of hazardous substances. Figure 5 presents the Ishikawa diagram which was made on the problem of environmental pollution.

The pollution of the Environment is caused by 4 types of reasons, including: Machines, Employee, Material and Remanufacturing process. From one point of view people are not aware of the Environment pollution problem. What is more, there are used old machines, which are energy-consuming. The remanufacturing process is often organized without taking care of waste which are additional result of it beside remanufactured product. Waste are not sorted. That situation leads in inappropriate waste and resource management.

The last examined sustainability dimension was "*Economy*". It was assumed that problems in the economic dimension primarily include inefficiencies (muda) which were analyzed using the Ishikawa diagrams. The analyzed types of muda include:

1. unnecessary transport;
2. unnecessary motion;
3. waiting;

4. defects;
5. overproduction;
6. excessive inventories;
7. inappropriate processing;
8. underutilization of people.

Result of the carried out analyses for all 8 types of muda is presented in the Table 4.

According to the developed analysis with the use of Ishikawa diagrams, the author stated that there is a great improving potential regarding sustainability. Remanufacturing is a kind of sustainable business from the nature—it ensures resource conservation. Although the nature the realization of the remanufacturing business and process should be sustain from the ecologic point of view as well as social and economic aspect.

4 Remanufacturing Challenges

Taking into account all mentioned problems in previous chapter it was assumed that the catalogue of remanufacturing challenges for analyzed company includes the following issues (Fig. 6).

Table 4 Identification of sources of muda in remanufacturing company under study

No	Primary Causes	Secondary causes	Thirdly causes
1	Several times transport/loading/unloading	Storing materials in many places	*Organization errors*
		Changes of storing places	*Organization errors*
	Mistakes in parts downloading	No/not clear identification of parts/containers	*Lack of universal system*
2	Organization of the workspace	Disorder	*Lack of control*
			Lack of standards
		Tool problem	*Lack of tools*
			Poor quality tools
		High physical effort	*Manually activities*
			Transport heavy parts without means of transport
		Forced position at work	
	Organization of the process	Long distance between workstations	*Organization errors*

(continued)

Table 4 (continued)

No	Primary Causes	Secondary causes	Thirdly causes
3	Waiting for material	Diversity in time of operation (longer time than it was planned)	*Diversity in cores quality condition*
			More attention due to poor quality
		Part's damage during reprocessing	*Poor quality (e.g. corrosion)*
			Reprocessing parts without analysis of susceptibility to reman
		No order (new parts)	*Lack of ordering procedure*
			Lack of information
		Mistake in order/reassembly	*No/not clear remarks of the core*
		Material matching restrictions	
	Waiting for machines	Breakdown	*Lack of maintenance*
			Lack of inspection plan
			Inappropriate service
		Machine is busy with other work	*Diversity in time of operation (longer time than it was planned)*
		Retrofitting the machine	*Many changes of production (small batch)*
	Waiting for tools	Tools are unavailable	*Not enough number of tools*
			Workers are using tools from other workstations
		Poor technical condition	*Lack of replacement of old tools*
4	Transport defects	Transport damages	*Lack of security/containers*
			Carelessness of the worker
			Long distance between workstations
		Parts loss	*Lack of security/containers*
			Lack of transport order
	Defects during reprocessing	Reprocessing damages	*Cores poor quality (e.g. corrosion)*
			Reprocessing parts without analysis of susceptibility to reman
			Wrong verification of the core
		Reprocessing parameters	*Lack of the procedure*
			Old machines
			Poor condition of tools
		Employees	*Carelessness*
			Lack of skills

(continued)

Table 4 (continued)

No	Primary Causes	Secondary causes	Thirdly causes
5	Planning problems	No cores sourcing planning	
		No balancing returns with demand	*No profitability analysis for remanufactured products*
	Remanufacturing process	Blocked material flow	*Long time of retrofitting*
			Limited resources (workers/machines)
			Limited space for storing
		No balanced workstations	
6	Planning problems	No balancing returns with demand	*No analysis for the market of remanufactured parts*
			Buying cores without limitations
	Storing problems	Parts quantity at the workstations exceed the daily need	*Lack of space*
		Warehousing products in many different places	*Space organization errors*
7	Technical problems	Expensive instrumentation	
		Corrections	*Low level of machine accuracy*
			Multi-service workers
			Poor quality of the core
	Employees	Lack of instructions	
		Lack of procedures	
		Low level of skills	*Lack of trainings*
		Lack of information about customer’s requirements	
8	Lack of motivation	Lack of promotions	
		Lack of trainings	
	Lack of initiatives	Lack of the necessary at the top management level	

Source Own elaboration

There were distinguished 6 categories of challenges including the remanufacturing process with its input and output processes as well as Management controlling the process and Technology with Employees used in the process realization.

All challenging categories are described in details in the matrix presented in the Table 5.

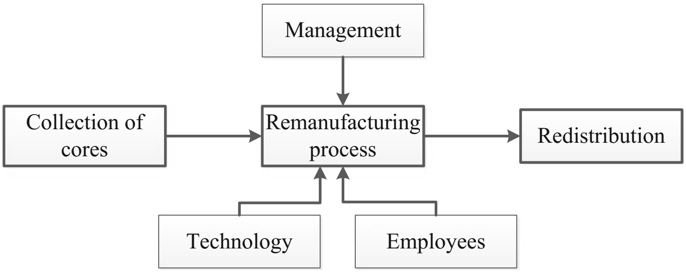

Fig. 6 Categories of challenges for the analyzed remanufacturing company. *Source* own elaboration

Table 5 Challenges for remanufacturing company under study

Technology	Employees	Management
Equip workstations with improved tools	Working conditions improvements	The sequence of production steps within reman process
Machines modernization	Box of ideas	Motivation system for workers
		Improvement of information flow (operation sheets, procedures for operation, standards)
Machine Inspection plan	Trainings (internal/external)	Reorganization of the space (min. distance)
Cores' collection	Redistribution	Remanufacturing process
Advertising services	Forecasting the demand	Simplify remanufacturing operations
		Increase batch size
Control the quality of cores		Automation of operations
	Building relationship with customer	Turning off machines when they are not used
		Waste sorting
Selecting the group of remanufactured cores		Parts/waste containers labelling (universal system)
		Simple means of internal transport

5 Conclusions

The aim of this chapter has been to explore the remanufacturing process from the perspective of the process flow, problems and challenges of the Polish remanufacturing company. There were presented constraints from the literature which were confronted to the reality.

The need to improve vital categories of the remanufacturing business is revealed. The major remanufacturing challenges for the analyzed company are identified and classified into six categories: remanufacturing process, cores collection, redistribution, employees, technology and management.

The findings of this research will contribute to the future development of improvement potential for remanufacturing company.

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Methodology for Determining Sustainable Improvements' Potential in Remanufacturing Companies Using RMC

Monika Kosacka and Paulina Golinska-Dawson

1 Introduction

Remanufacturing "*can be defined as industrial process in which returned products named as cores are restored to their full functionality in order to be used for at least another lifecycle*" (Golińska and Kübler 2014). During the process, the core (used product) passes through a number of remanufacturing operations. There are different classification of remanufacturing operations in the literature (Bras and Hammond 1996; Steinhilper 1998; Sundin 2004; Golińska 2013). Following Steinhilper (1998) and Sundin (2004) the generic structure of the remanufacturing process is defined, as follows:

- inspection,
- cleaning,
- disassembly,
- reprocess,
- reassembly,
- testing.

Remanufacturing is an example of sustainable practice due to the fact that it has positive impact in all dimensions of sustainable development (Fig. 1).

Remanufacturing requires less energy—typically it is 85% less energy than during manufacturing (Steinhilper 1998, p. 6). Moreover it allows processing of reused components and recycled materials, thanks to that, level of waste is lower.

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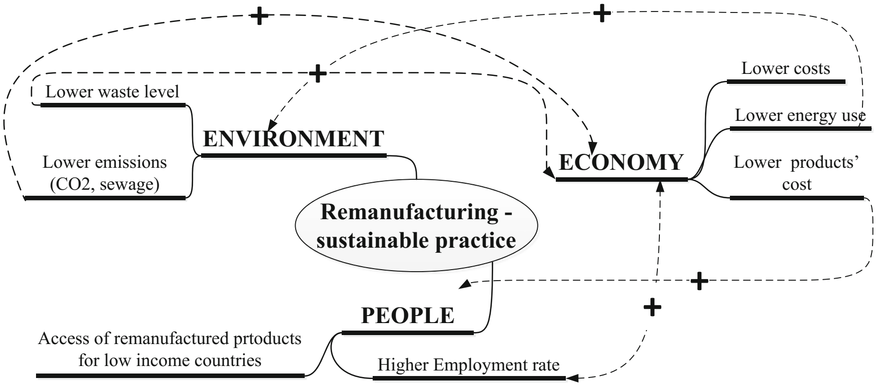


Fig. 1 Remanufacturing as a sustainable practice. *Source* Own elaboration based on (United States International Trade Commission 2012; Golińska 2014)

What is more the whole process generates less emissions (CO_2, sewage) (Charter and Gray 2007, p. 14). In the result, total cost of the process is lower.

The positive social impact is achieved mostly by the redistribution of remanufactured products to low-income markets and creating new working places (it is difficult to automate most of the remanufacturing operations) (Golińska 2014).

Remanufacturing companies are faced with many problems including: higher level of uncertainty in process, as well as unpredictability of cores (returned products or their parts) quality and quantity (Sundin 2006).

The greatest challenge for companies in the remanufacturing sector is integrating economic, ecological and social aspects in their daily business. Most of the remanufacturing companies are SMEs, which have lack capacity, know-how and technical infrastructure (Golińska and Kübler 2014). These features are some obstacles in implementing sustainable solutions.

There is a need for simple procedure for remanufacturing companies which will help them to identify optimization potentials for increasing sustainability of the remanufacturing process.

It was assumed that remanufacturing process is more sustainable, if there is efficient utilization of the resources. The basic requirement for efficient resource utilization is lack of waste of resources.

The possibility of achieving better effectiveness of processes realized in a company is waste identification elimination. It was assumed that the potential for improvements is hidden by muda (waste). The aim of this chapter is to discuss the method, which provides simple tool—Remanufacturing Muda Checklist for identifying and eliminating obstacles for increasing sustainability of the remanufacturing process.

2 Theoretical Background of Lean—Concept of Continuos Improvement

There are two main possibilities of process's improvement (Schmelzer and Sesselmann 2003):

- radical, resulting in alterations and reconstruction of processes (e.g. Business Process Reengineering),
- continuous, where changes are introduced step by step, what results in gradual improvements.

The Lean concept is example of continuous improvement, which originated from Toyota Motor Corporation in Japan (Monden 1983; Ohno 1988). The first use of the term "*lean*" was noticed in a work of Womack et al. (1990).

"Lean" refers to lean manufacturing or lean production, if it uses less of resources such as: people, tools, machines, energy, buildings etc., in comparison to mass production (Womack et al. 1990; Bayou and De Korvin 2008).

Pettersen (2009) stated, that there is lack of consensus on a definition of lean production among the experts. In the consequence, there appear problems for practitioners seeking to implement lean as well as for researchers trying to capture the essence of that concept. Pettersen (2009) defined over 30 lean production characteristics addressed by the most cited authors in this field (based on results from Scopus and ISI). It was noticed that only continuous improvement and set-up reduction were discussed by all the analyzed authors (Golińska 2014).

The lean application in remanufacturing is problematic issue which was described by Guide (2000) although it is present in the literature for almost 20 years (Golińska 2014).

Hines et al. (2004) distinguished two dimensions of lean: strategic and operational. The strategic orientation refers to creating a value chain for the customer taking into account all his requirements. The operational orientation should be focused on application of the shop-floor tools which will reduce waste in order to improve quality, cost and delivery.

In such a case, the focus should be on operational issues of lean implementation. The operational approach emphasizes "*shop-floor-focus*" on waste and cost reduction. That is equal to better utilization of resources, what is more friendly for the environment and brings savings from the economic perspective. Moreover, lean concept is focused on human relations management (Golinska 2014).

In many papers lean concept is presented as a concept of maximizing the process effectiveness by waste eliminating (Womack et al. 1990; Bayou and De Korvin 2008; Bhim et al. 2010). The main assumption of that chapter is, that process will be more sustainable, if there is efficient utilization of the resources, what depends on waste elimination.

The basic issue of lean concept is muda—what means waste. Muda are well—known in the literature (Ohno 1988). Ohno has identified seven types of waste including (1988):

- Overproduction;
- Waiting;
- Unnecessary motion;
- Transportation;
- Inventory;
- Inappropriate processing;
- Defects.

Some of researches (Liker 2004; Wahab et al. 2013) identify additional waste: *Waste of underutilized people*. All muda type are regarded as opportunities with the same significance for remanufacturing process improvement, in the context of sustainable development.

The reference model for the remanufacturing company is to achieve the state of "*zero muda*", what will be synonymous with *the best resource utilization*. Muda becomes an obstacle to achieve that desirable state, what means that muda should be eliminated. The greatest problem is: "*How to identify muda*?" When muda are identified, company will be able to take some further corrective actions to become more sustainable, therefore authors have prepared tool for identyfiying improvement potential in remanufacturing.

3 Improvements' Potential in Remanufacturing Companies Using RMC

In order to identify potential for improvements of sustainability in remanufacturing company, it was created a method on the base of modified Rapid Plant Assessment (RPA). The method is presented in (Fig. 2).

Firstly, the object (remanufacturing process) should be well recognized with the use of analysis such as Value Stream Mapping or IDEF0. In the next step there should be made a modified RPA analysis, resulting in the list of weakness and strengths. Weaknesses are verified with the Remanufacturing Muda Checklist, after which identified muda with a high priority become a source of the requirements for corrective actions. All identified strengths should be monitored.

The whole process of determining improvements' potential is presented in details in Fig. 3.

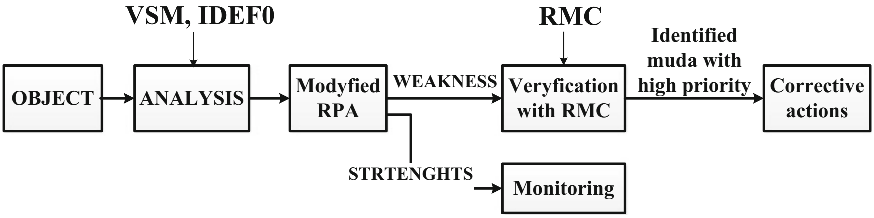


Fig. 2 Method of determining sustainable improvements' potential—basic scheme

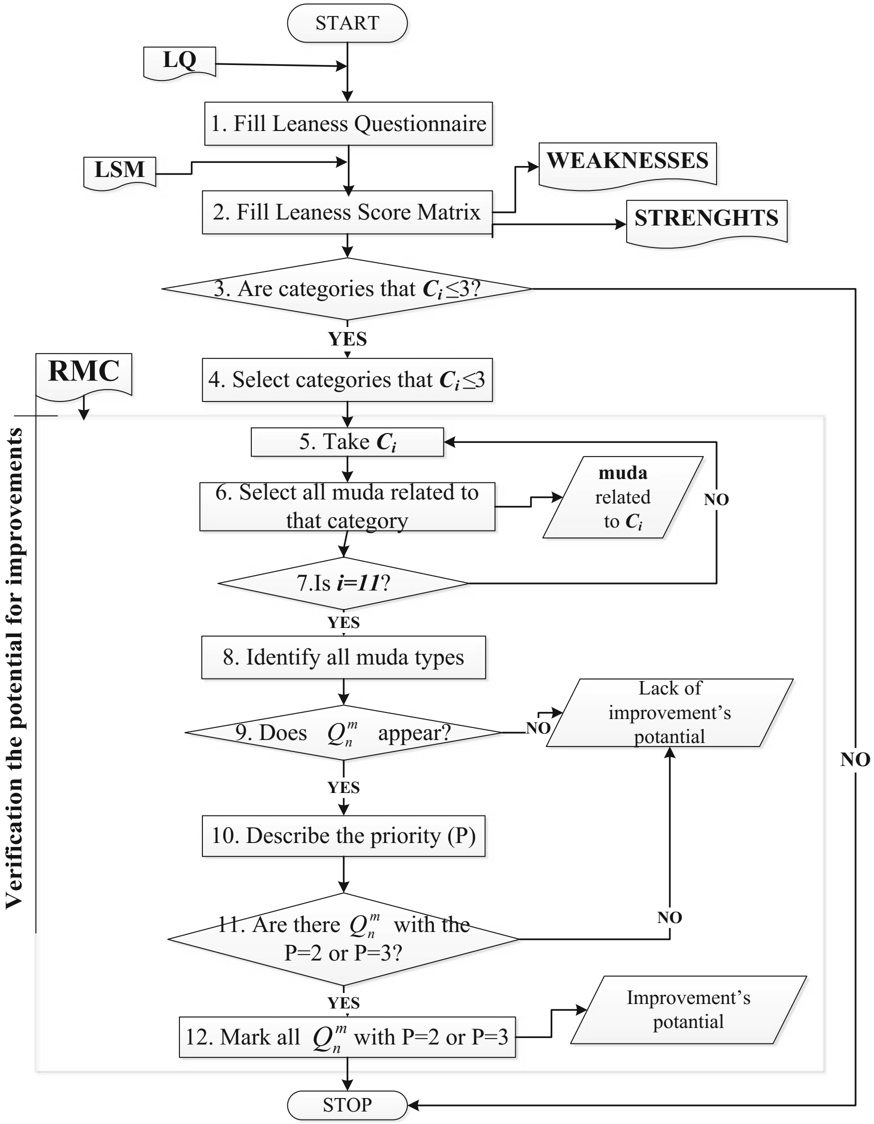


Fig. 3 Process of determining the improvement's potential

3.1 *Modified RPA as a Tool for Searching Weaknesses in a Remanufacturing Company*

RPA is a tool for leanness assessment of a plant elaborated by Goodson (2002). Traditionally that analysis consists of two forms in the following order (Goodson 2002):

- The Leanness Score Matrix (LSM, RPA rating sheet),
- The Leanness Questionnaire (LQ).

RPA was modified by researches in respect of order of realized steps and including a sustainability issues in the procedure. The first tool recommended to use, is the Leanness Questionnaire (Fig. 4).

The RPA questionnaire contains 20 yes/no questions to determine, if the plant uses best practices. It was assumed that after identifying pointed in the questionnaire situations, there is higher probability of adequately assessment in the Leanness Score Matrix. Those two forms are connected. The relationship between them is presented in Table 1.

It can be noticed that some of the questions are linked to only one category, but often there is a situation that a question is associated with a few categories.

The second tool is the Leanness Score Matrix (hereafter: LSM), presented in the Fig. 5.

LSM is a simple and logic table. Scoring is rather general and elaborated for production company taking in consideration 11 areas, where (Goodson 2002):

$\boldsymbol{C_i}$—the i-th category of the LSM, $\boldsymbol{i} \in <1, 11>$.

Those areas the same for production facility as well as for remanufacturing company. The scale for scoring includes 6 levels, as follows (Goodson 2002):

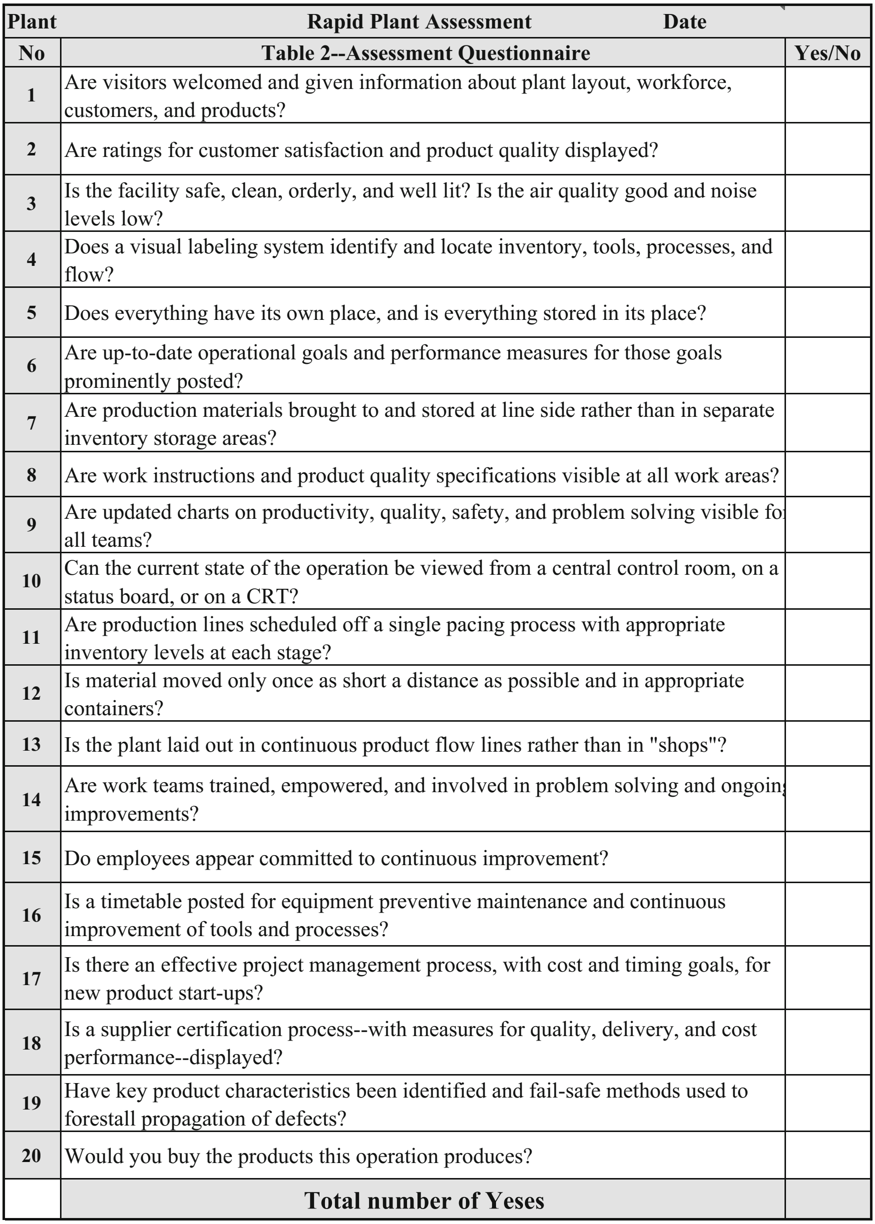
- Poor—1 point
- Below average—3 points,
- Average—5 points,
- Above average—7 points,
- Excellent—9 points,
- Best in class—11 points.

Company is assessed in each category. Value for the i-th category is determined as: $\boldsymbol{C_i} = \mathrm{x}$. As a result of that stage, there are identified categories (broad areas) of strengths and weaknesses of chosen company. The potential for improvements is hidden in the areas (categories) with low ratings (3 and less). Those areas should be a subject of immediate action, in order to provide the leanness (Sundin 2004).

The modified RPA assigns each category to adequate dimension of the sustainability (see Table 2):

- economic (ECON),
- ecological (ECO),
- social (SOC).

It can be noticed, that most of the categories are related to more than one dimension of the sustainability (e.g. Supply Chain Integration), what makes the analysis the multifaceted one. After that step, company has a knowledge about the condition of each dimension of sustainability.

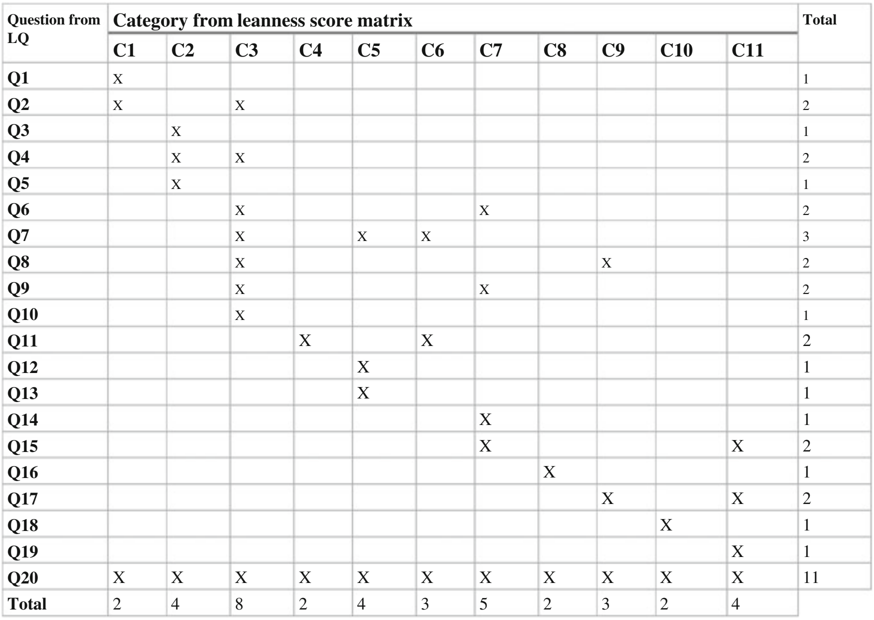


Plant	Rapid Plant Assessment Date	
No	**Table 2--Assessment Questionnaire**	**Yes/No**
1	Are visitors welcomed and given information about plant layout, workforce, customers, and products?	
2	Are ratings for customer satisfaction and product quality displayed?	
3	Is the facility safe, clean, orderly, and well lit? Is the air quality good and noise levels low?	
4	Does a visual labeling system identify and locate inventory, tools, processes, and flow?	
5	Does everything have its own place, and is everything stored in its place?	
6	Are up-to-date operational goals and performance measures for those goals prominently posted?	
7	Are production materials brought to and stored at line side rather than in separate inventory storage areas?	
8	Are work instructions and product quality specifications visible at all work areas?	
9	Are updated charts on productivity, quality, safety, and problem solving visible fo all teams?	
10	Can the current state of the operation be viewed from a central control room, on a status board, or on a CRT?	
11	Are production lines scheduled off a single pacing process with appropriate inventory levels at each stage?	
12	Is material moved only once as short a distance as possible and in appropriate containers?	
13	Is the plant laid out in continuous product flow lines rather than in "shops"?	
14	Are work teams trained, empowered, and involved in problem solving and ongoin improvements?	
15	Do employees appear committed to continuous improvement?	
16	Is a timetable posted for equipment preventive maintenance and continuous improvement of tools and processes?	
17	Is there an effective project management process, with cost and timing goals, for new product start-ups?	
18	Is a supplier certification process--with measures for quality, delivery, and cost performance--displayed?	
19	Have key product characteristics been identified and fail-safe methods used to forestall propagation of defects?	
20	Would you buy the products this operation produces?	
	Total number of Yeses	

Fig. 4 The leanness questionnaire. *Source* (Goodson 2002)

To ensure, that method will include sustainable issues, there was made survey about the correlation between categories from RPA rating sheet and muda types (Golińska 2013). The questions from LQ and in the Categories from LSM were divided into 8 muda types **m**, where **m = {1, 2, 3, 4, 5, 6, 7, 8}**), namely:

Table 1 Relationship matrix of leanness questionnaire and leanness score matrix



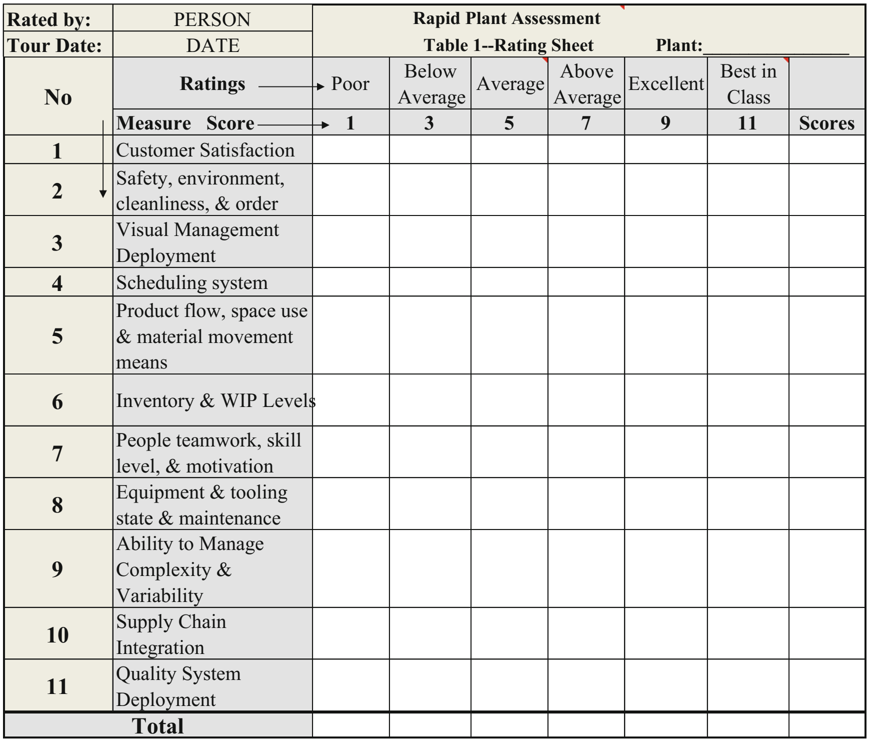
Question from LQ	Category from leanness score matrix											Total
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	
Q1	x											1
Q2	x		x									2
Q3		x										1
Q4		x	x									2
Q5		x										1
Q6			x				x					2
Q7			x		x	x						3
Q8			x						x			2
Q9			x				x					2
Q10			x									1
Q11				X		X						2
Q12					X							1
Q13					X							1
Q14							X					1
Q15							X				X	2
Q16								X				1
Q17									X		X	2
Q18										X		1
Q19											X	1
Q20	X	X	X	X	X	X	X	X	X	X	X	11
Total	2	4	8	2	4	3	5	2	3	2	4	

- m = 1 stands for Overproduction,
- m = 2 stands for Excess inventory,
- m = 3 stands for Waiting,
- m = 4 stands for Inappropriate processing,
- m = 5 stands for Transport,
- m = 6 stands for Unnecessary Motion,
- m = 7 stands for Defects,
- m = 8 stands for Underutilization of Employees.

The results are presented in Table 3.

RPA categories are determined as a linkage between muda type and sustainability dimension. The connections between muda types and RPA categories are presented in Fig. 6:

As he result of previous analyses, there is a completed RPA rating sheet. From the perspective of future decisions making, in the area of interest are all categories with the score 1 or 3 (weaknesses).



Rated by:	PERSON	**Rapid Plant Assessment**						
Tour Date:	DATE	**Table 1--Rating Sheet**			**Plant:________________**			
No	**Ratings** →	Poor	Below Average	Average	Above Average	Excellent	Best in Class	
	Measure Score →	**1**	**3**	**5**	**7**	**9**	**11**	**Scores**
1	Customer Satisfaction							
2	Safety, environment, cleanliness, & order							
3	Visual Management Deployment							
4	Scheduling system							
5	Product flow, space use & material movement means							
6	Inventory & WIP Levels							
7	People teamwork, skill level, & motivation							
8	Equipment & tooling state & maintenance							
9	Ability to Manage Complexity & Variability							
10	Supply Chain Integration							
11	Quality System Deployment							
Total								

Fig. 5 The leanness score matrix. *Source* (Goodson 2002)

Table 2 Categories of the RPA assessment

Dimension	C_i	Category description
ECON/SOC	C_1	Customer satisfaction
SOC	C_2	Safety, environment, cleanliness, & order
SOC/ECON	C_3	Visual management deployment
ECON	C_4	Scheduling system
ECON/SOC	C_5	Product flow, space use & material movement means
ECON	C_6	Inventory & WIP Levels
SOC/ECON	C_7	People teamwork, skill level, & motivation
ECON/ECO	C_8	Equipment & tooling state & maintenance
ECON	C_9	Ability to manage complexity & variability
ECO/ECON	C_{10}	Supply chain integration
ECON/SOC	C_{11}	Quality system deployment

Source Golinska (2014)

Table 3 Classification of leanness results (RPA) into muda type

	RPA Q	RPA category	Muda type (m)
C_1	Q1, 2, 20	Customer satisfaction	7, 8
C_2	Q3–5, 20	Safety, environment, cleanliness, & order	5, 6
C_3	Q2, 4, 6–10, 20	Visual management deployment	1, 2, 4, 6, 7, 8
C_4	Q11, 20	Scheduling system	2
C_5	Q7, 12, 13, 20	Product flow, space use & material movement means	2, 3, 5
C_6	Q7, 11, 20	Inventory & WIP levels	2
C_7	Q6, 9, 14, 15, 20	People teamwork, skill level, & motivation	1, 8
C_8	Q16, 20	Equipment & tooling state & maintenance	4
C_9	Q8, 17, 20	Ability to manage complexity & variability	1, 7
C_{10}	Q18, 20	Supply chain integration	7
C_{11}	Q15, 17, 19, 20	Quality system deployment	1, 7, 8

Source Golinska (2013)

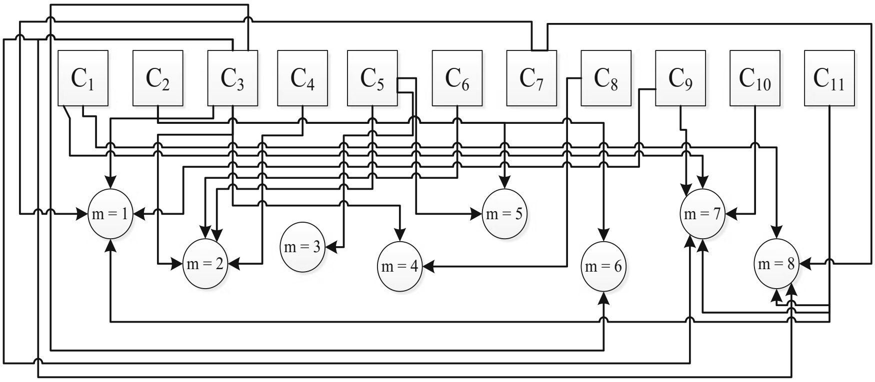


Fig. 6 Connection between muda and RPA categories

3.2 RMC—A Way to Find Sustainable Improvements' Potential in Remanufacturing Facility

For determining the potential for improvements, there was prepared Remanufacturing Muda Checklist (hereafter:RMC), which allow decision makers in a remanufacturing company, to find a potential for changes. RMC is a simple questionnaire, which collects the following data:

(A) Type of muda (m)—there were distinguished 8 types of muda, which can be identified in a remanufacturing company.
(B) Qualifying question (Q_n^m)—there were elaborated lists of situations (from 1 to n) related to each type of muda (m), which can appear in remanufacturing company, according to interviews with experts and visits in surveyed companies.
(C) Appearance—there is a place for answer for the question: Does this situation, defined by qualifying question exist? There is possible the response of the two options: YES or NO.
(D) Priority (P)—there is defined a priority of appeared situation (muda) according to the following scale (Table 4).
(E) Sustainability dimension (S)—each qualifying question was analyzed from the perspective of sustainability dimension. In some cases there are pointed a few options of sustainable development.

The RMC questionnaire is presented in Table 5.

The presented questionnaire is simple tool, that allows quick analysis. It can be easily used in each remanufacturing company, even a very small. The case study presenting the application of the method in small size remanufacturing company is presented in the next subsection.

3.3 Searching Improvements' Potential with the RMC for More Sustainable Remanufacturing Process—Case Study

The case study was conducted in a small size remanufacturing company, which specializes in remanufacturing of engines for cars and tractors. During facility visit, there were made analyses of remanufacturing process with the VSM and IDEF0 for better recognition of the company and remanufacturing process.

In the next step there was made LS, which results are presented in Table 6.

In the next stage there was made LSM (Fig. 7).

As the result of the previous analysis, there were defined the weaknesses of the company in the following categories (areas of the company):

Table 4 Priority of identified muda

P	Description of the importance	Requirements for corrective actions
0	No importance	No
1	Small importance	No
2	Large importance	Yes
3	Very large importance	Yes

Table 5 The RMC questionnaire

Muda (m)	Qualifying question	Appearance		Priority (0–3)	Sustainability
		No	Yes		
Overproduction	1. Lack of production planning				ECON
	2. Production plans/task for workers are often changed				ECON
	3. Long refitting time				ECON
	4. Processing available cores irrespective of the demand				ECON
	5. Overcapacity				ECON
	6. Unbalanced production flow (e.g. different daily standards for workplaces)				ECON
	7. Increasing inventory				ECON, ECO
	8. Breakdowns				ECON, ECO
	9. Remanufacturing defects				ECON, ECO
Inventories	1. There is not enough place for waste				ECON, ECO
	2. Product inventory/WIP partially block the passage of the workplace				SOC
	3. Store new/regenerated parts in the workplace in an amount greater than the current needs (for example. the daily production)				SOC, ECON
	4. There are formed bottlenecks during waiting for documents/decisions/materials processing				ECON, SOC
	5. Lack of place for stored parts				ECON, ECO
	6. Waste are stored on the workplace				ECON, ECO
	7. There is not enough space for waste				ECON, ECO
	8. Cores are bought irrespective of the demand				ECON
Waiting	1. Waiting for the machine (e.g. dryer)				ECON, SOC
	2. Waiting for information/instructions from superiors/staff from other positions				ECON, SOC
	3. Waiting for the material from previous workplace				ECON, SOC
	4. Waiting for tools used by other workers				ECON, SOC

(continued)

Table 5 (continued)

Muda (m)	Qualifying question	Appearance		Priority (0–3)	Sustainability
		No	Yes		
	5. Waiting for the means of transport				ECON, SOC
	6. Absence of workers is high				ECON, SOC
	7. Waiting for parts (new)				ECON, SOC
	8. Waiting for parts (regenerated)				ECON, SOC
	9. Waiting for cores (processed products)				ECON, SOC
	10. Waiting for the parts' picking before the final assembly				ECON
Inappropriate processing	1. Performing more actions than it is required				ECON, ECO
	2. Unclear/lack of customer's specification				ECON
	3. Repeated cleaning of parts				ECON, ECO
	4. Worker makes mistakes during downloading replacement parts (new)				ECON, ECO
	5. Frequent breakdowns of machines				ECON, ECO
	6. Before work, the employee have to get permission from a few departments				SOC, ECON
	7. Processing cores which should be rejected during the pre-selection				ECON, ECO
	8. Lack of procedures				ECO, SOC
	9. Repeating regeneration operations on the same component				ECON, ECO
	10. Wrong order of operations				SOC, ECO, ECON
	11. Too many variants of processed cores				ECO, ECON
	12. Lack of standards for regeneration components (large variety)				ECO, ECON
	13. Several times indexing parts /cores				SOC, ECON, ECO
Transportation	1. Large distance between the workplaces				ECON, SOC
	2. Worker carries material /parts between workstations				ECON, SOC

(continued)

Table 5 (continued)

Muda (m)	Qualifying question	Appearance		Priority (0–3)	Sustainability
		No	Yes		
	3. Required repeatedly transport and unloading/loading materials during the work				ECON, SOC, ECO
	4. Subsequent operations are performed at workplaces in different parts of the company				ECON, SOC
	5. Waste containers are located in different parts of the company				ECON, SOC, ECO
	6. The order is divided into too many transport containers				ECON
	7. Many different storage locations of the new and /or regenerated parts				ECON, ECO
Unnecessary motion	1. Looking for tools for realization the basic/remanufacturing process				ECON, SOC
	2. Looking for documents/data				ECON, SOC
	3. Looking for materials/parts at the workplace				ECON, SOC
	4. Frequent stooping during work				SOC
	5. Frequent rotation				SOC
	6. Materials are moved manually between workplaces				ECON, SOC
	7. Work requires considerable physical effort				SOC, ECON
	8. Employee gets on his own material /parts to carry out his work				SOC, ECON
	9. Worker has got in his duties some unnecessary activities				ECON, SOC
	10. Lack of fixed procedures for work				ECON, SOC
	11. Work is carried out mostly in the forced position (standing)				SOC
	12. Too much tools at the workplace				ECON, SOC
	13. Poor technical condition of tools				ECON, SOC
	14. The dispersion of materials /tools				ECON, SOC
	15. Time-consuming cleaning the workplace				

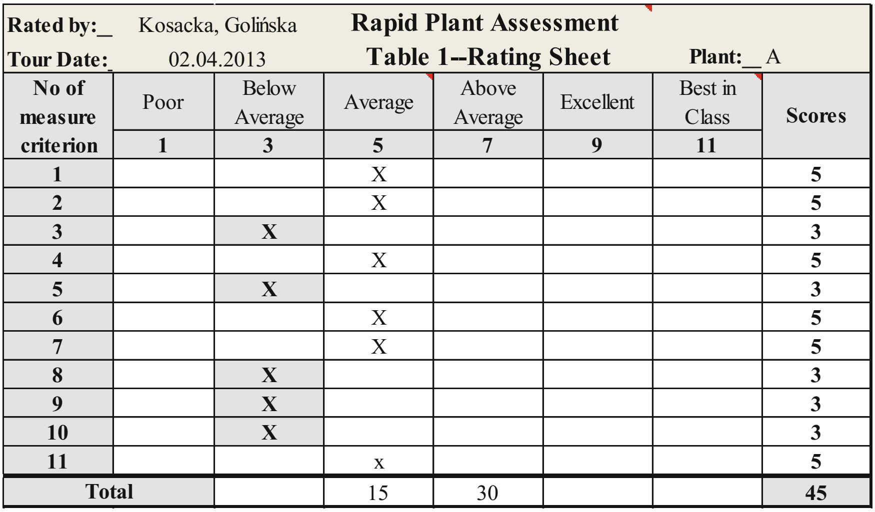
(continued)

Table 5 (continued)

Muda (m)	Qualifying question	Appearance		Priority (0–3)	Sustainability
		No	Yes		
					ECON, SOC, ECO
Defects	1. Damages of materials/products during transport				ECON, ECO
	2. A large number of returns and complaints from customers				ECON, ECO
	3. Inadequate new parts				ECON, ECO
	4. Incomplete cores				ECON, ECO
	5. The problem of identifying cores				ECON
	6. Damages of materials/products during processing				ECON, ECO, SOC
	7. Problems with maintaining the predetermined ratio deficiencies				ECON, ECO
	8. Damaged core				ECON, ECO
Underutilization of employees	1. Employees do not report any improvements				SOC, ECON, ECO
	2. Lack of internal trainings (e.g. in the case of processing unusual product)				SOC, ECON
	3. People report some improvements but they are not implemented				SOC, ECON, ECO
	4. Lack of work instructions				SOC, ECON
	5. Lack of rotation between the workplaces				SOC
	6. Working in excessively burdensome conditions				SOC, ECON, ECO
	7. Unbalanced workplaces				SOC, ECON
	8. Conflicts between co- workers				SOC

Table 6 LS results in the analysed remanufacturing company

Answer in the assessment questionnaire	Question number	Total
Yes	1, 4, 6, 7, 8, 14, 19, 20	8
No	2, 3, 5, 9, 10, 11, 12, 13, 15, 16, 17, 18	12



Rated by:_ Kosacka, Golińska **Rapid Plant Assessment**

Tour Date:_ 02.04.2013 **Table 1--Rating Sheet** **Plant:**_ A

No of measure criterion	Poor **1**	Below Average **3**	Average **5**	Above Average **7**	Excellent **9**	Best in Class **11**	**Scores**
1			X				**5**
2			X				**5**
3		**X**					**3**
4			X				**5**
5		**X**					**3**
6			X				**5**
7			X				**5**
8		**X**					**3**
9		**X**					**3**
10		**X**					**3**
11			x				**5**
Total			15	30			**45**

Fig. 7 LSM for chosen remanufacturing company

- Visual Management Deployment—C_3;
- Product flow, space use & material movement means—C_5;
- Equipment && tooling state & maintenance—C_8;
- Ability to Manage Complexity & Variability—C_9;
- Supply Chain Integration—C_{10}.

The identified categories of weakness ($C_{3,}$ $C_{5,}$ C_8, $C_{9,}$ C_{10}), are then related to the potential relevant muda type. There are identified all the 8 types of muda in the company. All stated muda types should be analysed with the use of The RMC questionnaire (Table 5) in order to find potential for improvements. During this survey each type of muda was analysed according to the procedure presented in Fig. 8.

Due to the size of the analysis, in this chapter we present only the application of RMC for one type of muda, namely defects. For that muda type there were identified 8 qualifying questions in RMC. Each relevant question from Table 5 section "defects" was asked. The "no" answer was given for questions number: 2, 4 and 8. For the remaining question the answer was positive (yes), so further priority analysis was unnecessary. The priority was assigned with the use of scale presented in Table 4 (where $P \in \{0,1,2,3\}$). The biggest improvement potential was with assigned priority ($P = 2$ or $P = 3$).

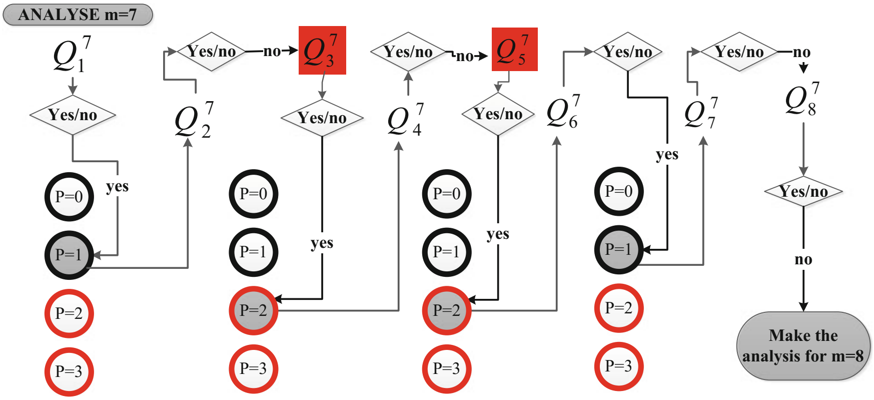


Fig. 8 RMC questionnaire filling procedure

Complete RMC analysis was conducted in the analyzed remanufacturing company, but due to the size of that document there are presented here only partly results (Table 7).

As the result, there were identified examples of situations adequate for 7 types of muda excluding transport, connected with all sustainability dimensions.

There were identified 16 areas with the potential of improvements, especially in the economic dimension (81.25% of all areas). Introducing some improvements company will achieve better situation regarding the economic context mostly. Moreover, there will be positive result for social and environment dimension.

Company can decide about the priority of corrective action according to organizational and economic possibilities. There should be taken in the first place actions in the areas with the priority number P = 3. In case of the analyzed company, that highest priority was reported for action number 9, namely "waiting for parts" (new, regenerated).

3.4 Further Development of the RMC Tool

In the context of muda distinction between three aspects of sustainable development, the method allows to identify potential for improvements in easy way. The assignment of the qualifying question to a specific aspect of sustainability dimension (economic, environmental, social) has been identified on the basis of brainstorming without the analysis of the strength of belonging.

Relich (2015) atated, that there should be taken into consideration not only traditional binary sets (where variables may take on true or false values). Fuzzy sets model phenomenas are more accurately and precisely, because also reflect intermediate states, which also makes the model closer to people. Fuzzy logic allows for

Table 7 Potential for improvements for analysed company

No	Area of the company with the potential	Muda	Sustainability dimension
1	Unbalanced production flow (e.g. different daily standards for workplaces)	Overproduction	ECON
2	Breakdowns		ECON, ECO
3	Not enough place for waste	Excess inventories	ECON, ECO
4	Product inventory/WIP partially block the passage of the workplace		SOC
5	Bottlenecks during waiting for documents/decisions/materials processing		SOC, ECON
6	Waiting for the machine	Waiting	ECON, SOC
7	Waiting for information /instructions from superiors /staff from other positions		ECON, SOC
8	Waiting for the material from previous workplace		ECON, SOC
9	Waiting for parts (new, regenerated)		ECON, SOC
10	Repeating regeneration operations on the same component	Inappropriate processing	ECON, ECO
11	Frequent stooping during work	Unnecessary motion	SOC
12	Work requires considerable physical effort		SOC, ECON
13	Work is carried out mostly in the forced position (standing)		SOC
14	Inadequate new parts	Defects	ECON, ECO
15	The problem of identifying cores		ECON
16	Working in excessively burdensome conditions	Underutilization of employees	ECON, ECO, SOC

the separation of the object between the two sets, while it is a part of each of them (Zadeh 1965).

In the case of describing the dimension of sustainable development of each qualifying question, there might be applied fuzzy logic. Respondents can express their judgement as a degree of membership corresponding to the linguistic variables, so it becomes possible to give a real number between 0 and 1. Assessment of belonging to the sustainable aspect could be carried out according to the formula presented in Table 8.

The weight corresponding to a linguistic variable is different among respondents. Respondents do not have to state that they completely agree with the statement (1) or disagree (0). Due to that fact, there is a chance of getting more realistic data. Taking into consideration fuzzy logic according to Relich (2015), there was provided a guidance for future research to expand the search for potential optimization methodology, taking into account all aspects of sustainable development. It may be resulted in better sustainable policy in a company.

Table 8 Analysis of analysis of the qualifying question belonging to the category of sustainable development

Sustainable dimension			Economic		
Qualifying question			Lack of production planning		
Linguistic variable value	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
Respondent 1		0.7	0.3		
Respondent 2					1
Respondent 3			0.4	0.6	
Respondent 4	0.8	0.2			

Source Own elaboration based on Relich (2015)

4 Conclusions

Presented method allows small and medium sized remanufacturing company to assess they processes in easily and quickly. Its application does not require complicated software or training. The output is an information about the weakness of the current operations and identification of existing resources waste (muda). Created tool, namely RMC allows to identify the potential improvements and to prioritize them. Decision-makers in a company often struggle to introduce changes. The main advantage of the RMC method is, that it allows company to be more sustainable, what is becoming the more key value in today business. The method is characterized by low demand for data—a study visit (1–2 days) is sufficient. Method allows implementation of the principles of lean manufacturing strategy by elimination of muda (waste), thus achieving more economical, environmental friendly operations.

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A Comparison of Neural Network and DOE Regression Analysis for Predicting Resource Consumption of Manufacturing Processes

Frank Kübler and Rolf Steinhilper

1 Introduction

The aspect of resource consumption gains more and more attention since resources are running shorter and the resulting costs per manufactured part are directly associated with this development (Böhner et al. 2013). Manufacturing process optimization is usually performed on process level with the adaptation of process variables to find a reliable operation state. In the past, the main purpose was a reduction of manufacturing cost and cycle time. The preliminary definition of the process values is typically part of the process planning stage and often done as off-line process control. Selection of process variables is traditionally based on a machine book or the operator's experience.

Now the decrease of process related resource consumption is taken into account as additional target (Kübler et al. 2013). In metal cutting processes, optimization is typically done by adjusting three impact factors,

- cutting speed v_c,
- feed rate f,
- depth of cut a_p,

while maintaining the required product quality. Model supported process planning is therefore a step forward and provides better and faster results for a stable and a multi object oriented manufacturing of products. Off-line process planning uses process models to select process variables based on experimental results like the influence of cutting parameters on quality features like surface roughness. Measured values are used to determine the expected values according to an analytical model. Therefore, off-line process control depends on the quality and

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accuracy of data available for modeling, and the capability of the applied analytical model.

Venkata Rao (2011) gives a detailed review of contemporary methodologies and practice on the modeling and optimization of manufacturing processes. Different modeling methodologies have been applied for solving constrained problems of predicting manufacturing costs and cycle time in metal cutting processes, like design of experiment, fuzzy logic and regression analysis as well as neural networks.

For example, Bajić and Belajić (2006) and Oktem et al. (2005) used response surface methodology, while Ezugvu et al. (1995) as well as Benardos and Vosniakos (2002) used back propagation neural network approach. Neural networks were also used for prediction of milling strategies (Klančnik et al. 2010). Regarding tool wear estimation and tool breakage detection, Dong et al. (2006) used the Bayesian multilayer perceptrons and Bayesian support vector machines for tool wear estimation, while Hsueh and Yang (2009) used the support vector machines methodology for tool breakage detection in modeling the face milling process precisely. Braun and Heisel (2012) included simulation based energy consumption in process modeling.

Manufacturing and technological processes nowadays claim implementation of control systems using sophisticated mathematical methods for efficiency purposes. In particular the prior task is to determine those values of the process parameters that will allow achievement of the demanded product quality. Second task is to optimize manufacturing process performance under the constraint of minimizing the cost effective resource consumption.

Due to the high number of different resource consumptions on process and machine level shown in Fig. 1, research is needed to get the mathematical approximations of machining processes including resulting resource consumption to be considered as optimization target.

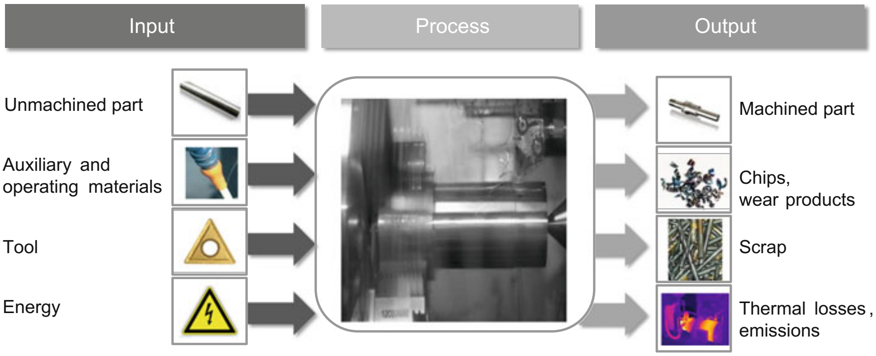

Fig. 1 Characteristic resource consumption of a turning process

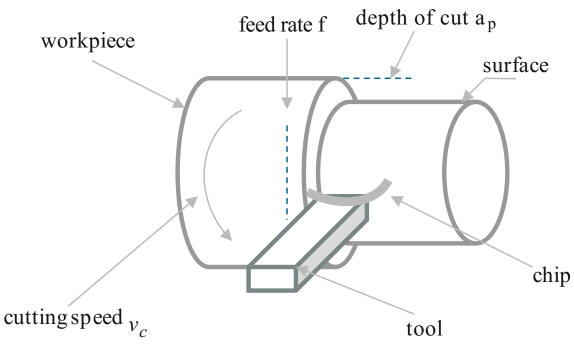

Fig. 2 Process parameters of the turning process

The aim of this research is to build mathematical models that relate the resource consumption represented by process energy and work piece surface roughness with three cutting parameters, the cutting speed (v_c), the feed per turn (f) and the depth of cut (a_p), of a surface turning process shown in Fig. 2. The work piece surface roughness as quality determining feature has a significant impact on resource efficiency of the manufacturing process. Since poor work piece quality demands reworking by additional resource consumption, or leads to scrap as material loss.

In this work two different approaches have been used in order to get two mathematical models. The achieved results will be compared regarding prediction accuracy of the selected resource consumptions as basis for further integrated optimization approaches.

The first approach is a DOE based regression analysis, and the second is modeling by means of ANN related to Özel and Karpat (2005), Benardos and Vosniakos (2003) and Roy (2010). DOE based regression analysis is a common and widespread parametric approach to quantify the impact of various machining parameters on different output parameters (Montgomery 2013). ANNs have been proved as a non-parametric regression method with great ability for mapping very complex and nonlinear systems and are therefore increasingly applied. Also the transferability to various manufacturing processes represents the universality of this model. The turning process and the related resource consumptions are an example of such a complex system and that justifies the usage of ANNs.

2 Design of Experiment

The planning of experiments means prior prediction of all crucial factors and actions that will influence the manufacturing process. The experiments have been carried out using the factorial design of experiments. Turning is characterized by many factors, which directly or interconnected act on the course and outcome of an experiment. It is necessary to manage experiments with the statistical multifactor method due to the statistical character of a machining process. In this work,

Table 1 Input factors of the turning process

Coded values	Levels	−1	−0.5	0	0.5	1
Physical values	X1 = v_c (m/min)	310	337	365	393	420
	X2 = a_p (mm)	0.35	0.525	0.7	1.05	1.4
	X3 = f (mm/turn)	0.3	0.338	0.375	0.413	0.45

the design of experiments was achieved by the central composite design (CCD). In the experimental research, modeling and adaptive control of multifactor processes the CCD of experiments is very often used because it offers a decent database for modeling (Siebertz et al. 2010). The CCD provides the necessary data points using following empirical second-order polynomial in Eq. (1):

$$y = b_0 + \sum_{i=0}^{k} b_i \cdot X_i + \sum_{1 \le i < j}^{k} b_{ij} \cdot X_i \cdot X_j + \sum_{i=1}^{k} b_{ii} \cdot X_i^2 \tag{1}$$

where b0, bi, bij, bii are regression coefficients, and Xi, Xj are the coded values of input parameters. The required number of experimental points for CCD is determined as follows in Eq. (2):

$$N = 2^k + 2k + n_0 = n_k + n_\alpha + n_0 \tag{2}$$

where k is the number of parameters, n_0 is the repeated design number on the average level, and n_α is the design number on central axes. In total CCD of experiment demands 20 observed experiment conditions, 8 experiments with 3 factors on two levels, 6 experiments on the central axes and 6 experiments on the average level. The theory of the design of experiments and mathematical-statistical analysis use coded values of input factors of the turning process. The coded values of the 3 selected independent input factors are given in Table 1.

3 Neural Network Modeling

ANNs are non-linear and non-parametric mapping systems, first used in the fields of cognitive science and engineering as universal and highly flexible function approximator in the form:

$$F(x, w) = y \tag{3}$$

As opposed to parametric model-based methods like RA, ANNs are approaches which can capture nonlinear data structures without prior assumption about the underlying relation. Basically they consist of simple neuron processor units, shown in Fig. 3, linked by weighted interconnections. The first propagation state summarizes all connected inputs ***x*** modified by their respective weights ***w***. The resulting

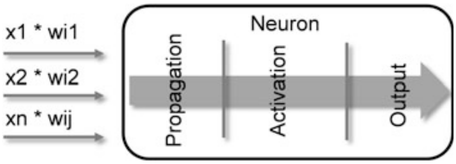

Fig. 3 General structure of an artificial neuron processor

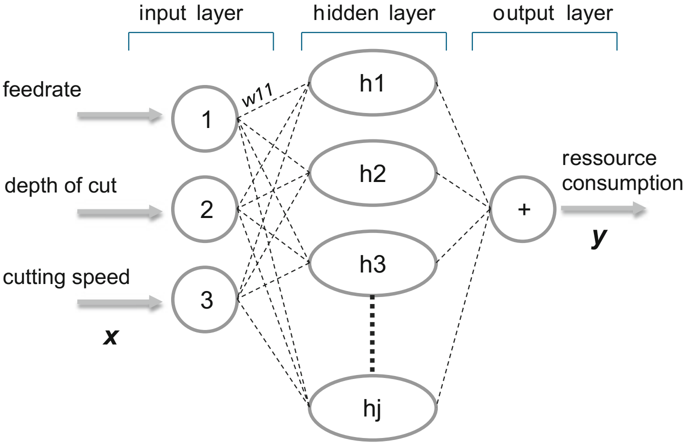

Fig. 4 Neural network model

value will be handed to the activation stage where a activation function calculates the output amplitude of the neuron. If a defined threshold is reached, the neuron broadcasts a related signal to the output and all further connected neurons. The neurons are organized in general in an input layer, one or more hidden layer and an output layer as shown in Fig. 4. The input layer receives the values from the initial variable, the hidden layer performs the operations designed to obtain certain characteristics from the presented dataset, and the output layer shows the resulting network answer regarding Eq. (3).

Fitting neural network parameters as a supervised learning task, allows the mapping of given input $\boldsymbol{x}$ to known output values $\boldsymbol{y}$. During the learning procedure the ANN tries is to find a set of connections $\boldsymbol{w}$ which establishes a mapping that fits the training set well. The ANN model chosen in this contribution is a multilayer feed-forward network, where the data flow is strictly from input units to the output unit. The network consists of one input layer with three input neurons for the three process parameters f, a_p and v_c, one hidden layer with ten hidden neurons using sigmoid activation functions and one output layer with one linear output neuron. The network is trained by the simple and robust Levenberg-Marquardt back propagation algorithm with the CCD dataset. This is the most commonly applied model setting for manufacturing processes (Venkata Rao 2011).

The network architecture shown in Fig. 4 has been used for modeling each of two selected physical resource consumption relations separately. The network setups are named as:

Setup 1—relates cutting parameters and surface roughness Ra,
Setup 2—relates cutting parameters and process energy consumption E_P.

4 Experimental Setting

The type of machine tool used for the turning process was the universal lathe TC 300 manufactured by Spinner. The test sample used in experiments was a cylinder made of steel 42CrMo4 with dimensions 150 mm length and a diameter of 60 mm. The turning experiments were executed by the tool TP2500 MF5390, produced by Seco. Each run was executed with a new and unused cutting tool. Process power P_P was measured by utilizing the Beckhoff three phase power measuring terminal EL3403 and the Janitza cable split core current transformer 400A/1A at the Siemens Sinumerik 840D frequency converter of the Spinner turning lathe. Process power consumption data was then handed via bus coupler to a sql database each 5 ms. Process energy is calculated by numerical integration of the process power. The average work piece surface roughness Ra was measured by a Perthometer S2, produced by Mahr. Measurements of surface roughness were taken at five predetermined places on each work piece. The sampling length was 10 mm. All measuring instruments were calibrated before testing. The experiments were carried out with 6% cooling and lubrication agent concentration at 3 bar application pressure. Altogether 33 experiments were conducted. Twenty experiments from the CCD setup (Table 2) were in order to allow performance of regression analysis Eq. (1), and an additional 13 experiments to obtain additional data for ANN modelling and verification of both models (Table 3). For those experiments, cutting parameter values were randomly chosen within the range. 15 data pairs out of the CCD set have been chosen for the procedure of training and testing the ANN model. Five experiments were not considered because CCD demands six repetitions at the center point. For this purpose five of the additional experiment values were used. Before the training and testing, all input and output data was scaled to an interval of −1 to 1. Both models were tested for their generalization ability after training.

Testing of the DOE RA and ANN modeling was performed with the eight additional randomly selected experiment datasets marked with an asterisk (*) in table 3 and 4, that had not been used in the training process. In order to conduct training and testing of the neural network models, the MATLAB neural network toolbox was used (Mathworks 2013a). For modeling the DOE RA the MATLAB statistics toolbox was applied (Mathworks 2013b).

Table 2 Measured experimental data

Exp. numb.	X1	X2	X3	Ra (μm)	E_P (Wh)
1	1	0	0	4.03	169.87
2	0	0	0	3.13	181.26
3	0	−1	0	3.51	184.40
4	0	0	−1	3.37	268.88
5	0	0	0	2.77	165.17
6	0	0	1	3.49	146.47
7	−1	0	0	3.32	202.32
8	0	1	0	3.17	182.75
9	0.5	0.5	0.5	4.11	157.04
10	−0.5	0.5	−0.5	2.72	222.35
11	0	0	0	3.13	173.23
12	0	0	0	3.13	181.26
13	−0.5	0.5	0.5	2.89	165.05
14	0	0	0	3.55	180.27
15	−0.5	−0.5	0.5	3.25	163.79
16	−0.5	−0.5	−0.5	2.79	222.65
17	0.5	0.5	−0.5	3.52	201.22
18	0.5	−0.5	−0.5	3.96	201.13
19	0	0	0	2.47	186.35
20	0.5	−0.5	0.5	4.16	153.09

Table 3 Additional measured experimental data

Exp. numb.	X1	X2	X3	Ra (μm)	E_P (Wh)
21	0.5	0.5	−0.5	3.52	201.22
22	0.5	−0.5	0.5	4.158	153.09
23	0.5	−0.5	−0.5	3.963	201.13
24	−0.5	−0.5	−0.5	2.793	222.65
25	0	0	1	3.486	146.47
26*	1	−1	0	4.41	169.87
27*	0	−1	0	3.80	184.40
28*	1	−1	−1	4.23	202.32
29*	0	−1	−1	3.55	268.88
30*	1	−1	1	4.53	272.09
31*	1	0	−1	4.47	149.58
32*	1	0	1	4.26	129.29
33*	−1	0	−1	2.96	144.09

5 Modelling Regression Analysis and Artificial Neural Network

The measured values of surface roughness and process energy, obtained by 20 CCD based experiments, are presented in Table 2. The average process energy for each experiment run is used for modelling.

By applying regression analysis, the coefficients of regression factors of Eq. (1) have been assessed and the mathematical models for surface roughness Ra and the process energy Ep were obtained as follows:

$$\begin{aligned} Ra = 3.04 + 0.201f + 0.69v_c - 0.2a_p + 0.42f^2 \\ + 0.67v_c^2 + 0.33a_p^2 + 0.08v_cf - 0.03v_ca_p + 0.05fa_p \end{aligned} \tag{4}$$

$$\begin{aligned} E_p = 177.37 - 15.79v_c - 56.65f - 0.21a_p + 7.07v_c^2 \\ + 28.65f^2 + 4.55a_p^2 + 11.97v_cf + 1.54v_ca_p \\ + 2.71fa_p \end{aligned} \tag{5}$$

Table 3 shows 13 additional measured experimental datasets. Marked data with an asterisk (*) was not used neither in the network training nor in the regression analysis. These datasets were utilized for validation of both, regression analysis and ANN modeling. Table 4 shows the values of surface roughness and process energy obtained from both types of modeling, i.e. from the regression equations and from the simulation of ANN setups.

Figure 5 show the results obtained from both models in form of a graphical representation of process energy and its dependence on cutting speed and feed per turn. Depth of cut has been kept constant at 0.7 mm. It can be seen that the RA method predicts that the process energy depends almost linearly in the center area on both, cutting speed and feed per turn. In the graphical representation of the ANN method, a nonlinear surface can be seen. The minimum values of process energy are

Table 4 Values obtained by RA and ANN model

Exp. numb.	RA	RA	ANN	ANN
	Ra (μm)	Ep (Wh)	Ra (μm)	Ep (Wh)
26*	3.86	168.70	4.94	234.75
27*	3.24	181.72	3.98	233.88
28*	3.86	246.86	4.11	235.62
29*	3.26	269.09	3.77	232.82
30*	4.11	246.86	4.30	226.26
31*	3.63	241.99	4.83	203.70
32*	3.91	152.63	4.30	175.80
33*	2.89	297.50	2.90	208.62

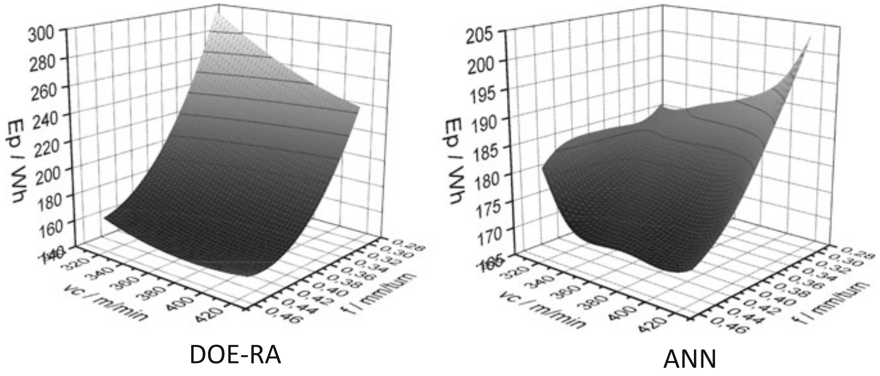

Fig. 5 Response surface for process energy E_p as a function of cutting speed v_c and feed per turn f obtained from the RBF ANN $a_p = 0.7$ mm = const

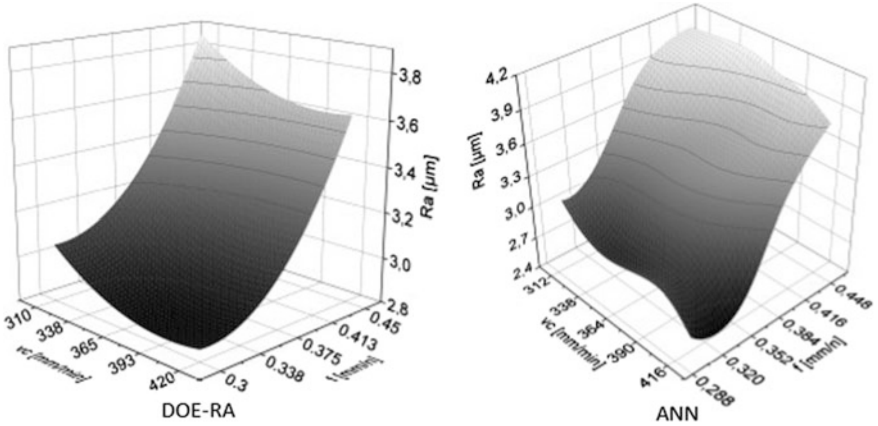

Fig. 6 Response for surface roughness Ra as a function of cutting speed v_c and feed per turn f obtained from the DOE RA at $a_p = 0.7$ mm = const

achieved with both models when feeds per turn reach their maximum and cutting speed is close to its maximum. Increasing cutting speed increases the angle of inclination of the plane shear layer separated materials, and reduces the length of the shear plane at constant shear strength. The force required for deformation of the material is then reduced. A high feed per turn value reduces the process time and with this the required energy. The effect of reduced time exceeds the effect of reduced cutting power demand.

Observing the changes of Ra in Fig. 6 with increase of cutting speed, the connection between the phenomenon of built-up edges is established. Cutting speed is closely related to emergence of built-up edge and that implies its effect on resulting machined surface roughness. By increasing the cutting speed the influence of

Table 5 Relative prediction error for the Ra and Ann models

Exp. numb.	RA	RA	ANN	ANN
	Ra (%)	Ep (%)	Ra (%)	Ep (%)
26*	12.52	0.71	11.84	12.04
27*	14.68	1.46	4.65	13.22
28*	8.77	22.01	2.81	20.44
29*	8.30	0.08	6.08	8.26
30*	9.25	9.27	5.08	36.81
31*	18.77	61.78	7.93	14.17
32*	8.19	18.05	0.81	11.34
33*	2.65	106.47	2.16	19.78
Average	10.39	25.81	5.17	26.74

built-up edges is reduced, and it also increases surface quality by reduced Ra values. However, the dominating factor for surface quality is the feed per turn.

With increasing radial feed per turn, the resulting grooves affects surface quality strongly. From the geometrical point of view, depth of cut has no direct influence on surface roughness, because the height and form of roughness profile are independent of depth of cut. It is indirect influenced through the forming of build-up edges, chip deformation, cutting temperature, vibration etc.

In order to test, which modeling method gives a better prediction, a relative error of deviations from measured values has been determined. Validation of both models was performed with the testing data set that had not been used in the training process. Relative errors obtained using RA and ANN methodologies have been compared, and the results of testing are presented in Table 5. The results from this table indicate that the ANN model offers the best prediction capability with total average relative error of 5.17%. The minimum achieved deviation of 0.08% was for the surface roughness Ra by RA. Here the nonlinearity of the ANN exceeds the quadratic RA with the underlying data set. In contrast, the RA shows the largest maximum deviation for process energy with 106.47%. This is the result of the second-order polynomial behavior at the solution space edge. ANN with its nonlinearity can avoid this steep assent. This behavior can be seen in Fig. 6 Regarding the limited and scattering data set for the process energy consumption results in an larger relative error.

6 Conclusion

The purpose of this study is the research of the capability of parametric (RA) and a non-parametric regression (ANN) for resource consumption modeling of a turning process. The comparison gives an answer regarding the information necessary for modeling and the achieved prediction results of the two models with the applied CCD based data set. The influences of cutting speed, feeds per turn and depth of cut on surface roughness Ra and process energy E_p as selected resources in the turning process have been examined in the study. In order to model dependency between those parameters, RA and ANN methodology were successfully used. The results were positively evaluated for their behavior with respect to the valid fundamentals of machining. Regarding the results, both methodologies are found to be capable of accurate predictions of the surface roughness and process energy with an average error below 11% over all methods and models. Although the ANN model gives a better predictions of surface roughness, with approximate relative error of 5.17%, RA performs slightly better when it comes to process energy prediction. The research has shown that when the training data set is relatively small, as in the study, ANN models based on an empirically chosen standard setting are comparable with the RA methodology. The ANN models are already showing better results without additional optimization of the network settings e.g. number of neurons or change of applied learning algorithm when exposed to the less scattering surface roughness data set.

Due to the fact that accurate predictions are substantial to improve off-line process control resulting in significant reduction of machining cost and resource consumption, both methods are considered to be suitable for this purpose. Nevertheless, only a small amount of modern technology has been transferred to manufacturing. Therefore, off-line process control as an approach that demonstrates its capabilities to be applied in practice and easily integrated in existing conditions represents the key for successful and resource efficient machining. As a next step to advanced manufacturing processes, the established models have to be applied to multi objective optimization methods to determine suitable parameters for cost, time and resource efficient operating points.

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Sustainability Assessment in Remanufacturing Companies—Qualitative Approach

Paulina Golinska-Dawson and Frank Kübler

1 Introduction

The international initiatives like, The World Business Council for Sustainable Development and the Global Reporting Initiative (GRI 2002a, b), as well as OECD initiatives (OECD 2002) have contributed adoption of sustainability management in many industrial sectors.

Krajnc and Glavic (2005) developed a standardized set of over 40 sustainability Indicators, which might be implemented in a company. These indicators cover economic, environmental, and social aspects of sustainability. They combine individual indicators using specific weights into composite sustainable development index, which makes reporting more useful for decision makers. They stated that the proposed model can be easy applicable in the company. The Krajnc and Glavic (2005) approach is very valuable, however it is suitable for big size companies which perform sustainability reporting. It requires a big scope of data and significant calculating effort which is a barrier for small and medium sized companies, who don't have enough resources which might be allocated to collecting such data on regular basis.

Bebbington et al. (2007) stated that "there is a widely recognized need for individuals, organizations and societies to find models, metrics and tools for articulating the extent to which, and the ways in which, current activities are unsustainable".

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The quantitative methods for sustainability assessment allow evaluating the performance. They are providing information to decision makers on how to improve processes which have big impact on the various dimensions of sustainability (economic, environment and social aspects). The overview on the quantitative methods for sustainability assessment was provided by Singh et al. (2012).

The small and medium size remanufacturing enterprises struggle to adopt complex theoretical models. Remanufacturing particularly contributes to the objectives of sustainable development by paving the path for creating the closed loop in product life cycles (Nasr and Thurston 2006). Remanufacturing allows the recovery of used or obsolete products and full restoration of their original value (like a new). Often also it allows to increase the initial performance, through the replacement of worn parts and components with new ones of improved parameters (Golińska 2013).

In remanufacturing typical phases of the primary production are additionally complemented by such steps as disassembling, cleaning and reprocessing. Due to the diversity of operations performed in remanufacturing it is an excellent field for research on all aspects of sustainable development in a production environment. In this chapter we focus on the automotive components remanufacturing, which is dominating activity in the remanufacturing sector (Guidat et al. 2015).

This chapter aims to answer following questions:

- Q1: How can be assessed the level of sustainable resources utilization in small and medium size remanufacturing enterprise (RSME)?
- Q2: How can be provided the assessment model using only existing expert's knowledge?
- Q3: How can be provided cross company valid sustainability assessment criteria?

The high level of sustainable resources utilization is defined as (Golinska and Kübler 2014) such an approach in running everyday business operations, that there is secured:

- economical utilization of the resources,
- environmental friendly utilization of the resources,
- utilization of the resources in the way, which provide ergonomics and safety at the facility and minimum external burden to affect the surrounding communities.

The chaper discusses the qualitative method for assessment of the maturity level of remanufacturing process created by the authors. The subsequent sections present research methodology, main elements the methods and the pilot study from application of the method in the companies.

2 Assessment Method

The proposed method results from the literature review and the case studies conducted in the remanufacturing companies. The focus was placed on the holistic assessment framework which takes into consideration economic, social and environmental aspects.

According to Ness et al. (2007): “There is still a strong focus on environmental parameters, particularly among the product-related assessment tools, where (except from LCC), the tools largely disregard social and/or economic aspects”.

We decided to apply process approach instead of product-related analysis. Due to the lack of suitable theoretical approach among existing sustainability assessment tools we decided to look for alternative maturity concepts.

The developed methodology involves assessment of the level of maturity of companies in various dimensions of sustainable development. It is assumed that the evaluation should not impose on a company need to gather additional quantitative data. Qualitative assessment requires less data than quantitative assessment and may be based on expert knowledge. The following research steps were conducted:

1. research questions definition,
2. literature review,
3. definition of the maturity levels,
4. design of the initial expert’s questionnaire and its verification by small sized remanufacturing companies and industrial experts,
5. revision of the questionnaire,
6. method testing and results assessment.

In order to define maturity levels we applied process approach. The maturity levels are defined based on reference model of process maturity from the standard ISO/IEC 15504 Information technology—Process assessment. In Fig. 1 is presented the reference model for assessment of maturity level of the sustainable resources utilization in remanufacturing process. The maturity of the remanufacturing process is rated on a scale from 0 (minimum) to 4 (maximum).

The scope of the maturity questionnaire is based on the results from the literature review and the previous case studies, which included:

- partners’ remanufacturing companies involved in the project SIRO (Sustainability in Remanufacturing Operations),
- enterprises, which the authors visited in earlier research projects,
- automotive remanufacturing cases described in the literature, which were identified within the desk research.

The expert’s questionnaire covers the economic, environmental and social aspects.

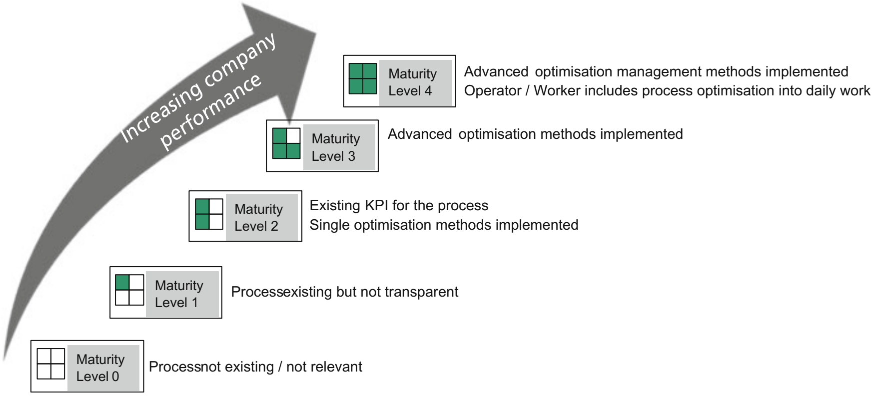


Fig. 1 Maturity model (Golinska and Kübler 2014)

The economic aspects address the common problems with the performing remanufacturing process. They were addressed by the various authors (Gagnon and Morgan 2014; Guide 2000; Saavedra et al. 2013; Kim et al. 2008) and also confirmed by the practitioners in our previous research (Golinska-Dawson et al. 2015). The factors which influence the economic performance can be summarized as follows:

- uncertain lead times,
- uncertain deliveries of cores,
- small batches of wide range of product variants and generations resulting in high inventories,
- materials matching restrictions,
- time consuming disassembly, cleaning and reprocessing, reassembly,
- problems to meet variable quality requirements.

The economic aspects in our method examine the categories, as follows: inventory, scrap and rework, remanufacturing process organization, disturbances in the process, quality management.

The environmental aspects cover the following issues:

- energy efficiency,
- material efficiency,
- disposal and recycling,
- compressed air,
- emissions.

The above mentioned categories (except from compressed air) were described in the literature by the various authors (e.g. Kim 2008; Sundin and Bras 2005; Sundin and Lee 2011). We decided to add the category "compressed air" because our case studies showed that the loss of energy through inefficient use of it was significant in companies.

The social aspects focus on both internal and external stakeholders, the categories are defined as follows:

- workplace design
- ergonomics and safety,
- training and development of employees,
- innovation management,
- corporate image.

The expert's questionnaire is used to perform self-assessment by the company. This self-assessment allows to identify the potential for optimization of resources utilization in the remanufacturing companies. The self-evaluation process is very simple and allows company to identify its maturity level with regard to sustainability. To each category are assigned 4 questions which respond to the subsequent maturity levels. The expert gives yes (1 point) and no (0 points) answers only. If the answer is no then all the subsequent questions in that category are blocked. It is based on the assumption that the subsequent maturity level cannot be achieved if the previous level has not been met (maturity level 3 cannot be achieved without meeting requirements of the maturity level 2). Figures 2, 3 and 4 presents the maturity questioners for environmental, economic and social dimensions.

The questionnaire was first tested during BIG R Show organized by the APRA —Automotive Parts Remanufacturers Association (Las Vegas in November 2013. The feedback from the remanufacturing companies and industrial experts allowed to improve the tool structure.

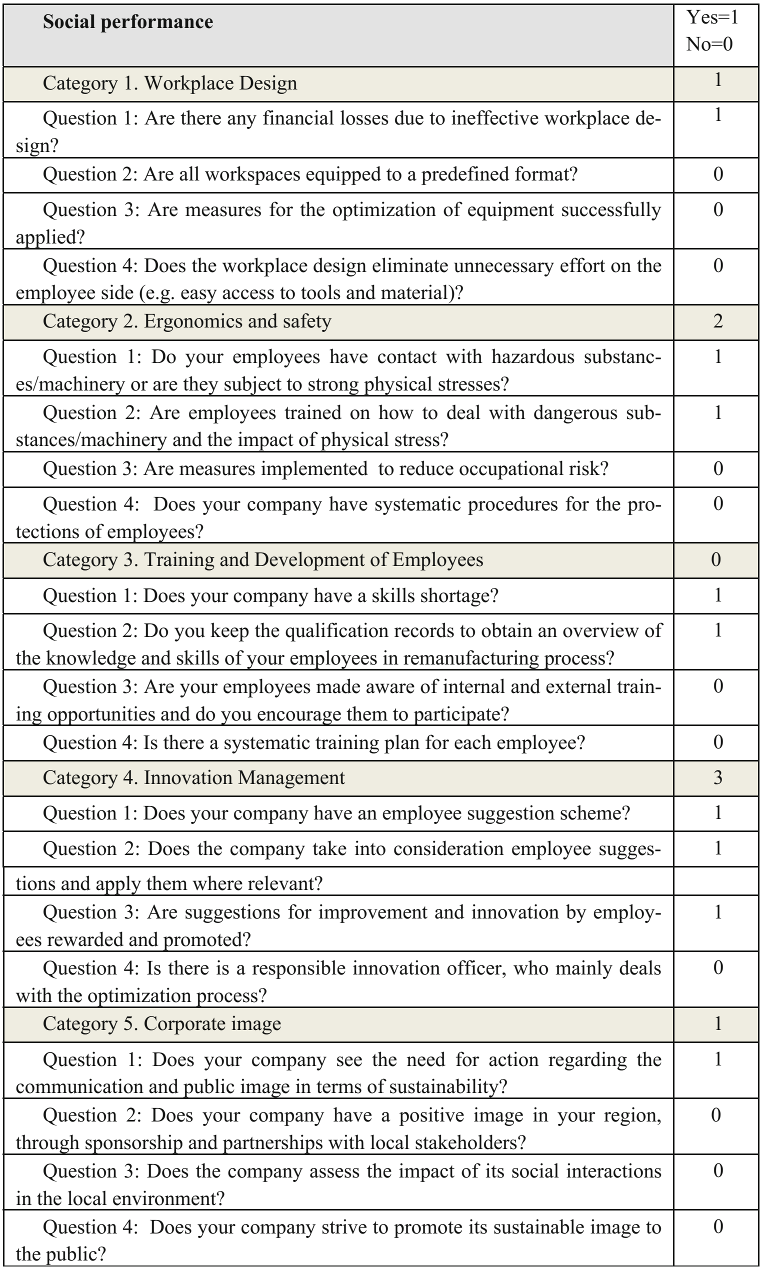
The presented in Figs. 2, 3 and 4 example of questionnaire allow by the process of self-assessment to structure the expert's knowledge which already exists in the company. It helps to identify the areas which need improvement actions. For example in Fig. 2 for category "Disposal and Recycling" the self-assessment shows that maturity level 3 is achieved. That means that the company managed to structure the process, have implemented sufficient optimization measures, however the workers are not implementing them systematically in everyday operations. At the same time the company archived maturity level 2 in category "Materials management" what means that there are some action taken towards optimization of materials utilization in the remanufacturing process but they are not yet sufficient enough and the systematic approach is still missing.

Environmental performance	Yes=1 No=0
Category 1.Energy Efficiency	2
Question 1: Are energy costs significant in your company?	1
Question 2: Is there an overview of the distribution of energy consumptions of existing equipment (e.g. machine, lighting..)?	1
Question 3: Do you implement measures to lower energy consumption?	0
Question 4: Does an energy management system exist (e.g. ISO 50.001)?	0
Category 2. Material Efficiency	2
Question 1: Do you lose production materials in your company due to defective goods and offcuts?	1
Question 2: Is the material input and material output for each stage of production/remanufacturing process known and quantifiable?	1
Question 3: Does your company apply any procedures to reduce materials / parts usage?	0
Question 4: Do you have a standardized procedure in your company, which supports the minimal and environmentally friendly usage of resources?	0
Category 3. Disposal and Recycling	3
Question 1: Do you create production and packaging waste in your company(surplus material, packaging, waste water)?	1
Question 2: Does your company monitor the amount of production and packaging waste?	1
Question 3: Does your company apply procedures/methods to reduce the amount of waste?	1
Question 4: Do you have procedures/systems which separate waste according to recycling strategies?	0
Category 4. Compressed Air	3
Question 1: Does your company use compressed air in the production process?	1
Question 2: Is the amount of compressed air consumption, the net infrastructure and the compressor technology known?	1
Question 3: Are vulnerabilities and leaks detected and immediately fixed?	1
Question 4: Does a periodic review of the compressed air network take place for vulnerabilities and leaks (including a review of compressed technology)?	0
Category 5. Emissions (including CO2 and waste water)	2
Question 1: Is your company able to identify emissions and potential toxic substances in production/remanufacturing processes?	1
Question 2: Does your company monitor and document places in production/remanufacturing where emissions/toxic substances are created?	1
Question 3: Is there a standardized system/procedure to reduce these emissions and substances?	1
Question 4: Are additional actions (beyond fulfillment of law regulations) performed in order to reduce the emissions level?	0

Fig. 2 The example of the maturity self-assessment questionnaire for “environmental performance”

Economic performance	Yes=1 No=0
Category 1. Inventory	2
Question 1: Are sufficient inventories for materials and semi-finished products available?	1
Question 2: Are the material needs well monitored and is the replacement time known for these?	1
Question 3: Do you try to keep stocks as low as possible to reduce the capital commitment?	0
Question 4: Do you use a system that allows to reduce the current inventory and defines the reorder policy (e.g. just in time)?	0
Category 2. Scrap and rework	3
Question 1: Are there financial losses due to rejects and rework?	1
Question 2: Are material losses caused by defective process and waste documented?	1
Question 3: Are measures to reduce waste and residual materials successfully implemented?	1
Question 4: Is there an automated process to reduce scrap and rework as well as to increase the process quality (e.g. Six Sigma)?	0
Category 3. Remanufacturing process organization	3
Question 1: Is there potential to reduce operations lead time?	1
Question 2: Are individual setup times and machine utilization, as well as transport and storage times documented?	1
Question 3 Does the production planning process include procedures to optimize set-up times?	1
Question 4: Is there an ongoing analysis of the remanufacturing process (lead time, order time) to reach a minimum process time?	0
Category 4.Disturbances in the process	3
Question 1: Is there organizational and technical related downtime in production?	1
Question 2: Are disturbances and their root cause (e.g., machine failures, unwilling standing material) documented?	1
Question 3: Are measures of preventive maintenance performed?	1
Question 4: Do you perform a process of continuous improvement and Total Productive Maintenance (TPM)?	0
Category 5. Quality management	4
Question 1: Are there complaints regarding product quality?	1
Question 2: Do you document the quality problems and their root causes?	1
Question 3: Is the staff able to quickly and flexibly identify quality problems and respond to them?	1
Question 4: Is there a quality management system that is focused on the optimization of processes and product quality?	1

Fig. 3 The example of the maturity assessment questionnaire for “economic performance”



Social performance	Yes=1 No=0
Category 1. Workplace Design	1
Question 1: Are there any financial losses due to ineffective workplace design?	1
Question 2: Are all workspaces equipped to a predefined format?	0
Question 3: Are measures for the optimization of equipment successfully applied?	0
Question 4: Does the workplace design eliminate unnecessary effort on the employee side (e.g. easy access to tools and material)?	0
Category 2. Ergonomics and safety	2
Question 1: Do your employees have contact with hazardous substances/machinery or are they subject to strong physical stresses?	1
Question 2: Are employees trained on how to deal with dangerous substances/machinery and the impact of physical stress?	1
Question 3: Are measures implemented to reduce occupational risk?	0
Question 4: Does your company have systematic procedures for the protections of employees?	0
Category 3. Training and Development of Employees	0
Question 1: Does your company have a skills shortage?	1
Question 2: Do you keep the qualification records to obtain an overview of the knowledge and skills of your employees in remanufacturing process?	1
Question 3: Are your employees made aware of internal and external training opportunities and do you encourage them to participate?	0
Question 4: Is there a systematic training plan for each employee?	0
Category 4. Innovation Management	3
Question 1: Does your company have an employee suggestion scheme?	1
Question 2: Does the company take into consideration employee suggestions and apply them where relevant?	1
Question 3: Are suggestions for improvement and innovation by employees rewarded and promoted?	1
Question 4: Is there is a responsible innovation officer, who mainly deals with the optimization process?	0
Category 5. Corporate image	1
Question 1: Does your company see the need for action regarding the communication and public image in terms of sustainability?	1
Question 2: Does your company have a positive image in your region, through sponsorship and partnerships with local stakeholders?	0
Question 3: Does the company assess the impact of its social interactions in the local environment?	0
Question 4: Does your company strive to promote its sustainable image to the public?	0

Fig. 4 The example of the maturity assessment questionnaire for “social performance”

3 Method Verification and Results Discussion

The method verification includes case studies in 8 companies from Poland and Germany, which are involved in the remanufacturing of automotive parts. Due to the confidentiality issues the names of the companies are not revealed.

Table 1 presents the simplified characteristics of the enterprises. The companies represent different types of remanufactures, which were mentioned before in the literature by Seitz (2007) and Sundin and Dunbäck (2013):

- Original automotive parts manufacturers and suppliers, who remanufactured only their own products (OEM/OES),
- Independent remanufacturers (IR),
- Contract subcontractor (i.e. CR—Contracted remanufacturers)—who perform processes of re-manufacturing on behalf of the OEM.
- Remanufacturing service providers (RSP).

Table 2 presents the summary of the results of maturity level assessment in the analyzed companies.

The results can be analyzed on the individual company level in the respective dimensions of sustainability or as aggregated values in order to achieve the overall maturity index ($M_{sru)}$. The maturity index M_{sru} is calculated as average weighed value of the individual assessments. The individual company assessment might be further use for cross companies comparison. Distribution of results is also shown in Fig. 5.

The companies on average achieved the best results in the environmental dimension. The highest level of maturity (level 3 or higher) regarding the sustainable resources utilization is achieved in the category "Disposal and Recycling". It is mainly caused by the legal obligations regarding the waste treatment which are imposed in most of the European countries. Moreover the companies also see the possibility of additional income resulting from scraping the malfunctioning metal parts or cores which are not suitable for further remanufacturing. The medium level of maturity <2; 3) is achieved in all the other environmental categories, however the

Table 1 The group of companies for method testing

Company	Type	Products
A	IR	Alternators, starters, pumps
B	RSP	Engines
C	OEM	Engines, transmissions
D	IR/CR	Turbochargers
E	IR/CR	Diesel fuel injection pumps
F	OEM	Fuel injection pumps
G	CR	Alternators, starters
H	OEM	Steering racks, remanufactured calipers, remanufactured power steering pumps and mechatronics

Table 2 The maturity assessment in the analyzed companies

Categories	A	B	C	D	E	F	G	H
Energy efficiency	3	1	2	0	4	4	1	3
Material efficiency	2	2	3	0	4	3	3	4
Disposal and recycling	4	2	1	4	1	4	4	4
Compressed air	3	1	1	4	4	3	1	4
Emissions	2	2	4	0	4	1	2	4
Inventory	3	2	1	2	3	3	4	4
Scrap and rework	2	2	2	0	3	3	3	4
Remanufacturing process organization	2	2	2	2	4	2	1	4
Disturbances in core process	3	2	1	0	2	2	2	4
Quality management	4	2	2	4	0	4	4	4
Workplace design	2	1	4	0	3	4	1	4
Ergonomics and safety	2	2	3	0	0	3	2	4
Training and development of employees	3	2	3	4	0	3	3	4
Innovation management	3	1	4	3	3	4	3	3
Corporate image	1	1	0	1	0	3	1	2

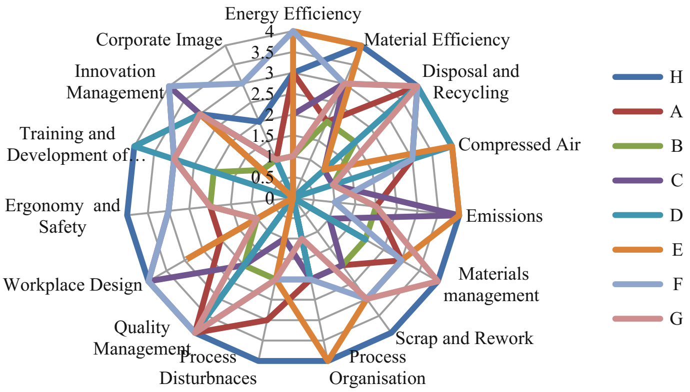


Fig. 5 The results of maturity assessment in the analyzed companies

areas which need improvements are: “energy efficiency” and “emissions”. During our case studies the companies stated that they are struggling to monitor the emissions and energy efficiency because they lack the procedures to allocate them directly to the remanufacturing process. They don’t measure on regular basis those values. The only available data for comparison come from the monthly bills for electricity and water usage and sludge generation. None of the analyzed companies was able to accurate measure the CO_2 emission from remanufacturing process.

In the economic dimension the highest level of maturity was achieved for category “quality management”. The companies treat the quality management as an important tool to be competitive on the market. Most of the companies are certified with regard to the ISO quality standards. The procedures to monitor and to maintain high quality are present. The medium level of maturity was achieved for the categories:

- Materials management
- Scrap and Rework
- Remanufacturing process organization

The lowest level of maturity was observed in the category of "process disturbances" (borderline value between medium and low maturity level). The previous studies of Guide (2000) and Gagnon and Morgan (2014) confirm these findings. There is high level of uncertainty in the remanufacturing process regarding the lead times, high variability of the cores. Also Guidat et al. (2015) stated: "The processes of remanufacturing are difficult to standardize partly due to the variability of components parts, products and processes". These conditions make small and medium sized remanufacturers more vulnerable to occurrence of process disturbances.

The lowest level of the maturity assessment was achieved in the social dimension. None of the companies reached the maximum assessment in the category of "image" and the average assessment in this category was "low maturity level" (below 2). High level of maturity <3; 4> was on average achieved in the category "Innovation management". During the case studies the companies have declared that due to the complexity and variability of the remanufacturing process they have to develop in house solutions (process and organizational innovation) and very often main source of them are employees.

During method verification we tried to find a benchmark to assess the maturity gap. For this reason we have conducted the maturity assessment on a group of American remanufacturers. Those remanufacturers had a similar characteristics as the case studies companies. The American market was chosen as a benchmark, because as Sundin et al. stated (2008) it is more developed than European market.

In Fig. 6 are presented the maturity gap results. The biggest gap exists in the following categories (see Fig. 6):

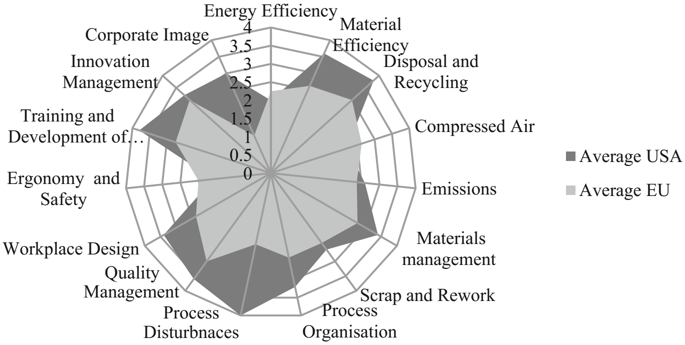


Fig. 6 Maturity assessment—maturity gap

- Process disturbances,
- Process organization,
- Material efficiency,
- Disposal and recycling
- Work place design,
- Training and development,
- Company image.

The first two categories have direct influence on the profitability of the remanufacturing process which is consistent with previous finding of Guide (2000, 2003) and Sundin et al. (2008). The higher maturity level of the material efficiency and disposal & recycling is usually related to lower uncertainty of cores supplies in US. It is easier to obtain high quality cores in the US, than in EU. Due to higher market maturity and closeness to the final customers it is easier to predict the returns patterns.

The gap which appears in the social categories (work place design, corporate image and training & development) is related to market characteristics. The remanufacturing market in the US is more visible than in EU. The acceptance of remanufactured products by customers is high. Moreover the customers are aware of existence of remanufacturing products. The higher profitability of remanufacturing makes it easier to invest in the human related area like training and workplace design.

The presented method is providing a cross company valid assessment of sustainable resource utilization based on the maturity concept. The qualitative approach allows to use the existing expert's knowledge in a company.

The benefit of the method is its simplicity and relatively short time need for assessment. The limitation is that it was tested on relatively small group of companies, however we made a significant effort to choose companies with various characteristics (see Table 1). The presented method is implemented into on-line tool, which is available at http://www.siro-research.eu/en/survey.html. This tool allows a company to make the self-assessment and to identify the areas which need implementing some improvements measures.

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Sustainability Indicators System for Remanufacturing

Paulina Golinska-Dawson, Monika Kosacka and Karolina Werner-Lewandowska

1 Introduction—The Importance of Performance Assessment in Remanufacturing

The relevance of indicators is high, because they allow to assess the current situation and to determine the direction of further actions. A good indicator alerts about a problem before it gets very bad (Sustainable Measures 2010).

Darton (2005) in his work quoted the statement Ross Clark, the journalist, that: "*In the absence of any precise meaning, the concept of sustainability is pointless. It could mean virtually anything, and therefore means absolutely nothing. It has become merely a marketing slogan*".

That statement demonstrate clearly the need for the parameterization of the term sustainability. If there is a possibility of measuring, taking planned and coherent action to change it in a desired direction will be available (Darton 2005).

In order to better identify the current situation of company and to find the optimization potential there is a need for a system of performance measures. In the company a performance assessment helps the managers to follow up, coordinate, control and improve different aspects of the organizational activities (Kollberg et al. 2005). The sustainability measures should allow to assess the company performance in the three dimensions as proposed by Brundtland Commission (1987):

- economic,
- ecological,
- social.

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The performance measures allow to create a possibilities for decision-makers to gain knowledge about what happens in company at present and to direct future actions (Elg 2007).

The study on definition of the key performance indicators for remanufacturing by Graham et al. (2015) provides a complex and interesting framework for the assessment. They apply the balanced score card approach and focus on six areas to measure a remanufacturing business: Finance, Customers & Quality, Internal processes, Innovation & improvement, Employee satisfaction, Environment (Graham et al. 2015). Graham et al. (2015) designed the toolbox for remanufacturing with 25 KPIs. The proposed by them key performance indicators are developed based on the experiences of experts mainly from big size companies which have sufficient resources and experiences to conduct more advance monitoring of remanufacturing process.

The application of the complex indicators system in the small and medium sized companies id difficult, because the majority of them have limited human and material. Our previous experiences have showed that SMEs in order to implement size companies (SMEs) need some more guidelines. Such guidelines should inform how to identify optimization potentials and how to implement the needed improvements. It is important for SME to have an effective decision support model for a goal-oriented analysis and implementation of appropriate measures for increasing its sustainability. In case of the remanufacturing the assessment of the performance is even more difficult than in manufacturing SMEs due to the high level of uncertainty.

When creating a system of indicators of sustainability, it is vital to remember that they are different from traditional indicators, because there are close relationships between them (Sustainable Measures 2010).

During the process of definition SSIR there were identified five requirements for valuable sustainability indicator in remanufacturing business, determined by the acronym ACRUS (Fig. 1).

Availability of data—we made assumption that the calculation of the indicators values has to be based on already existing data in the company and no additional staff or resources should be allocated to collect the necessary data. This condition is especially important in the case of SMEs companies with limited resources.

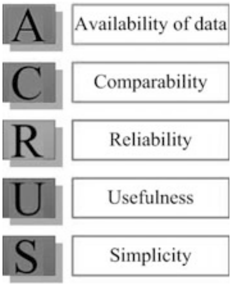

Fig. 1 ACRUS—requirements for sustainability indicators in remanufacturing business. *Source* Own elaboration based on (Feng and Joung 2009; UN 2008)

Comparability—the users of the indicators have to be able to compare the values of the indicators over time (to identify trends) and make benchmarking (if possible with other companies).

Reliability—the indicators should provide true, complete and balanced view of the actual situation in the remanufacturing process from sustainability point of view. Information provided by indicator should be useful and objective.

Usefulness—the indicators should provide a current, complete picture of the situation in a company, free from excess data.

Simplicity—the indicators should be as simple and logical, as possible both in the construction and interpretation, that even a non-expert should be able to understand and interpret then for future decision making.

The subsequent sections present the process of sustainability indicators definition.

2 Sustainability Indicators

The literature review was conducted in order to identify the available sustainability indicators and their potential for implementation in case of the small and medium size remanufacturing companies. After literature review were conducted formal and informal interviews with industrial experts. They aimed to find out what were their requirements and expectations regarding the performance indicators. The authors also applied the outputs from four detailed case studies at SMEs remanufacturing facilities. An iterative analysis process was used to establish the system of indicators.

The next sections present the indicators dividing them into three pillars of sustainable development, as follows: economic performance, environmental performance and social performance.

2.1 Economic Performance

In the literature the most frequently cited method for assessing the economic aspect of sustainable development is the LCC method. Table 1 presents an overview of the current research in the field of economic assessment in the case of remanufacturing of automotive components.

Referred to in Table 1 methods for the evaluation of the economic aspect of sustainable development are in the opinion of the authors hard to implement in small and medium size enterprises, because of difficulties in obtaining the necessary data for calculation.

According to the authors' opinion the economic performance in the case of the assessment of the remanufacturing process should focus on operational excellence and should take into consideration dimensions which comprise problems typical for

Table 1 Current research in the field of economic assessment in the case of remanufacturing of automotive components

Evaluation method of the economic aspect of the sustainable development	Reference
LCC—life cycle costing	Shau et al. (2011)
TCA—total cost assessment	Lai et al. (2008)
Categories of measurement for the economic dimension of sustainability:	Fiksel et al. (1999)
• Direct costs (raw material cost, labor cost and capital cost)	
• Hidden costs (recycling revenue and product disposition cost), potential costs (employee injury cost and customer warranty cost)	
• Relationship costs (loss of goodwill and business interruption)	
• Externalities (loss of the ecosystem productivity and resources)	
The costs which are allocated to the remanufacturing process	Sundin and Bras (2005)

production planning and control in the remanufacturing, as identified by Guide (2000):

- the uncertain timing and quantity of returns,
- the need to balance returns with demands,
- the disassembly of returned products,
- the uncertainty in materials recovered from return items,
- the requirements for a reverse logistics network,
- the complication of material matching restrictions,
- problems of stochastic routings for materials for remanufacturing operations and the highly variable processing times.

2.2 Environmental Performance

The environmental aspects of the remanufacturing were described in the literature by various authors, but none common standard has been so far introduce in the business practice. Table 2 presents the summary of the literature review for environmental performance assessment in case of automotive parts remanufacturing.

The direct indicators are relatively easier to calculate and requires less data but there are some difficulties in companies to define their minimal number and combination to provide the reliable feedback on current performance.

The indirect indicators provide more complex picture of the company situation but the data needed to calculate them is extensive and usually not available for small and medium sized remanufacturing company.

Table 2 Environmental indicators

Indicator type	Performance indicator	Reference
Direct	Energy consumption	Gutowski et al. (2011), Kim et al. (2008) Liu et al. (2013)
	Water consumption	Kim et al. (2008)
	Landfilled waste/general waste (waste generation)	Kim et al. (2008)
	GHG emissions	Kim et al. (2008)
	CO_2 equivalent	Kara (2009)
Indirect	LCA	Amaya et al. (2010), Gutowski et al. (2011), Lindahl et al. (2006), Shau et al. (2012)
	LCC	Shau et al. (2011)

Source adopted from Sundin and Lee (2012)

2.3 *Social Performance*

Referring to the Greiner (2001) there is a chance to point three main purposes of social sustainability indicators in remanufacturing process:

- to raise awareness and understanding of the issues it indicates,
- to help in decision-making of improving areas of functioning remanufacturing company,
- to measure the achievement of established goals related to sustainability.

Each of the aspects of sustainable development is equivalent, but the social aspect is relatively often ignored or treated differently in relation to the environmental and economic aspects (Cuthill 2009; Vavik and Keitsch 2010). Furthermore there are various interpretations regarding issues which should be included in social aspect of sustainability (Dixon and Colantonio 2008). The diversity of problems in the social dimension after literature review is presented in the Fig. 2.

In the social dimension, there were distinguished four categories. It was difficult to assign issues to chosen category because of blurring of the boundaries between them. There are issues related to: basic human rights, standard and quality of life, health and safety at work and outside it and employment.

The literature on social performance assessment of the remanufacturing process is rather limited. Moreover taking into account presented classification some important facts should be considered, as followed:

- Presented approach is well suited to describe the social dimension of sustainable development of the region, country, organization, but it is not sufficient for the assessment of enterprises, especially remanufacturing companies struggling with specific problems of conducted business.
- It is imperative that, indicators should be adapted to the country characteristic (e.g. problems of developing countries and developed countries are different).

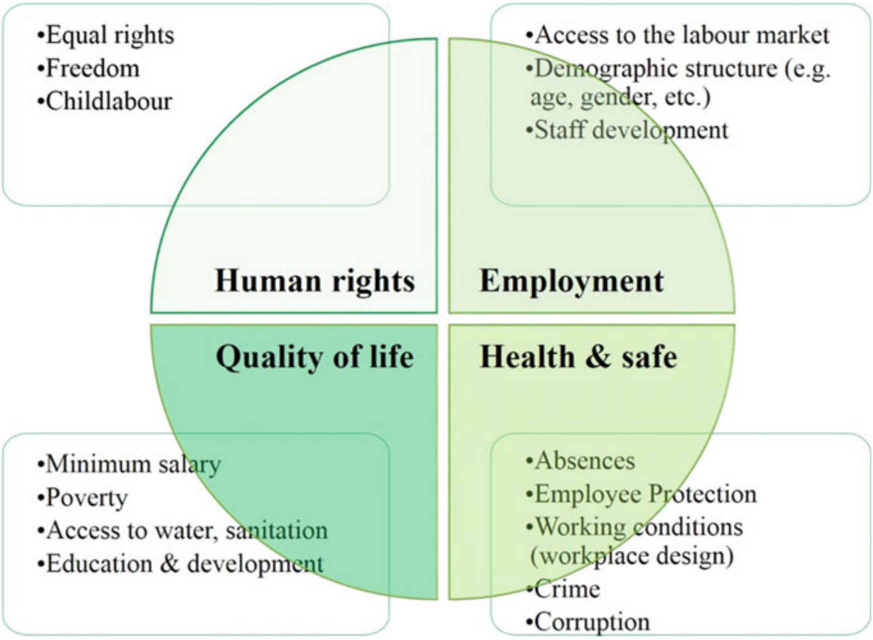

Fig. 2 Social performance indicators' classification. *Source* Own elaboration based on (Fatimah et al. 2013; Shau et al. 2011, 2012; UN 2008; USW 2011; Matuszczak 2009)

At the moment, social issues are gaining very high interest—people are treated as a basis for building competitive advantage (Rosińska 2007), development strategies are based on the concept of sustainable development emphasizing the social dimension such as Europe 2020 strategy. In this strategy "*the Union has set five ambitious objectives—on employment, innovation, education, social inclusion and climate/energy—to be reached by 2020*". That startegy draw the attention to the issue of employment, improve social care system, improve conditions for micro, small and medium size enterprises (Europe 2020).

3 Proposed Sustainability Assessment Indicators

3.1 Economic Performance Assessment of the Remanufacturing Process (ESDIS)

Recognizing the lack of common methods for the evaluation of the economic aspect of sustainable development, and recognizing the difficulties in applying the recommended methods, the authors have developed Economic Sustainable

Development Indicators System for the assessment of enterprises processing end of life vehicles (ELV).

ESDIS is especially dedicated for SMEs operating in the automotive remanufacturing sector, like: dismantling stations, remanufacturing of parts, recycling, and the others.

Due to the lack of clearly defined and commonly applied in practice set of economic indicators for sustainability assessment of the automotive parts remanufacturing process, the authors propose the approach, as shown in Table 3.

The criteria should be easily applied in small and medium size enterprises. The authors made the assumption that the data for calculation of the indicators should be easy accessible in the company and in the case, when the numerical data is not available the indicator can be calculated based on the expert knowledge of decision makers (Golinska et al. 2015).

The first indicator Overall Equipment Effectiveness (OEE) is often used in the companies who implemented the lean management principles. In the authors opinion it also might be applied for assessment of different aspects of the sustainability.

For OEE calculation three important information are taking into consideration, as follows (Golinska et al. 2015):

- the availability rate—it measures downtime losses from equipment failures, setups and adjustments [in % of scheduled period time (t)],
- the performance rate measures losses due to lower than design process speed cause mainly by idling or minor stoppages,
- the quality rate expresses losses due to scrap and rework as a percentage of total parts run.

OEE allows for identified losses caused by low inefficient organization of the remanufacturing process and associated waste like scrap and rework.

In practice, the generally accepted World-Class (Table 4) values of each factor are presented in the Table 4.

Worldwide studies indicate that the average OEE rate in manufacturing plants is 60%. As you can see from the hereinbefore table, a World Class OEE is considered to be 85% or even better.

The second indicator RPF shows the information about the current process smoothness. It indicates the ratio of the downtime in the total time of the executing remanufacturing process in the analyzed period of time (shift, day, week etc.).

In case the detailed data for calculation is not available this indicator can be also assessed in the simplified way based on the expert knowledge of decision-makers (see Table 5).

The third economic indicator PA (planning adequacy) allows to compare the planned lead time per batch to the real execution time. It allows to measure the disturbances in the remanufacturing process.

The fourth indicator AMT Availability of machines and tools allows to measure how often do failures occur in the production machines/tools. Due to the fact that

Table 3 Economic performance of sustainability of the remanufacturing process

No	Criterion	Description	Formula/assessment	Unit	Ref. value
1	OEE	Overall equipment effectiveness	$Availability\ rate \times Quality\ rate \times Performance\ rate$	%	85%
2	RPF	Remanufacturing process flow	$\frac{Unplanned\ downtime\ in\ the\ process\ in\ period\ t}{Total\ time\ of\ the\ process\ in\ period\ t} \times 100\%$	%	0%
			$Qualitative\ assessment - expert's\ questionnaire$	1–5	5
3	PA	Adequacy of remanufacturing process planning	$\frac{Planned\ batch\ remanufacturing\ lead\ time}{Real\ batch\ remanufacturing\ lead\ time} \times 100\%$	%	100%
4	AMT	Availability of the machines and the tools	$\frac{Time\ of\ availability\ of\ machines/tools\ in\ the\ process\ in\ period\ t}{Total\ time\ of\ the\ process\ in\ period\ t} \times 100\%$	%	100%
			$Qualitative\ assessment - expert's\ questionnaire$	1–5	5
5	SL	Service level	$\frac{Number\ of\ executed\ orders\ in\ period\ t}{Total\ number\ of\ planned\ orders\ in\ period\ t} \times 100\%$	%	100%
6	OOS	Availability of the materials (overall out of stock)	$Quantitative\ assessment - expert's\ questionnaire$	1–5	5

Source adopted from Golinska et al. (2015)

Table 4 OEE factor—world class

OEE factor	World class (%)
Availability	90.0
Performance	95.0
Quality	99.9
Overall OEE	85.0

Source http://www.oee.com/world-class-oee.html, accessed 30 December 2014

Table 5 Expert's questionnaire for RPF (Golinska et al. 2015)

Expert's questionnaire	Scale
RPF	
How often are there unplanned downtime in the production process?	
Quarterly	5
Once a month	4
Once a week	3
Once a day	2
More than once during a shift	1

small and medium size remanufacturing companies don't keep detailed record on the maintenances, we decided that this indicator can be calculated both based on the quantitative data (when available) or by the expert (e.g. shop floor shift manager) using simple questionnaire. The scale which is applied in the questionnaire is the same, as that in case of RPF indicator.

The fifth indicator "Service level" measures the performance regarding customers' orders execution. It allows to assess how many orders were executed on time (as planned).

The sixth indicator OOS allows to assess the availability of materials. The remanufacturers struggle to provide all the necessary components for reconditioning as well as new materials. The materials matching problem is broadly discussed in the literature (e.g. Ostlin 2008). For this reason it is important to systematically measure the performance in this field. It is very difficult to obtain the numerical data on materials availability in SMEs, for that reason we have applied again the experts assessment, as follows "How often do shortages in raw materials occur in the production process?"

- raw material is always available 5
- quarterly 4
- once a month 3
- once a week 2
- once a day 1

The assessment of the economic performance is followed by the environmental and social performance evaluation.

3.2 Environmental Performance Assessment of the Remanufacturing Process (EnSIR)

The small and medium size remanufacturing enterprises contribute to achieving goals of sustainable policy. The environmental benefits of remanufacturing are mainly that it safes energy embodied in the products in the primary production, allows to lower the rate of materials which are landfilled, reduces the raw materials demand. The remanufacturing also helps to increase the productivity of resources because the same amount of resources can be reused many times. However, there are a few reports and limited research available concerning the environmental benefits of remanufacturing (Sundin and Lee 2012). The industry practice shows that SMEs in remanufacturing sector relatively rarely monitor environmental impact of their operations. In our research we propose to assess the environmental performance in the area, as follows (see Table 6):

- energy consumption,
- waste generation,
- material recovery rate,
- generated emissions (CO_2, water, sewage).

The proposed indicators allows to measure different aspects of the environmental performance using rather limited input data.

3.3 Social Performance Assessment of the Remanufacturing Process (SSIR)

During the definition of SSIR it is essential to draw attention to remanufacturing companies' stakeholders.[1] Stakeholders' analyses are at present presumably more important than ever due to the increasingly interconnected nature of the world (Bryson 2003). What is more stakeholders theory is inherently related to more popular Corporate Social Responsibility (CSR),[2] what emphasizes the importance of social issues. It is crucial for proper SSIR definition, to take into account stakeholders of remanufacturing company (Fig. 3).

Five groups of stakeholders can be distinguished, as follows:

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[1] According to Freeman (1984) stakeholders are "*any group or individual that can affect or be affected by the realisation of a company's objectives.*"

[2] The European Commission defines CSR as "*a concept whereby companies integrate social and environmental concerns in their business operations and in their interaction with their stakeholders on a voluntary basis*" (2001).

Table 6 Environmental performance of sustainability of the remanufacturing process

No	Criterion	Description	Formula/assessment	Unit	Ref. value
1	ECL	Energy consumption level	$Quantitative\ assessment - expert's\ questionnaire$	1–5	1
2	WGEL	Waste generation level	$\frac{Amount\ of\ waste\ in\ period\ t}{Amount\ of\ material\ used\ for\ production\ in\ period\ t} \times 100\%$	%	0%
3	MRR	Material recovery rate	$\frac{Number\ of\ recovered\ cores\ in\ period\ t}{Number\ of\ cores\ feedin\ process\ in\ period\ t} \times 100\%$	%	100%
4	GEL	Amount of emissions (CO_2, water, sewage) per one core	$\frac{Amount\ of\ emissions\ in\ period\ t}{(Amount\ of\ cores\ remanufactured \times weight\ of\ core)\ in\ period\ t} \times 100\%$	%	0%

Source adopted from Golinska et al. (2015)

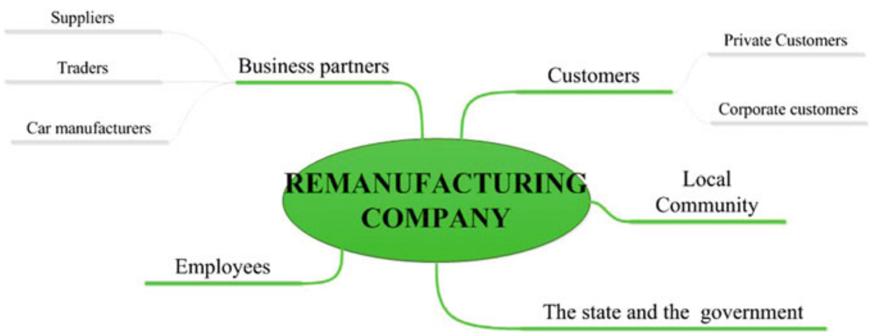


Fig. 3 The map of remanufacturing companies stakeholders. *Source* Own elaboration based on (Bryson 2003; UN 2008)

1. Business partners—they pay attention to the implementation of the principles of sustainable development particularly in relation with staff and working conditions, respect for human rights, respect for the law (crime, corruption, etc.),
2. Customers—they are interested in information about the products. Particularly important information regards: the impact on life and health, product quality and warranty associated with it, the availability, development of new products, implementation of processing especially in the context of the employment conditions.
3. Employees—they directly execute remanufacturing process and might be affected by the negative outputs of the process at their workplace. In the context the important issues are: the prospect of development, working conditions, safety and health, risk, ergonomics, comfort in the workplace.
4. Local community—they interests might be due to possibilities of jobs (creating jobs) but also potential threats (noise, smell, quality of water, etc.) related to specific business.
5. Government—these stakeholders can imposed on a company numerous legal obligations, including those related to the implementation of the concept of sustainable development.

In order to assess the social performance of the remanufacturing process, we proposed five indicators, as presented in Table 7.

The first indicator presents the change in employment level in a company. It is calculated as quotient of the number of employees during two consecutive periods. Employment change reflects the internal situation of the company, furthermore it presents also the situation on the labour market (it is essential for unemployment rate reduction).

The greatest problem with this indicator was related to the reference value, as the comparison between companies is almost impossible. The number of employees might change over time and there are considered three possible situations, which are and assigned to appropriate ratings of this indicator (Table 8).

Table 7 SSIR—final definition

No	Index	Measurement	Unit	Ref. value
1	Employment (E)	$\frac{Number\ of\ Employee\ in\ period\ t}{Number\ of\ Employee\ in\ period\ t-1} \times 100\%$	%	2
2	Staff training (ST)	$\frac{Number\ of\ employees\ in\ training\ in\ period\ t}{Total\ number\ of\ employees\ in\ period\ t} \times 100\%$	%	100%
3	Harmfulness of the reman process (HRP)	$W = \sum_{i=1}^{N} (300D + 10S + M) \times L_i$	1–5	1
		Where		
		D—number of threats to the *i-th* workplace, of which there is a large risk		
		S—number of threats to the *i-th* workplace, of which there is a medium		
		M—number of threats to the *i-th* workplace, of which there is a small risk		
		L_i—number of people to the *i-th* workplace, subject to the impact of hazards (D, M, S)		
		N—number of work stands performing task		
4	Comfort at the workplace (CAW)	$(1 - \frac{Number\ of\ identified\ muda\ in\ company}{Total\ number\ of\ potential\ muda\ in\ RPA}) \times 100\%$	%	100%
5	Innovation level (IL)	$\frac{Number\ of\ accepted\ innovation\ per\ period\ t}{Total\ number\ of\ proposed\ innovation\ in\ period\ t} \times 100\%$	%	100%

Table 8 The scale for the employment indicator

Value of employment's number change	<100%	100%	>100%
Situation of employment in a company	Decrease	No change	Increase
Rating	0	1	2

The second indicator for social aspects assessment is focusing on staff training This indicator express a percentage of employees participating in additional training arranged by the company (excluding obligatory training e.g. Health and Safety course).

The indicator presents, whether a company invests in employees' development. Staff development is linking many advantages: new knowledge and skills for workers, what increases their value as a resource for the company and society, integration of co-workers, developing relationships between people decreasing conflicts.

The indicator "Harmfulness of remanufacturing process" refers to the consequences associated with hazard to safe and health of workers in the remanufacturing process. In the literature there can be found many references to the measurement of health and safety at the workplace (e.g. Górny 2012; Stellman 1998). The employees' safety is usually related to the issues, as listed below (Butlewski 2012; Butlewski and Tytyk 2012; Misztal 2012):

- Workplace conditions (e.g. lighting, noise, vibrations);
- Characteristics of machines (e.g. design, construction, use);
- Prevention of harmful physical or mental stress due to the conditions of work;
- Work hazard due to dangerous substances, wastes and residues, etc.;
- Facilities: sanitary installations, washing, changing and storing clothes, supply of drinking water, first-aid treatment, protective equipment.

Proposed indicator allows the analysis the remanufacturing process impact on the health and safety of direct employees. According to the Polish and EU's law Employer is obliged to perform a risk analysis for each job position, therefore this indicator do not need additional data. Grading scale for indicator is presented in Table 9. The indicator value is influenced by (Pawłowska and Pietrzak 2000):

- the number of hazards resulting from the process,
- the level of occupational risk associated with these hazards,
- the number of people who carry the risk.

The indicator "Comfort at the workplace" helps to assess the overall organization of the work stands. The greatest problem was to create adequate measurement method, therefore comfort was defined as the work in conditions without any unnecessary activities (muda/waste). The more comfortable workplace is, the less disturbances appear during performing the operations.

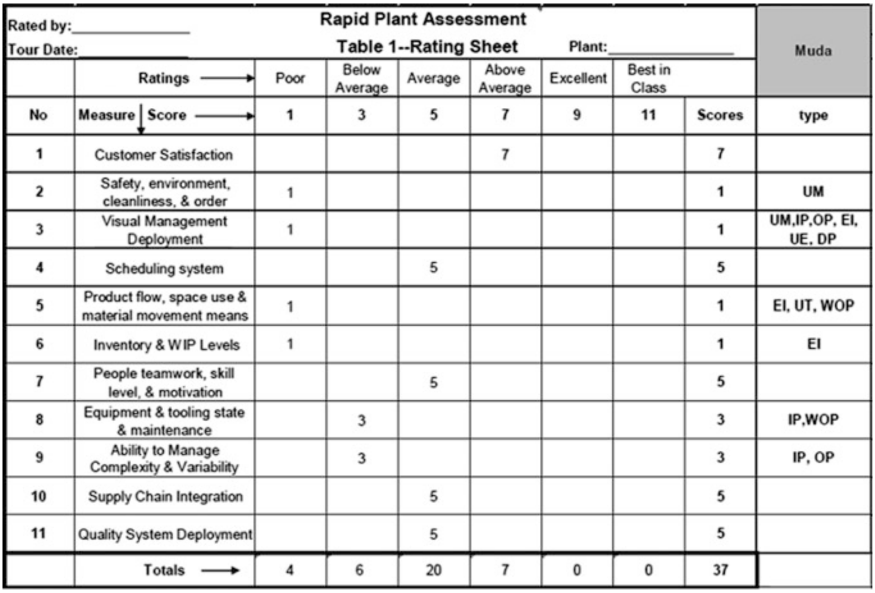
The measurement method of this indicator is based on the modified Rapid Plant Assessment method (RPA). RPA was elaborated in late 90s by Goodson (2002). This tool support the lean management in a plant. It allows to evaluate so called "leanness" of a company. It is based on a simple RPA questionnaire provides 20 yes/no questions to verify using the best practices. The next step of method includes is using leanness score matrix, where scoring is taking in consideration 11 areas (see Goodson 2002). The company is scored from "*poor*" (1) to "*best in class*" (11) for each category. The scale for scoring contains 6 options assessed by increased of 2 point for each subsequent class. As a result, the categories (broad areas) of strength and weakness can be explored. Categories with low ratings are having the potential for improvement, and should be explored first to provide the leanness (Sundin 2004).

For assessing the comfort level at the workplace the modified RPA (mRPA) was established. The low score of RPA shows the weaknesses of the remanufacturing facility organization, which influence the comfort of work of employees. If scores are low in any of the RPA categories, then additional questions are selected from a simplified list of muda questions (sMQ). The example is presented in Fig. 4.

Table 9 The values of the harmfulness of the remanufacturing process

Value	$W < 10$	$100 > W \geq 10$	$300 > W \geq 100$	$1500 > W \geq 300$	$W \geq 1500$
Harmfulness level	Very small	Small	Medium	High	Very high
Mark	1	2	3	4	5

Source Pawłowska and Pietrzak (2000)



Rated by:______________
Tour Date:______________

Rapid Plant Assessment
Table 1--Rating Sheet
Plant:______________

	Ratings →	Poor	Below Average	Average	Above Average	Excellent	Best in Class		Muda
No	Measure ↓ Score →	1	3	5	7	9	11	Scores	type
1	Customer Satisfaction				7			7	
2	Safety, environment, cleanliness, & order	1						1	UM
3	Visual Management Deployment	1						1	UM,IP,OP, EI, UE, DP
4	Scheduling system			5				5	
5	Product flow, space use & material movement means	1						1	EI, UT, WOP
6	Inventory & WIP Levels	1						1	EI
7	People teamwork, skill level, & motivation			5				5	
8	Equipment & tooling state & maintenance		3					3	IP,WOP
9	Ability to Manage Complexity & Variability		3					3	IP, OP
10	Supply Chain Integration			5				5	
11	Quality System Deployment			5				5	
	Totals →	4	6	20	7	0	0	37	

Fig. 4 Example of modified RPA (mRPA)

The sQM is created from general muda type database, which covers about 60 questions, divided into eight categories (see Fig. 4):

- defects,
- unnecessary motion (UM),
- unnecessary transport (UT),
- unnecessary waiting for operations (WOP),
- underutilization of employees (UP),
- inappropriate processing (IP),
- overproduction (OP),
- excess inventory (EI).

All the above listed categories affects the effectiveness of the employee. For example unnecessary motion, can lead to uncomfortable working position (low ergonomics of work stand). Also unnecessary transport, especially a manual one can put on an employee additional physical stress. Overproduction or inappropriate processing might cause overload of the employee with unnecessary operations which are not contributing to the company remanufacturing process effectiveness. Excess inventory are very often build up at the work station. Employee in order to find proper component or material is losing time searching for it, which negatively effects is overall effectiveness and it contributes to the unnecessary tiredness. The detailed description of this modified RPA assessment procedure is presented in Golińska (2013).

The last social indicator allows to assess the “Innovation level” in a company. It is calculated as a percentage of implemented improvements. Innovations expresses the ability to create, develop and implement new ideas to improve the operation of the company, increasing its effectiveness. It is essential from perspective of the workers’ motivation to allow them to make proposals on improvements. That reinforces the self-esteem, employees feel perceived, what results in increasing effectiveness.

4 Conclusions

The presented Sustainability Indicators System for Remanufacturing (SISR) provides a framework for assessing the environmental, economic and social aspects of remanufacturing operations.

The system is dedicated to small and medium size remanufacturers and allows to make assessment with the limited availability of data. The main advantage of the presented SISR is its simplicity. In case where companies struggle to obtain numerical data also an expert questionnaire is provided which allows qualitative assessment.

The main limitation of the proposed approach is that the indicators were elaborated based on data from the plant visit in automotive remanufacturing facilities. The indicators are reflecting the organizational conditions in those facilities. In authors’ opinion some additional studies might be required to make the SISR more universal tool.

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Determining the Importance of the Criteria for Assessment of Sustainability in Remanufacturing Companies

Monika Kosacka and Rafał Mierzwiak

1 Introduction

Determining the importance of assessment criteria of a sustainability requires using an appropriate methodical procedure, which would include two essential postulates. The first one is adequacy of the method used for a big set of criteria in order to avoid the effect of the importance blurring. The second one is minimising the time of the experts' involvement in such a way, that makes it possible to use a simple questionnaire survey. Those two postulates are fulfilled in a sufficient way by Thurstone's Law of Comparative Judgment. This method allows examining the preferences according to an established comparative scale referring to various assessment criteria, for example, products' brands. The method is also called a preference analysis for the third Thurstone's quarter. A methodical basis is a preference analysis which descends from a mathematical psychology.

Thurstone's Law of Comparative Judgment allows to build a linear metrical preference scale on the basis of information about preferences which were achieved due to the use of a paired comparison scale. Information about present preferences, which constitute a basis for indicating the meaning of particular examined criteria, can also be introduced with an order scale. Order scales are of a relative and comparative character due to which they determine a place of the examined attribute towards another examined attribute. A construction of those scales makes it possible to consider only transitive preferences (Sagan 2009).

An absolute requirement in order to use the methodology is a determined number of experts, namely minimum five people, who ensures reasonableness of

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the results. The bigger number of experts, the more precise the outcome is. In this method there are no limitations referring to the number of criteria being examined. However, an interval variability of numbers, which refer to the importance should be modified in an appropriate way.

The Law of Comparative Judgment proceeds according to the stages presented in Fig. 1.

Firstly, there should be chosen criteria which will be assessed. Secondly, a way of data presentation is established. There can be used a paired comparison or an ordered scale. With the use of a questionnaire survey, respondents are presenting their preferences according to the evaluated criteria. In a result, there are achieved data about preferences referring to objects being examined (a table of proportion). In other words, there can be determined information about dominating criteria and the value of the dominance. Received empirical results are standardised according to tables of normal distribution. In the final stage, there is carried out a normalization procedure. Consequently, received results are the basis for a preference scale construction, according to which, the importance assessment may be made.

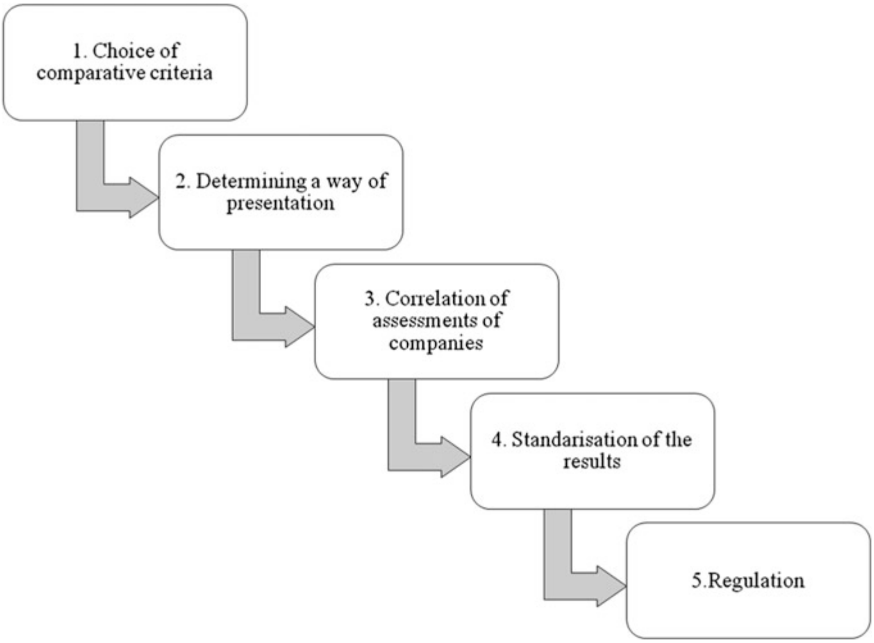

Fig. 1 Stages of Thurstone's law of comparative judgment. *Source* Elaborated based on Bazarnik et al. (1991)

2 The Use of a Preference Analysis for the Third Thurstone's Quarter for the Assessment of the Importance of Sustainability Indexes

In order to determine the importance of indexes assessing a level of a sustainability, a modified Thurstone's Law of Comparative Judgment was used, namely a preference analysis for the third Thurstone's quarter. Figure 2 presents an algorithm which demonstrates particular stages in the analysis.

The first important data in the methodology is a list of analyzed indexes (criteria of the sustainability).

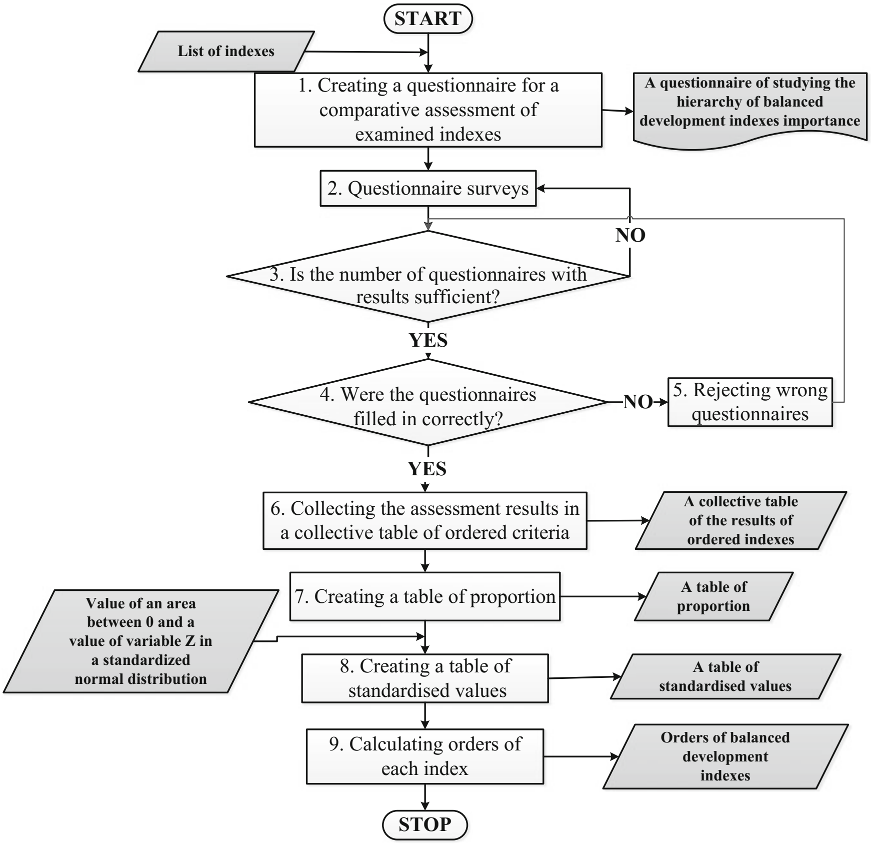

Fig. 2 An algorithm of importance identification for indexes of a sustainability assessment. *Source* Elaborated on the basis of Sagan (2009)

The sustainability measures should allow to assess the company performance in the three dimensions, as proposed by Brundtland Commission (WCED 1987):

- economic,
- ecological,
- social.

Ecological measures

In the literature there are many criteria for the assessment of sustainability from the environmental point of view e.g. energy consumption, water consumption, waste generation, GHG emissions, CO_2 equivalent, Life Cycle Assessment (LCA) (Amaya et al. 2010; Kara 2009; Kim et al. 2008; Sutherland et al. 2008).

Economic measures

Very often the economic measures indicate effectiveness of the inocurred cost comparing to the achieved effects (Fiksel et al. 1999). The most popular method in literature provided for assessing the economic aspects of sustainable development is the Life Cycle Cost (LCC). An example of using LCC analysis in the car parts remanufacturing context can be found in the study Schau et al. (2011).

Social measures

In the literature there is a big number of social indicators. They may be divided into five categories (Fatimah 2013; Ke et al. 2011; Schau et al. 2011; UN 2008):

- Health and safe (e.g. absences, means of protection, working conditions, etc.),
- Human rights (e.g. discrimination, child labour, people freedom, etc.),
- Employment (e.g. staff training, employment rate, turnovers, structure of Employment etc.),
- Living conditions,
- “Out of law” including crime, corruption, etc.

For the assessment of a sustainability level in a remanufacturing company, a list of 15 indexes (the indexes are arranged in Table 1) was made. The list of indexes is a complement list of criteria for measuring sustainability level in remanufacturing SMEs.

The indexes are distinguished in three categories of a sustainability: economical, ecological, and social. The mentioned indexes draw attention to various aspects of a sustainability in a production company. It was assumed that presented indicators present diversified importance levels. Thus, with the use of a modified Thurstone’s method, there were conducted research in order to determine the importance of each index within an assessment of a remanufacturing company.

In the next stage of research, a questionnaire was created. The questionnaire was filled in by all indicators, which should be ordered in ascending order by minimum five experts. The questionnaire was completed correctly by 14 independent experts including representatives of a production and management sphere. The assessment took place according to the following rules, namely:

Table 1 Indexes of a sustainability in a remanufacturing company

No.	Index category	Index	Index description
1	Economical	OEE	Overall equipment effectiveness
2		RPF	Remanufacturing process flow
3		Planning adequacy	Adequacy of remanufacturing process planning
4		AMT	Availability of machines and tools
5		Service level	Level of executed orders
6		OOS	Availability of materials (overall out of stock)
7	Ecological	Energy consumption level	Level of energy use per one regenerated core (product)
8		Waste generation level	Amount of waste generation per one regenerated core (product)
9		MRR	Material recovery rate
10		Generated emissions level (CO_2, water, sewage)	Amount of emissions (CO_2, water, sewage) per one regenerated core (product)
11	Social	Employment	Change of employment record in an examined period
12		Staff training	Number of people who undergone additional trainings
13		Harmfulness of production process	Index of production process harmfulness
14		Average level of comfort at the workplace	Comfort level on a workplace
15		Innovation level	Number of improvements proposed by employees and implemented in a company

Source Golinska et al. (2015)

1. strict ordering i.e. without a possibility to repeat the assessment (two indexes cannot get the same assessment),
2. orders given to indexes from 1 to 15, where 1—the least important index; 15—the most important index.

After collecting correctly completed questionnaires, a collective summary of the results was created. It was introduced in Table 2. There was also created a fictional criterion in the collective summary of the results, in order to ensure appropriate results at the stage of for standardization and regulation. That criterion got the smaller values from all evaluated indicators.

Considering the results a table of proportions (see Table 3), it was created according to the following rules, namely:

1. The equal number of rows and columns in the Table, as a result of indicators' number,
2. Fictional index included in the Table,

Table 2 A collective table of the results of ordered indexes

Expert no.	Indexes															
	OEE	RPF	Planning adequacy	AMT	Service level	OOS	Energy consumption level	Waste generating level	MRR	Generated emissions level	Employment	Staff training	Harmfulness of production process	Average level of comfort at the workplace	Innovation level	Fictional/ apparent (f/a)
1	16	11	12	10	9	13	8	15	14	7	4	2	5	6	3	1
2	8	7	3	6	16	11	15	12	14	13	5	2	10	4	9	1
3	16	5	13	3	8	7	11	14	15	9	2	6	12	4	10	1
4	16	15	14	9	13	8	2	4	12	3	5	6	11	10	7	1
5	11	15	9	14	16	3	12	8	13	5	7	2	6	4	10	1
6	9	7	11	8	4	6	13	14	12	15	2	3	16	5	10	1
7	9	7	11	8	4	6	13	14	12	15	2	3	16	5	10	1
8	14	13	12	9	16	8	11	10	15	4	5	3	2	6	7	1
9	11	15	9	14	16	3	12	8	13	5	7	2	6	4	10	1
10	4	9	15	3	10	7	14	8	16	6	13	5	12	2	11	1
11	16	13	2	14	11	10	8	3	15	4	9	6	7	5	12	1
12	6	7	11	5	4	10	14	16	15	13	9	3	12	8	2	1
13	16	11	12	8	13	14	7	10	15	4	3	6	5	9	2	1
14	16	15	11	14	7	13	12	5	10	6	8	3	4	2	9	1

Table 3 A table of proportion

Indexes	OEE	RPF	Planning adequacy	AMT	Service level	OOS	Energy consumption level	Waste generating level	MRR	Generated emissions level	Employment	Staff training	Harmfulness of production process	Average level of comfort at the workplace	Innovation level	Fictional/ apparent
OEE	0.00	0.29	0.29	0.14	0.29	0.21	0.50	0.36	0.64	0.36	0.14	0.07	0.36	0.07	0.29	0
RPF	0.71	0.00	0.50	0.21	0.50	0.36	0.43	0.43	0.71	0.36	0.14	0.07	0.43	0.07	0.36	0
Planning adequacy	0.71	0.50	0.00	0.36	0.43	0.36	0.57	0.50	0.86	0.36	0.14	0.07	0.36	0.14	0.29	0
AMT	0.86	0.79	0.64	0.00	0.57	0.43	0.50	0.64	0.79	0.43	0.14	0.14	0.50	0.29	0.36	0
Service level	0.71	0.50	0.57	0.43	0.00	0.43	0.43	0.36	0.64	0.29	0.21	0.00	0.36	0.21	0.43	0
OOS	0.79	0.64	0.64	0.57	0.57	0.00	0.64	0.71	1.00	0.50	0.21	0.00	0.57	0.21	0.50	0
Energy consumption level	0.50	0.57	0.43	0.50	0.57	0.36	0.00	0.50	0.71	0.21	0.14	0.07	0.29	0.14	0.14	0
Waste generation level	0.64	0.57	0.50	0.36	0.64	0.29	0.50	0.00	0.71	0.36	0.29	0.14	0.36	0.07	0.43	0
MRR	0.36	0.29	0.14	0.21	0.36	0.00	0.29	0.29	0.00	0.14	0.00	0.00	0.14	0.00	0.00	0
Generated emissions	0.64	0.64	0.64	0.57	0.71	0.50	0.79	0.64	0.86	0.00	0.50	0.21	0.64	0.29	0.57	0
Employment	0.86	0.86	0.86	0.86	0.79	0.79	0.86	0.71	1.00	0.50	0.00	0.36	0.57	0.50	0.71	0
Staff training	0.93	0.93	0.93	0.86	1.00	1.00	0.93	0.86	1.00	0.79	0.64	0.00	0.86	0.79	0.86	0
Harmfulness of production process	0.64	0.57	0.64	0.50	0.64	0.43	0.71	0.64	0.86	0.36	0.43	0.14	0.00	0.21	0.36	0
Average level of comfort at the workplace	0.93	0.93	0.86	0.71	0.79	0.79	0.86	0.93	1.00	0.71	0.50	0.21	0.79	0.00	0.71	0
Innovation level	0.71	0.64	0.71	0.64	0.57	0.50	0.86	0.57	1.00	0.43	0.29	0.14	0.64	0.29	0.00	0
Fictional/apparent	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0

3. Value “0” inlcuded on the table’s diagonal, (in the place of each row “j” and each column “i” intersection),
4. Including in each cell of the table, a value reflecting, the dominance of a particular index over the another one (direction from columns to rows),
5. The value in each cell of the table, except the cells which are situated on a table’s diagonal, should be calculated in the following way:
    - a comparison always concerns a pair of indexes,
    - a comparison of an index from a given column takes place with the index from a given row,
    - during the analysis of a collective table of results, there are summarized total numbers of advantage achieved by index from a given column over the compared index from a row,
    - the number of predominance is divided by a total of a number of experts who made the assessments.

A table of proportions (Table 3) is a projection of dominance of a given index over the another one. It is essential from the perspective of another stage of calculations, so values in the table need to be rounded to 2 decimal places.

Results obtained in Table 3 are transformed with the use of Table 4 which presents the area between 0 value and a value of variable Z in the scope from 0 to 1 in a standardised normal distribution (see Table 4).

As a result of a process of standardisation, a table of standardised values was achieved (Table 5).

The table of standardised values will be determined, when there will be made assignment of each value from a table of proportion with the use of suitable value from Table 4. For instead, for a value 0.8, it will be a value 0.2881. However, for a value 0.81, it will be a value 0.2910. Standardised values allow to determine the importance of particular indexes according to the following formula (1)

$$W_n = \frac{Z_n - Z_{\min}}{Z_{\max} - Z_{\min}} \tag{1}$$

where:

Z_n arithmetic average for a column “*i*”;
W_n importance of a given index, which can be established according to a formula;
Z_{min} minimum value of arithmetic averages among averages Z_n (0.00);
Z_{max} maximum value of arithmetic averages among averages Z_n (0.2818).

Table 4 Value of area between 0 and a value of variable Z in a standardized normal distribution

	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	0.0000	0.0040	0.0080	0.0120	0.0160	0.0199	0.0239	0.0279	0.0319	0.0359
0.1	0.0398	0.0438	0.0478	0.0517	0.0557	0.0596	0.0636	0.0675	0.0714	0.0753
0.2	0.0793	0.0832	0.0871	0.0910	0.0948	0.0987	0.1026	0.1064	0.1103	0.1141
0.3	0.1179	0.1217	0.1255	0.1293	0.1331	0.1368	0.1406	0.1443	0.1480	0.1517
0.4	0.1554	0.1591	0.1628	0.1664	0.1700	0.1736	0.1772	0.1808	0.1844	0.1879
0.5	0.1915	0.1950	0.1985	0.2019	0.2054	0.2088	0.2123	0.2157	0.2190	0.2224
0.6	0.2257	0.2291	0.2324	0.2357	0.2389	0.2422	0.2454	0.2486	0.2517	0.2549
0.7	0.2580	0.2611	0.2642	0.2673	0.2704	0.2734	0.2764	0.2794	0.2823	0.2852
0.8	0.2881	0.2910	0.2939	0.2967	0.2995	0.3023	0.3051	0.3078	0.3106	0.3133
0.9	0.3159	0.3186	0.3212	0.3238	0.3264	0.3289	0.3315	0.3340	0.3365	0.3389
1.0	0.3413	0.3438	0.3461	0.3485	0.3508	0.3531	0.3554	0.3577	0.3599	0.3621

Source (www.statsoft.pl)

Table 5 Table of standardised values

Indexes	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	f/a
1	0	0.1141	0.1141	0.0557	0.1141	0.0832	0.1915	0.1406	0.2389	0.1406	0.0557	0.0279	0.1406	0.0279	0.1141	0
2	0.2611	0	0.1915	0.0832	0.5	0.1406	0.1664	0.1664	0.2611	0.1406	0.0557	0.0279	0.1664	0.0279	0.1406	0
3	0.2611	0.1915	0	0.1406	0.1664	0.1406	0.2157	0.1915	0.3051	0.1406	0.0557	0.0279	0.1406	0.0557	0.1141	0
4	0.3051	0.2852	0.2389	0	0.2157	0.1664	0.1915	0.2389	0.2852	0.1664	0.0557	0.0557	0.1915	0.1141	0.1406	0
5	0.2611	0.1915	0.2157	0.1664	0	0.1664	0.1664	0.1406	0.2389	0.1141	0.0832	0	0.1406	0.0832	0.1664	0
6	0.2852	0.2389	0.2389	0.2157	0.2157	0	0.2389	0.2611	0.3413	0.1915	0.0832	0	0.2157	0.0832	0.1915	0
7	0.1915	0.2157	0.1664	0.1915	0.2157	0.1406	0	0.1915	0.2611	0.0832	0.0557	0.0279	0.1141	0.0557	0.0557	0
8	0.2389	0.2157	0.1915	0.1406	0.2389	0.1141	0.1915	0	0.2611	0.1406	0.1141	0.0557	0.1406	0.0279	0.1664	0
9	0.1406	0.1141	0.0557	0.0832	0.1406	0	0.1141	0.1141	0	0.0557	0	0	0.0557	0	0	0
10	0.2389	0.2389	0.2389	0.2157	0.2611	0.1915	0.2852	0.2389	0.3051	0	0.1915	0.0832	0.2389	0.1141	0.2157	0
11	0.3051	0.3051	0.3051	0.3051	0.2852	0.2852	0.3051	0.2611	0.3413	0.1915	0	0.1406	0.2157	0.1915	0.2611	0
12	0.3238	0.3238	0.3238	0.3051	0.3413	0.3413	0.3238	0.3051	0.3413	0.2852	0.2389	0	0.3051	0.2852	0.3051	0
13	0.2389	0.2157	0.2389	0.1915	0.2389	0.1664	0.2611	0.2389	0.3051	0.1406	0.1664	0.0557	0	0.0832	0.1406	0
14	0.3238	0.3238	0.3051	0.2611	0.2852	0.2852	0.3051	0.3238	0.3413	0.2611	0.1915	0.0832	0.2852	0	0.2611	0
15	0.2611	0.2389	0.2611	0.2389	0.2157	0.1915	0.3051	0.2157	0.3413	0.1664	0.1141	0.0557	0.2389	0.1141	0	0
f/a	0.3413	0.3413	0.3413	0.3413	0.3413	0.3413	0.3413	0.3413	0.3413	0.3413	0.3413	0.3413	0.3413	0.3413	0.3413	0
z	0.24859	0.22213	0.21418	0.18347	0.23598	0.17214	0.22516	0.21059	0.28183	0.159963	0.11266	0.06141	0.183181	0.100313	0.16339	0
Wn	0.88204	0.78817	0.75994	0.65099	0.83731	0.61079	0.79893	0.74721	1	0.56757	0.39976	0.21792	0.649953	0.355923	0.57974	0

Table 6 A combination of indexes according to meaning for a remanufacturing process assessment

Index	Order
MRR	1.00
OEE	0.88
Service level	0.84
Energy consumption level	0.80
RPF	0.79
Planning adequacy	0.76
Waste generation level	0.75
AMT	0.65
Harmfulness of production process	0.65
OOS	0.61
Innovation level	0.58
Generated emissions level	0.57
Employment	0.40
Average level of comfort at the workplace	0.36
Staff trainings	0.22

3 Results

As a result of the carried out studies, it was proved that particular indicators used for remanufacturing assessment are not representing the same importance level, however, what should be considered in a performed assessment.

In Table 6 there are demonstrated results from the importance level analysis with the use of described method.

The biggest importance for the remanufacturing process was identified for an efficiency of materials' use (MRR).

Among indicators representing a high importance level, there were also indexes of economic and ecologic aspect of sustainability. However, social indexes represents a slightly smaller importance, what was proved by the results of other studies. The results confirmed the global trend where the economic and ecologic issues are dominating in the sustianability context.

Results of this study will be used in further researches of the level of sustainability of Polish remanufacturing enterprises.

4 Conclusions

Authors have presented original approach for criteria evaluation from the perspective of their importance for analyzed process, which is characterized be features which makes it better than AHP method. The major advantage of that method is that the number of the assessed criteria (indexes) is not limitation of the method. Even when there is used a big set of criteria, effect of the importance blurring is eliminated.

The limitation of the method is that the basis are questionnaires results. The group of experts in the survey should be closely related to the area where the method is used. What is more, the analyzed criteria should be well defined, that there will be no misunderstanding during experts assessment. In the case when the number of compared criteria is large number, there may appear some difficulties in the sequencing them.

It was stated in the Introduction that one of the advantages of the presented method it is also simplicity of the mathematic calculation. In the case of large number of experts as well as surveys it may be quite difficult to make the calculation with the use of simple spreadsheet, although nowadays it is not a problem. There is an access to many various programs such us Statictica, which support evaluation made with the use of presented method. That problem may be eliminated thanks to the software (e.g. Statistica) which allow to introduce data without making some indirect calculations (e.g. Table of proportion, Table of standardised values).

The presented method is a valuable alternative in the case of importance level determination issue.

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The Mixed Method for Sustainability Assessment of Remanufacturing Process Using Grey Decision Making

Paulina Golinska-Dawson, Monika Kosacka, Rafał Mierzwiak and Karolina Werner-Lewandowska

1 Introduction

Sustainable development is commonly defined as „development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987). This definition suffers through its generality and is more suitable to ex-post assessment of sustainability of economic growth. The more recent definition states that (Sachs 2015).

"Sustainable Development is the Holistic Integration of Economic, Social, and Environmental Objectives in an Approach to Scientific Analysis, Governance, Problem Solving, and Human Action."

It is still a rather general definition not providing clear guidelines to decision-makers. So far there is lack of well-defined characteristics of the sustainability economic growth, because (Irmen 2015):

- there is no solution for ongoing environmental degradation,
- international policy coordination on energy and climate issues is not efficient,
- new technologies haven't so far overcome the scarcity of natural resources,
- there are distributional conflicts.

The concept of sustainable development is even more difficult to implement at the micro scale at an enterprise level. On a company level the requirements of the sustainable policy can be translated as (Golinska and Kübler 2014):

- Economical utilization of the resources,
- Environmental friendly utilization of the resources,

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- Utilization of the resources in the way, which provide ergonomics and safety at the facility and minimum external burdens affecting the surrounding communities.

Small and medium size companies face problems when it comes to integrating economic, ecological and social aspects in their daily business. SME often lack capacity, know-how and technical infrastructure for adapting complex theoretical models. There is a need for methods and tool which guide SMEs on how to identify optimization potentials in their processes, then derive and implement improvements.

Sustainability assessment can be defined as "*a process that guides decision making towards sustainability*" (Hacking and Guthrie 2008). Most of the sustainability methods are dedicated to macro level assessment at country or regional level (see Singh et al. 2012). In case of the business entities most of the measuring and reporting initiatives are designed for big companies.

In this chapter the authors aim to find answer to the questions, as follows:

- Q1: How can we measure sustainability at a micro level (remanufacturing company)?
- Q2: How can we aggregate uncertain or incomplete data to define sustainability level?
- Q3: How can we use the results of assessment in order to improve the sustainability level of a remanufacturing company.

Despite the fact that there are many possibilities of sustainability measurement there are problems with relating them to the manufacturing (see (Moldavska and Welo 2015). In case of the remanufacturing SMEs the assessment is even more challenging.

Limited human and financial resources of those companies lead to the requirement for a simple performance measurement system. The greatest challenge of the sustainability assessment in remanufacturing is the high level of uncertainty in contrast to the manufacturing business.

The major purpose of this chapter is to develop the method of sustainability level assessment which is dedicated for remanufacturing sector. In order to find the answer to the research question Q1, the authors define the indicators, then present their formulation strategy and scaling. Searching for the answer to research question Q2 we present normalization, weighting and the aggregation method. Research question Q3 focuses on interpretation method of the achieved sustainability level. We present a IT tool which facilitates the improvement of the sustainability level of remanufacturing company.

The sustainability level is defined as the overall score of the sustainability of company's remanufacturing operations. It is calculated as an aggregated value, which results from summarizing the values of the individual indicators. The application of Grey Decision Making, allows using even data with inherent uncertainty or which is partly incomplete. The proposed method was verified using data from Polish remanufacturing companies.

2 Sustainability Assessment—Framework for Remanufacturing

In the literature there are examples of the sustainability assessment on the global level such as the Indicators of Sustainable Development from the United Nations (UN 2007), what makes possible the measurement of the sustainability of the country. Sustainability assessment at the company's level can be performed with the use of Dow Jones Sustainability Index (Joung et al. 2012) or the Global Report Initiative (GRI 2013).

Moreover sustainability assessment might be done in reference to each sustainability pillar, pointing out problems just in the social, economic or environmental dimension (Singh et al. 2014; Veleva and Ellenbecker 2001; Krajnc and Glavic 2005).

There are several attempts to classification of existing sustainability assessment methods. Ness et al. (2007) have divided sustainability assessment methods into three categories:

(a) the indicators/indices that are further divided into integrated (e.g. Human Development Index—HDI, Ecological Footprint—EF) and nonintegrated (e.g. Environmental Pressure Indicators—EPIs;
(b) methods focused on the material and/or energy flows of a product or service from a life cycle perspective including: Life Cycling Costing (e.g. LCCA), Product material flow analysis (e.g. Material Intensity Analysis), Product energy analysis;
(c) methods focused on assessing projects and policies (e.g. Environmental Impact Assessment).

Examples of that sustainability methods categorization and detail information are presented in the paper of Ness et al. (2007).

Small and medium-sized enterprises (SMEs) have to respond to the challenges related to sustainable development as other. In that case there are many challenges of sustainability assessment including following major issues (Chen et al. 2014):

- Time consuming assessment due to the complexity and amount of required data, what is related to the high cost of the assessment (e.g. using LCC or LCA method);
- Lack of applicability at the factory level;
- Theoretical character of the assessment tools (Rosen and Kishawy 2012; Singh et al. 2014).

Most of the companies in UE are SMEs—According to statistics from the European Commission, 99.2% of the companies in the European manufacturing sector are SMEs (Tepelmann 2013).

SMEs face several specific obstacles: on the one hand they are characterized by lack transparency of their current situation and knowledge of the best ways for improvement. On the other hand, SMEs have limited resources in terms of personnel, time and capital, what enables them implementation of complex performance measurements systems (Thiede et al. 2013).

Taking into account all presented information there is another problem of the sustainability assessment in remanufacturing. There are research which assess economic and environmental (e.g., Feng and Joung 2009) or social aspects of remanufacturing. The majority of them focus on LCA (life cycle assessment) of the remanufactured products in comparison to the new products or recycled products (e.g. Schau et al. 2012). In practice LCA or LCC analyses require a big scope of data what usually is not available for SMEs. In the work of Sundin and Lee (2011) there was provided a comparison of studies focused on the assessment of the environmental performance of remanufacturing, resulting in the classification of the environmental indicators used for assessment of the remanufacturing process, as following (Schau et al. 2012):

- Direct: consumption of materials, energy and waste generated, which translates this directly to resource savings,
- Indirect: Life Cycle Assessment methods, which calculates eco-points to assess the environmental impact, they assess the long-term potential environmental impact.

After literature review and case studies in remanufacturing companies a need for elaboration of sustainability assessment method has been identified. The authors specified requirements for the sustainability assessment method for remanufacturing company, as follows:

1. Applicable at the factory level;
2. Considering SME remanufacturing company's resource limitations;
3. Helping decision—makers to introduce improvements actions in order to have more sustainable operations;
4. Not generating demand for additional data;
5. Providing holistic assessment of sustainability of operations.

In the next subsection there is presented method which fulfill all the above mentioned requirements.

3 Developing Assessment Method

3.1 Grey Systems Theory as a Method's Background

The theory of the Grey System was established in 1982 by Professor Deng Julong (1989). Grey Systems Theory is focused on the study of problems characterized by poor information and small samples. It concerns systems with uncertain data and insufficient information to in order fully characterize the system (Liu 2010).

In recent years, there were many Grey Systems Theory applications, particularly in the field of technical and economics sciences (Akay and Atak 2007; Wang et al. 2005). The theory of grey systems consists of the following fields (Zavadskas et al. 2009):

- foundation, consisting of grey numbers, grey elements and grey relations;
- grey systems analysis, including grey incidence analysis, grey statistics, grey clustering, etc.;
- grey systems modelling, through the use of generation of grey numbers or function so that hidden patterns can be found;
- grey prediction;
- grey decision-making;
- grey control.

Decision making is the process of identifying and choosing the best alternative from all possible based on the values and preferences of the decision maker (Harris 1998).

Grey Decision Making (GDM) is about making decisions using some decisions models where there are used solely grey systems elements or they are combined with general decision model (Liu 2010).

In the real world uncertain systems with poor information exist commonly. Remanufacturing facility fulfill requirements of those systems. In order to classify remanufacturing companies into one of sustainability levels, method of Grey Decision Making was used.

3.2 Method Description

The method providing the sustainability assessment for remanufacturing companies can be presented in a few steps, which are presented below (Fig. 1).

Step 1 includes the defining and calculating values of assessment criteria $j = 1, 2, \ldots, m$.

The criteria should meet the requirement of being easy applicable in small and medium size companies what is related to the possibility of calculating indicators on the basis of the expert’s (decision maker) knowledge in the situation when the numerical data is not available.

The list of assessment criteria includes (adopted from Golinska et al. 2015), as follows:

- j1 stands for Overall Equipment Efficiency (OEE),
- j2 stands for the remanufacturing process flow (RPF),
- j3 stands for the adequacy of remanufacturing process planning (PA),
- j4 stands for availability of machines and tools (AMT),
- j5 stands for the service level (SL),
- j6 stands for availability of the materials (overall out of stock) (OOS),

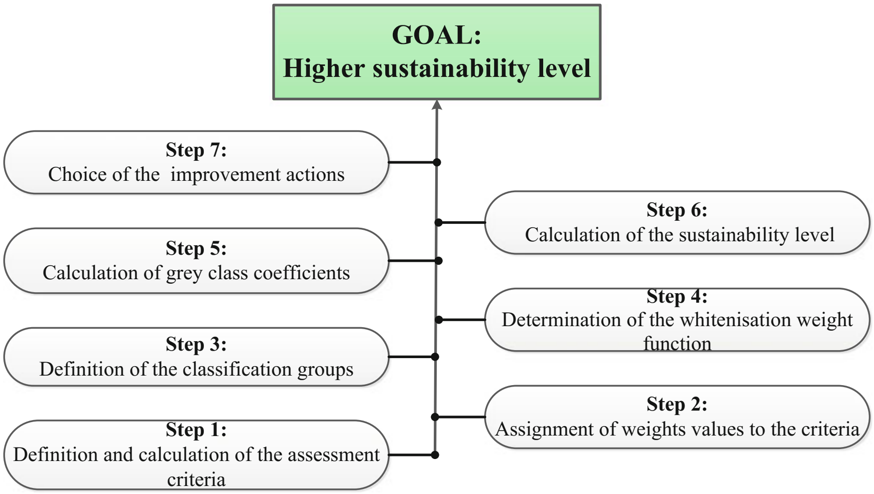

Fig. 1 Research method. *Source* own elaboration

Table 1 Importance level of indicators in the method of sustainability assessment for remanufacturing

j	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
η_j	0.88	0.79	0.76	0.65	0.84	0.61	0.8	0.75	1	0.57	0.4	0.22	0.65	0.36	0.58

Source own elaboration

- j7 stands for the energy consumption level (ECL),
- j8 stands for the waste generation level (WGEL),
- j9 stands for the material recovery rate (MRR),
- j10 amount of emissions (CO_2, water, sewage) per one core (GEL),
- j11 the change in the employment (E)
- j12 stands for staff training (ST)
- j13 stands for the harmfulness of the remanufacturing process (HRP)
- j14 stands for the comfort at the workplace (CAW),
- j15 stands for the innovation level (IL).

During that step the value of the *j-th* indicator is determined (x_j). The detailed description of each indicator can be found in the Chap. 7, entitled “Sustainability Indicators System for Remanufacturing”.

In the next step there were assigned weights to assessment indicators (η_j), where $0 < \eta_j \leq 1$. The closer the value of η_j to 1 mean the more important the indicator is. We use the third quarter preferential Thurstone’s analysis as presented in the Chap. 8, entitled “Determining the importance of the criteria for assessment of sustainability in remanufacturing companies”.

The summary of the assignment process of the weight values to the criteria (from Step 1) is presented in Table 1.

Table 2 Classification groups characteristic

k	Level of sustainability	Requirements	
		Description	Time horizon for implementation
1	Acceptable	Improvement actions	Long
2	Conditionally acceptable	Corrective actions	As soon as it is economically and organizationally possible
3	Unacceptable	Corrective actions	Short (required immediately)

Source Own elaboration

In the **Step 3** there are determined the classification groups (k). In the presented method there were identified three groups (Table 2).

Step 4 includes determination of the whitenisation weight function for each classification group (*k*) towards *j-th* indicator presented in the Eq. 1:

$$f_j^k(x_j) \tag{1}$$

The application of the whitenisation weight function allows comparability and aggregation of uncertain data. In grey theory when the information is fully known, then we deal with a white system. In opposite when the information is unknown, then we deal with a black system and a grey system includes information known partially (Li et al. 2007).

It allows to transform “grey number” into “white number”. A “grey number” has a precise lower and upper bound, but its position between the bounds is not known (Yang and John 2012). The “grey number” can belong to a discrete set of real numbers, fall within an interval of real numbers, or reside within any combination of intervals and discrete sets (Yang and John 2012).

In the determination of the whitenisation weight function there were taken into account the following issues:

- the desired direction of change of the analyzed indicator (min or max);
- the acceptable values of criteria (the range of variability).

The “grey numbers” don’t consider the distribution of possible values, for that reason they allow to solve decision problems with very limited information.

In the literature there is lack of strict definition of the whitenisation weight function. It should be selected taking into account the specifics of the classifications performed (Golinska et al. 2015). It is good practice to be a triangular function, because it is simple to designate its analytical form. The detail whitenisation weight functions for each indicator (from j1 to j15) were described by Golinska (2015).

In the **step 5** the weights of the grey class coefficients are computed (see Eq. 2):

$$\sigma^k = \sum_{j=1}^{m} f_j^k(x_j) \times \eta_j \tag{2}$$

According to the presented formula there will be three grey class coefficients $\sigma^1, \sigma^2, \sigma^3$ due to the fact that the basis for the assessment method are three sustainability levels (S_L = {1,2,3}).

Step 6. After determination the grey class coefficients there should be calculated the decision's indicator which indicates the sustainability level of the analyzed company (Eqs. 3, 4):

$$\sigma^{k^*} = \max\{\sigma^k\} for\, 1 \le k \le s \tag{3}$$

$$\mathrm{k}^* = \mathrm{S_L} \tag{4}$$

In the **Step 7** there are defined improvement actions according to the sustainability level (S_L). In addition to information about the necessary actions and the speed of reaction to the current situation, GDM also provides ranking of the actions. The SMEs in remanufacturing sector have limited human and material resources, and they are not able to take all required actions at the same time. It is relevant to prioritize the actions which should be carried out first.

In order to prioritize actions, it is crucial to analyze the achieved values of the function $f_j^k(x_j)$. The maximum value of this function is 1. The higher the value of the function, the higher place of the indicator in the priority ranking. In the Fig. 2 there is presented the ranking priority of actions procedure.

At the beginning all criteria j are sorted into one of the class k (sustainability level). All the criteria from the 3rd class have the highest priority, therefore they are analyzed in in the first place. All criteria are ranked by decreasing values of the weight of the criterion—η_j. There is assigned priority number *(p)* according to the weight value. The higher weight of index, the higher priority number of the action related to that indicator. The first priority is assigned to the index from the 3rd class with the highest importance level. In the second phase there are ranked criteria belonging to the class *k* = 2, sorted and prioritized in accordance with the same procedure.

3.3 Method Testing

The proposed method of sustainability assessment was pilot tested in three Polish remanufacturing companies—representing SMEs. The sample limitation to three companies was intentional, as they should fulfill predefined organizational requirements. The results of the indicators values in companies under study are presented in the Table 3.

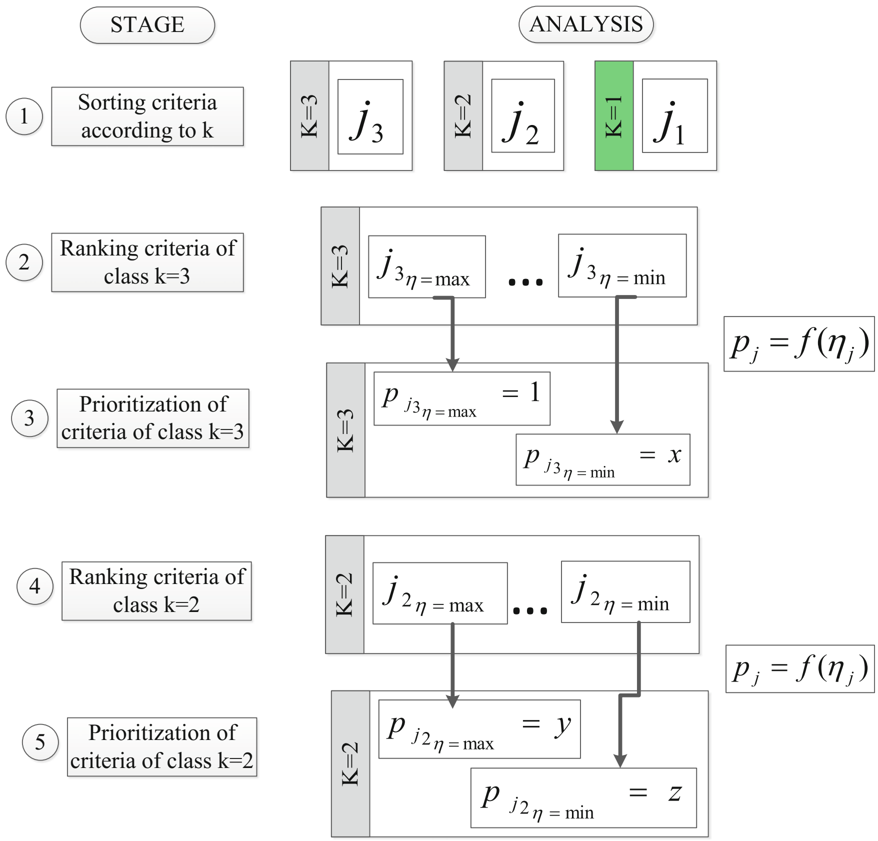

Fig. 2 Procedure of ranking improvement actions. *Source* own elaboration

In the further part of the chapter there will be analyzed case of the company 3 (C3). All required information are presented in the Table 4.

In order to get the information about the sustainability level (S_L) of the company in accordance to the adopted indicators systems and theirs weights there should be calculated:

- values of whitenisation weight functions for each classification group (k)—$f_j^k(x_j)$;
- grey class coefficients (the basis for them are results of multiplying whitenisation weight functions and weights of indicators)—σ^k;
- decision's indicator—σ^{k*}.

The analyzed company has conditionally accepted level of sustainability of remanufacturing operations (2nd level). However, as presented in Table 5 for some indicators the values are classified as level 3 (unacceptable level). That means that

Table 3 Values of indicators

Indicator (j)	Company 1 (C1)	Company 2 (C2)	Company 3 (C3)
1	90%	78%	58.31%
2	5	4	3
3	60%	35%	1%
4	4	4	3
5	97%	92%	90%
6	4	3	1
7	1	2	3
8	5%	10%	17%
9	95%	90%	85%
10	1	3	3
11	120%	100%	90%
12	75%	50%	30%
13	8	40	150
14	30%	30%	10%
15	75%	40%	30%

Source modified from Golinska et al. (2015)

Table 4 Sustainability class determination for the company 3—calculations

j	x_j	η_j	$f_j^1(x_j)$	$f_j^1(x_j) \times \eta_j$	$f_j^2(x_j)$	$f_j^2(x_j) \times \eta_j$	$f_j^3(x_j)$	$f_j^3(x_j) \times \eta_j$
1	58.31%	0.88	0.686	0.604	0.752	0.662	1	0.880
2	3	0.79	0.6	0.474	0.8	0.632	0.4	0.316
3	1%	0.76	0.01	0.008	0.2	0.152	0.99	0.752
4	3	0.65	0.6	0.390	0.8	0.520	0.4	0.260
5	90%	0.84	0.947	0.795	1	0.840	0.1	0.084
6	1	0.61	0.2	0.122	0.4	0.244	0.8	0.488
7	3	0.8	0.4	0.320	0.8	0.640	0.6	0.480
8	17%	0.75	0.83	0.623	0.34	0.255	0.17	0.128
9	85%	1	0.85	0.850	0.3	0.300	0.15	0.150
10	3	0.57	0.65	0.371	0.7	0.399	0.35	0.200
11	90%	0.4	0	0.000	0	0.000	0.9	0.360
12	30%	0.22	0.3	0.066	0.6	0.132	0.7	0.154
13	150	0.65	0.4	0.260	0.8	0.520	0.6	0.390
14	10%	0.36	0.1	0.036	0.2	0.072	0.9	0.324
15	30%	0.58	0.3	0.174	0.6	0.348	0.7	0.406
Sustainability level determination			σ^1	5.092	σ^2	5.716	σ^3	5.371
			$\sigma^{k*} = \text{Max}\ \{\sigma^1, \sigma^2, \sigma^3\}$					5.716
			$\boldsymbol{S_L}$					***2***

Source own elaboration

Table 5 Requirements for corrective actions—company 3

Classification group (*k*)	Criterion (*j*)	Weight (η_j)	Priority (*p*)
3	1 (OEE)	0.88	P1
	3 (PA)	0.76	P2
	6 (OOS)	0.61	P3
	15 (IL)	0.58	P4
	14 (CAW)	0.36	P5
2	5 (SL)	0.84	P6
	7 (ECL)	0.80	P7
	2 (RPF)	0.79	P8
	4 (AMT)	0.65	P9
	13 (HRP)	0.65	P10
	10 (GEL)	0.57	P11
	11 (E)	0.40	P12
	12 (ST)	0.22	P13

Source adopted from Golinska et al. (2015)

performance in the areas measured by those indicators should be improved first. The priority vales (p) shows the order of the corrective actions.

The most problematic areas which influence the overall sustainability level are: utilization of the equipment, the planning adequacy and availability of materials, which are related. They represent the economic dimension of operations. Also in the social domain they are problems related to the innovativeness and comfort at the workplace.

3.4 Sustainability Assessment Tool (SAT)

In accordance to support decision-makers in remanufacturing companies there was prepared a simple Sustainability Assessment Tool (SAT). Tool is available for all visitors on the project website (www.siro.put.poznan.pl). In this section we present the simplified structure of the tool (Fig. 3).

The tool consists of four parts, as follows:

1. General data about the company (basic business activity, headquarter, size (Employment), time of running a business);
2. Economic indicators;
3. Ecologic indicators;
4. Social indicators.

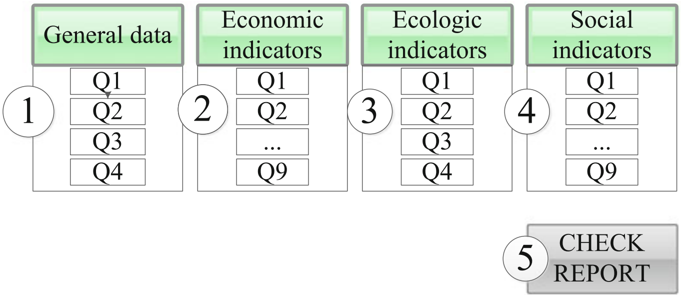

Fig. 3 Visualization of the SAT structure. *Source* own elaboration

The tool design is tuned to the needs and information structure of SMEs in remanufacturing sector and includes simple questions, which might be answered quickly by the experts. All questions are related to the indicators which are used in the presented method of the sustainability assessment. There are used different field's type in order to achieve the answer for the question, including:

- Radiobutton;
- Text box (only numbers);
- Checkbox;
- Combobox;
- Selector (values in %, between 1 and 100%).

In the Table 6 is provided characteristic of the indicator (j) in the SAT.

All questions require the answer. In the other case, there will appear the warning window informing about incompleteness of the data. After completing the required data the user has the ability to check the summarizing report after clicking on the button: "*Check report*".

In the summarizing report there are available the following information as presented in Table 7.

In the result the information about the assessment score is available in less than 15 min, what makes the whole method simple and useful.

The whole report content is not available without additional conditions. If the company will not introduce information about the contact to them (name of the contacted person, e-mail address and phone) and permission on the use of data to the University research purposes, there will be only available information from part 1 and part 2 highlighted on the computer screen. In the other case there will be available report in the format of the Portable Document Format including all parts presented in the above Table.

The SAT makes the procedure of the remanufacturing companies sustainability assessment and practical used.

Table 6 Indicators characteristic from the perspective of the analyzed computer tool

j	Number of questions	Type of box			
		Text box	Checkbox	Radio	Selector
1	3				X
2	1			X	
3	2	X			
4	1			X	
5	1				X
6	1			X	
7	1			X	
8	1				X
9	1				X
10	1			X	
11	2	X			
12	1	X			
13	4	X			
14	1		X		
15	1				X

Source own elaboration

Table 7 Report content description

No	Report part name	Description	Form of presented data	Availability
1	Sustainability indicators	There are presented all 15 indicators from the perspective of the achieved result as well as their reference values	Table	For all
2	Sustainability level	Characteristic recommendations	Verbal description	For all
3	Improvement's actions	Indicators are sorted according to the priority of the required actions	Table	Required permission to use introduced data

Source own elaboration

4 Conclusions

The chapter aims to present the Mixed Method for Sustainability Assessment of Remanufacturing Process Using Grey Decision Making and application of the designed method. The method is dedicated for small and medium sized enterprises from remanufacturing sector, what enables them to assess the sustainability level taking into account all aspects of sustainable development on the company's level.

The authors based on their previous experience and case studies conducted in SMEs in remanufacturing sector proposed set of universal indicators which can be assessed without any additional reporting effort, basing on expert knowledge of decision makers.

The main advantage of the proposed method is that it includes limitations of the specific sector which is remanufacturing. Moreover there was prepared Sustainability Assessment Tool which stands as a IT support. It enables company to assess their sustainability class including recommendation according to the required improvement actions (with their prioritization). The access to the tool is constant and open from home website of the project *SIRO*.

The major limitation of this method is the linkage between improvement actions and definition of the indicator. The presented method indicates the direction of changes without specification of the specific correction actions assigned to the indicator.

The further research steps will include the extension of the method in order to create a catalogue of actions recommended in order to achieve an improved sustainability level of the company.

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Simulation Modelling of Remanufacturing Process and Sustainability Assessment

Paulina Golinska-Dawson and Pawel Pawlewski

1 Introduction

The Circular Economy concept gains a lot of attention in many countries around the globe. Closing the loop of product lifecycle is crucial to meet the sustainable policy goals. Higher re-use rates could bring benefits for both the environment and the economy. The EC adopted the measures “to promote re-use and stimulate industrial symbiosis—turning one industry’s by-product into another industry’s raw material” (COM 2015). Circular Economy approach helps to cope with scarcity of natural resources and fossil fuels and recover the materials and energy which are already embodied in existing products. The focus is places on 3R (reduce, reuse, recycle). The Circular Economy policy aims to support recovery of products and encourages multiple life-cycles of them. Remanufacturing is one of the most energy and material efficient product’s recovery option.

Remanufacturing companies contribute to the Circular Economy goals. The previous studies (Steinhilper 1998; Kim et al. 2009; Gutowski et al. 2011; Warsen et al. 2011; Sundin and Lee 2012) highlighted the environmental and economic benefits of remanufacturing. However, as Butzer et al. (2016) stated, “there is a lack of knowledge when it comes to the assessment of remanufacturing processes (…) and the comparability of remanufacturing processes”.

Remanufacturing companies struggle to assess the economic and/or environmental impact of various technological or organizational variants of their processes. As Golinska-Dawson and Pawlewski (2015a) stated: “the decisions about resource allocation, changes in process organization or new investments should be considered taking into account their economic, environmental and social effects”. In the

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existing body of literature there are very limited studies on the sustainability assessment of the remanufacturing process.

The sustainability concept is rather vaguely defined in the literature. The most common definitions are not precise enough to provide easy measurable characteristics of sustainability. The concept of the three pillars of sustainability highlights the importance of meeting at the same time economic, environmental and social goals. At the level of the single organization it can be achieved by resource efficiency and ability to provide good relations with internal and external stakeholders.

This chapter aims to present how simulation approach can be used to model and assess different variants of remanufacturing process with regard to sustainability aspects. Authors discuss the theoretical background of this research and present the designed simulation method. We present how the simulation tools can combined with economic, environmental and social indicators. The achieved results allow to improve the remanufacturing process with regard to resource efficiency.

2 Modelling and Assessment of the Remanufacturing Process with Regard to Sustainability—Theoretical Background

2.1 Challenges for Modelling of Remanufacturing Process

The remanufacturing allows to recover end-of-life or preferably end-of-use products to like-a-new condition or even better performance with warranty to match (based on Sundin and Lee 2012; Steinhilper 1998; Ostlin et al. 2009). According to APSRG Report (2014) remanufacturing allows to gain a triple win, as it creates economic, environmental and social opportunities. Remanufacturing is a multi-operations and multi-variant industrial process (Golinska-Dawson and Pawlewski 2015b). The remanufacturing process can differ between products. The most generic stages of processes are: collection/delivery of cores, inspection, disassembly, cleaning, sorting, reprocessing, dispatching, reassembly and final testing. The materials flow is presented in Fig. 1.

The structure of the process is designed is such a way, that the flow of materials is divided after the disassembly operations and then it is joined together before the reassembly stage. There are three stages which have biggest influence on the modeling of materials flow through remanufacturing process, which are namely: inspection, disassembly and dispatching. During the inspection and disassembly operations components are dispersed.

The stage of reassembly requires that all needed components are available on time to be joined together. The inspection might be performed few times during the remanufacturing process. Its primary goal is to define whether a product is suitable for remanufacturing and to choose the most suitable recovery scenario (e.g. reprocessing, reuse as spare parts, recycling or disposal). The components of the initial

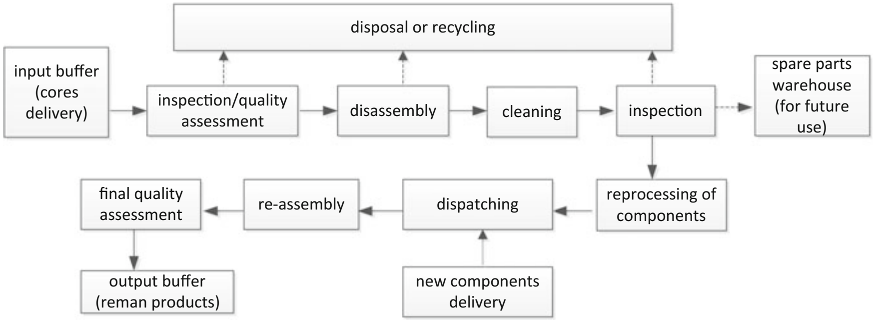


Fig. 1 Flow of materials in a remanufacturing process

products after disassembly are divided into three categories: components for reprocessing, components to be scraped or recycled, and components to be salvaged, as spare parts for purpose of a future use.

Reprocessing operations are usually performed in parallel at many work stations. The aim of reprocessing is to bring the components to “like-a-new” conditions. The components which reprocessing is not possible, or not cost-efficient are substituted with new components. The industry standards (e.g. APRA) often impose the requirements to substitute some components disregarding their technical state.

Dispatching is a crucial phase for modelling of materials flow through remanufacturing process. During dispatching (called also completion) are built the re-assembly sets. These sets include both reconditioned and new parts which were delivered from external suppliers.

The challenges in organization of the remanufacturing process were discussed by many authors (Golinska-Dawson et al. 2015; Gagnon and Morgan 2014; Guide 2000; Saavedra et al. 2013; Seitz and Peattie 2004; Kim 2008).

The modelling of remanufacturing process is complicated due to unique characteristics of its materials flow. The unique characteristics of the materials flow in remanufacturing process are, as follows (Andrew-Munot and Ibrahim 2013):

- highly uncertain quality conditions due to different degree of products’ usage,
- variable quantities of used products available (depending on a product’s life-cycle stage and rate of technological changes),
- variable quality yield which differs between the batches,
- variable disassembly yield that differs between the batches,
- variable reprocessing effort of constituent components between the products and the batches,
- multiple types of constituent components,
- by make-to-order remanufacturing there are often requirements to reassemble the same set of components into a final product,
- need to balance demand with the availability of used products in order to prevent excess inventory.

When modelling of remanufacturing process then it is necessary also to consider stochastic operation times of disassembly, reprocessing, and reassembly operations (Stanfield et al. 2006).

The existing approaches do not provide sufficient tools for modelling of the complex remanufacturing process. As Andrew-Munot and Ibrahim (2013) has stated that "analysis of a remanufacturing system would benefit immeasurably from the application of simulation technique".

2.2 Simulation Modelling of Remanufacturing Process and Sustainability Assessment

Simulation can be applied, in order to (Moon 2016):

- better understand a complex system,
- compare alternative plans and/or scenarios,
- predict behaviors of a complex system,
- support decision-making process,
- elaborate new tools for investigation and training.

Remanufacturing is usually more complex than primary production. Simulation allows to provide in-depth knowledge about a process behavior and to test alternative scenarios with regards to set of environmental, social and economic indicators.

As the previous research by Moon (2016) has showed, the most common methods for simulation modelling for sustainability purpose are Agent Based Simulation and simulation (ABS), Discrete Events Modelling and Simulation (DES), and System Dynamics Modelling and Simulation (SD). The works on simulation of remanufacturing process with regards to sustainability are limited. The previous works address rather narrow scope of problems, which are related to flow of materials in remanufacturing, like:

- reduction of inventory levels,
- planning and control,
- scheduling of disassembly operations,
- lot sizing problem,
- configuration of the reverse supply chain with remanufacturing.

A holistic approach to simulation modelling of materials flow in remanufacturing present Abdul-Kader and Haque (2011). They used Agent Based simulation modelling to identify the sustainable benefits of remanufacturing tires. They simulate the benefits of increasing the retread percentage of tires and associated material savings and reduction of waste by lowering scrap rate. Their work focuses on the interaction of the different agents, namely: central agent (tyre), collector, retreater and recycler. Qingli et al. (2008) also address the supply chain perspective.

They design a dynamic simulation model based on the principles of the system dynamics (SD) methodology to analyze inventory and bullwhip effect in "open" and "closed" supply chain with remanufactured products (economic aspects). They don't consider the environmental or social impacts of remanufacturing process.

The focus on environmental impact of remanufacturing process present Ismail et al. (2014). In that work the authors identified and classified various remanufacturing operations (processes) and then estimated their environmental impact. The main output of their work is a database, which contains formalized descriptions of types and variants of remanufacturing processes. The remanufacturing process library is used to the calculation of the environmental parameters, and the creation of the environmental impact simulator (Ismail et al. 2014). Proposed by them approach aims helping to design a low-environmental impact remanufacturing processes.

We aim to apply the simulation modeling to test different variants of remanufacturing process organization. The alternative scenarios are assessed with set of sustainability indicators (economic, environmental and social). Among the limited research on simulation modelling in remanufacturing with regards to suitability, there is a research gap, as previous research doesn't take into consideration the organization of the remanufacturing process. The authors in previous research have made assumption that remanufacturing always is sustainable. The previous studies mainly focus on materials flow among participants of the reverse supply chain or focus on the product design phase.

2.3 Assessment of the Remanufacturing Process

In our approach we apply set of indicators for sustainability assessment. The extensive literature review on sustainability assessment methods can be found in work of Singh et al. (2009). The indicators allow to summarize in a condensed way the data from complex and dynamic systems, and provide a manageable amount of information for decision-makers. As Bebbington et al. (2007) stated, "There is a widely recognized need for individuals, organizations and societies to find models, metrics and tools for articulating the extent to which, and the ways in which, current activities are unsustainable". There are many efforts to provide a set of appropriate sustainability indicators at national, regional and local level. In the context of remanufacturing the most interest gain environmental indicators (e.g. Sundin and Lee 2012; Gutowski et al. 2011; Warsen et al. 2011) or environmental and economic indicators (e.g. Kim 2008; Kim et al. 2009). The studies on social indicators are limited. The holistic approach to sustainability assessment is still a challenge. The detailed discussion on suitability indicators and their characteristics is provided in previous chapter of this book entitled "Sustainability Indicators System for Remanufacturing".

3 Modelling and Assessment of the Remanufacturing Process with Regards to Sustainability in Practice

3.1 Simulation Modelling Approach

For simulation modeling we use discrete event simulation experiments (DES Discrete Event System) offered in the software FlexSim. The objects in the FlexSim software library were not sufficient so we designed special objects that were more suitable for the modelling of the remanufacturing process. We added special objects for disassembly and dispatching operations. The model aims helping the decision maker to assess the impact of different process organization scenarios regarding, as follows:

- technology used in the process,
- allocation of resources,
- production planning scenarios,
- alternative machines capacities,
- usage of different means of internal transportation,
- changes in layout design.

The impact of the alternative scenarios can be assessed in a holistic way or individually by analyses of particular indicators, so called control parameters. Figure 2 presents the simplified graph of simulation modelling approach.

In the simulation modelling of remanufacturing process we use the environmental indicators, as follows (Golinska-Dawson and Pawlewski 2015b):

- ECL—Energy Consumption Level,
- WCL—Water Consumption Level,

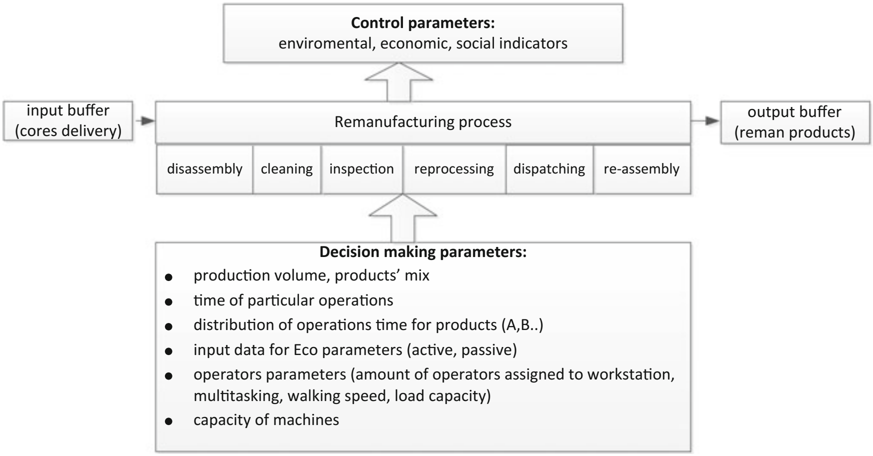


Fig. 2 Simulation modelling of remanufacturing process with regards to sustainability

- GEL CO_2—Generated Emission Level,
- GELsludge—Generated level of sludge,
- PCL—Pressure Consumption Level (compressed air)—which measures compressed air consumption where relevant.

In the simulation software FlexSim we have designed a special ECO-object. The Eco-object is a universal "plug" and can be connected to any objects in the process, in order to measure one or more of the listed environmental indicators (individually or in combination with other indicators). The algorithm describing, how the Eco-object works is discussed in details in our previous work (Golinska-Dawson and Pawlewski 2015b).

The economic indicators are, as follows (adopted Golinska-Dawson and Pawlewski 2015b):

- LTO (Lead time per production order)—as the order can consists of more than 1 container, then this indicator measures the time of execution of the whole order from the moment when the first container enters the first work station (input buffer) until the last container of a given order leaves the last station (output buffer).
- RPT (Remanufacturing process throughput)—amount of products which is remanufactured in certain period of time; it is standard statistics built-in FlexSim, and therefore is not further described here.
- RPTD (Remanufacturing process throughput daily)—amount of products which is remanufactured per day, only fully remanufactured products that have entered output buffer are considered
- OEE (Overall Equipment Effectiveness)—presents the composite indicator and it is multiplication of the three elements listed below:

  Availability rate = (Time available-downtime)/(Time available)
  Performance rate = (number of pieces produced per time unit)/(Planned production quantity per time unit)
  Quality rate = (Produced parts-Defects-Rework parts)/(Produced parts)

  OEE is used by manufacturers to determine productivity at the equipment level. It is a function of a number of components, such as availability efficiency, performance efficiency, and quality efficiency in order to quantify various types of productivity losses, like breakdown, set-up and adjustment, idling, reduced speed, and quality defect or rework (Huang et al. 2003)
  We used in the simulation model a Visual Tool, which calculates OEE for all machines which are connected to the central port of the meter. This allows to monitor the efficiency of the equipment and remanufacturing processes in real time (for any period of time and any machine). The algorithm for OEE calculation is discussed in our previous work (Golinska-Dawson and Pawlewski 2015b).
- RPC (Remanufacturing process cycle)—allows to control if an order is executed according to the plan and it is calculated as relation between a planned order lead time and a real lead time of the same order.

The amount of social indicators which can be assessed using simulation software is rather limited. We focus on the operators' comfort at work. The indicator "Average Level of Comfort" (ACW) presents the percentage of time that an employee spends on transport of cores, walking without load, idle time and working at the work station.

In the FlexSim software we have introduced "global tables" (see Fig. 3), which allow us to monitor the aggregated values regarding operators' behaviour regarding the distance travelled by each employee during a working shift. In Fig. 3 the letters P1-Pn represent particular workers ID (Golinska-Dawson and Pawlewski 2015b). The operator's comfort of work can be modelled regarding:

- the operator's speed,
- the maximum number of elements that the operator is allowed to carry.

As we have mentioned before the flow of materials though remanufacturing process is complex. In order to simply it we have designed a special multimodal container. In Fig. 4 is presented the simplified flow of materials through

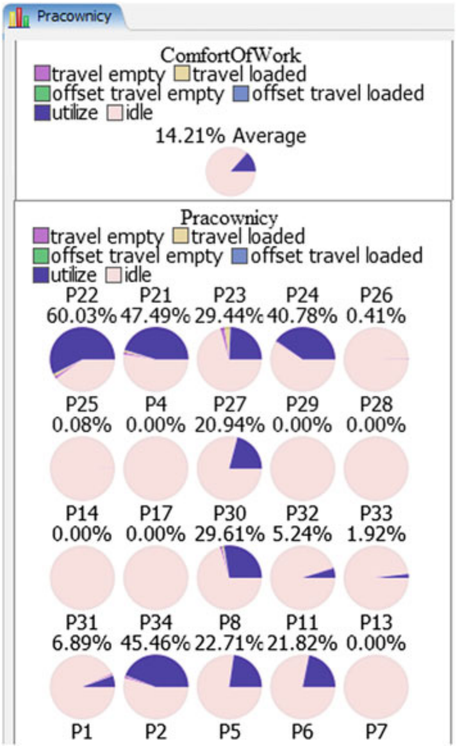


Fig. 3 An example of ACW indicator global table

remanufacturing process using a multimodal container (object called "POJ"). We have discussed in details the purpose of using multimodal containers in our previous work (see Golinska-Dawson and Pawlewski 2015a). A multimodal containers move between the transportation sectors and workstations in a cyclic way. The local cyclic process is characterized by: size of container, transport mode and the availability of employees. At first each order is divided to a corresponding amount of multimodal containers in the input buffer. Then the containers are transported to assigned workstations. Each operator after finishing the operations at his workstation, transports multimodal containers to the input buffer at the next station. After the last operation is completed, the containers are transferred to the output buffer. The usage of the multimodal containers is described in details in (Golinska-Dawson and Pawlewski 2015a). Figure 4 presents the simplified flow of materials in a remanufacturing process using the multimodal containers.

The application of multimodal container allows to deal better with local processes uncertainties and it provides for a flexible framework to define the flow of materials between local workstations.

The next section provides an example of the application of our simulation modelling approach.

3.2 Model Testing—Numerical Example

For model testing we used real life data. We analyzed the process of two products' families A (alternators) and R (starters). The products' mix is fixed as 1:2 ratios. We analyzed the set of 240 orders of total amount of 1170 units. The size of order is variable. The routings for multimodal containers are predefined and they don't change during the simulation experiments.

The simulation model includes sub-processes, as follows: cores delivery (input buffer), disassembly, inspection, cleaning, reprocessing, dispatching (completion), reassembly, and quality control and packing (output buffer). The overview of the simulation model is presented in Fig. 5.

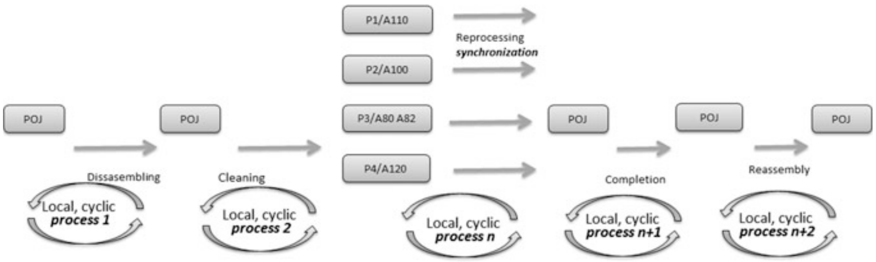
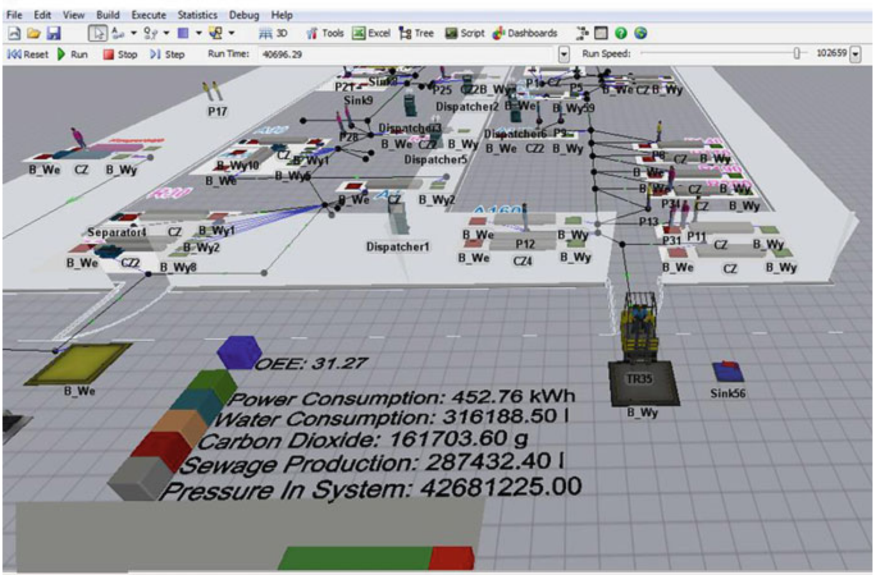


Fig. 4 The simplified flow of materials in remanufacturing process—multimodal approach (adopted from: Golinska-Dawson and Pawlewski 2015a)



Run Time: 40696.29

OEE: 31.27

Power Consumption: 452.76 kWh

Water Consumption: 316188.50 l

Carbon Dioxide: 161703.60 g

Sewage Production: 287432.40 l

Pressure In System: 42681225.00

Fig. 5 The overview of the simulation model

For purpose of running the numerical experiments we choose the sub-process of cleaning, as it has the biggest environmental impact (see: Ismail et al. 2014). We test two different variants of cleaning machine in order to assess the environmental and economic impact of different organization of the cleaning sub-process. The cleaning is usually automatized so the values of the social indicator ACW are almost the same in both scenarios, and for this reason they are not presented in this chapter.

The results for the first scenario are presented in Tables 1, 2 and 3. In first scenario we test the settings, as follows:

- Size of washer (A30): 10 pcs.
- Size of washer (R30): 20 pcs.
- Container size T2 (big): 50 pcs.
- Container size T1 (small): 2 pcs.
- Max. transportation mode' capacity for container type T2: 1 unit
- Max. transportation mode' capacity for container type T1: 20 unit

The results for the second scenario are presented in Tables 2 and 4. In the second scenario we test the settings, as follows:

- Size of washer (A30): 15 pcs.
- Size of washer (R30): 60 pcs.
- Container size T2 (big): 50 pcs.
- Container size T1 (small): 2 pcs.

Table 1 Numerical experiment daily values for the 1st scenario

Day	ECL	WCL	GEL CO_2	GEL sludge	PCL	OEE	RPT	RPTD
1	11.73	14,679.39	1835.84	14,679.39	2,469,314	36.6	0	0
2	41.14	33,558.92	7510.71	31,654.92	3,908,825.5	31.2	0	0
3	72.12	58,643.94	18,286.06	54,819.94	5,348,002	30.7	30	30
4	103.41	82,567.62	22,884.35	76,839.62	6,787,167	34.9	67	37
5	133.95	106,600.66	36,300.35	98,952.66	8,226,490.5	37.3	129	62
6	166.61	131,571.03	44,244.35	122,003.03	12,545,693	38.8	166	37
7	199.11	157,704.57	55,471.55	146,216.57	13,984,812	40.2	219	53
8	226.38	173,802.4	65,057.15	160,394.4	15,424,234	41.1	304	85
9	249.25	188,429.12	72,843.15	173,117.12	16,863,877	41.8	388	84
10	273.2	203,198.8	79,591.74	185,966.8	18,303,563	41.8	463	75
11	299.63	222,619.1	88,558.14	203,483.1	22,623,078	41.3	524	61
12	325.29	241,079.16	97,524.54	220,039.16	24,062,483	41	577	53
13	350.68	258,546.35	105,122.94	235,586.35	25,501,948	40.5	650	73
14	375.48	274,989.73	113,268.54	250,120.6	26,941,531	39.8	741	91
15	400.67	292,639.98	121,687.74	265,866.86	28,381,225	39.2	824	83
16	420.73	300,763.92	126,823.74	272,086.8	32,701,225	38.6	876	52
17	431.29	313,783.92	135,871.74	285,106.8	34,141,225	37.4	941	65
18	441.33	326,119.92	143,319.6	297,442.8	35,581,225	36.1	1029	88
19	451.41	338,113.92	150,025.2	309,436.8	37,021,225	34.6	1106	77
20	461.49	349,879.92	156,183.6	321,202.8	38,461,225	33.2	1170	64

- Max. transportation mode' capacity for container type T2: 1 unit
- Max. transportation mode' capacity for container type T1: 20 unit

The environmental indicators, as well as some economic indicators (OEE, RPT and RPTD) are analysed on daily bases. The pool of orders is performed during one month of production. The indicators values allow to constantly monitoring the impact of the remanufacturing process.

The values of RPC and LTO provide information about the bottlenecks and delays in the remanufacturing process.

The indicators values can be analysed multidimensional depending on the decision maker's goal. The values can be compared for particular indicator as a simple difference between the scenarios or they can be calculated as aggregated value considering many indicators or all of them. The example of the indicators' aggregation procedure is presented in previous work (Kosacka et al. 2015).

We don't discussed here the results in details, as the scenarios are only examples to better illustrate how the model works and how it can be used for modelling of remanufacturing process. The values of the indicators depend on the quality of the input data.

Table 2 Numerical experiment—daily values for the 2nd scenario

Day	ECL	WCL	GEL CO_2	GEL sludge	PCL	OEE	RPT	RPTD
1	11.73	14,679.39	1835.84	14,679.39	2,469,314	36.6	0	0
2	41.14	33,558.92	7510.71	31,654.92	3,908,825.5	31.2	0	0
3	72.12	58,643.94	18,286.06	54,819.94	5,348,002	30.7	30	30
4	103.41	82,567.62	22,884.35	76,839.62	6,787,167	34.9	67	37
5	133.95	106,600.66	36,300.35	98,952.66	8,226,490.5	37.3	129	62
6	166.61	131,571.03	44,244.35	122,003.03	12,545,693	38.8	166	37
7	199.11	157,704.57	55,471.55	146,216.57	13,984,812	40.2	219	53
8	226.38	173,802.4	65,057.15	160,394.4	15,424,234	41.1	304	85
9	249.25	188,429.12	72,843.15	173,117.12	16,863,877	41.8	388	84
10	273.2	203,198.8	79,591.74	185,966.8	18,303,563	41.8	463	75
11	299.63	222,619.1	88,558.14	203,483.1	22,623,078	41.3	524	61
12	325.29	241,079.16	97,524.54	220,039.16	24,062,483	41	577	53
13	350.68	258,546.35	105,122.94	235,586.35	25,501,948	40.5	650	73
14	375.48	274,989.73	113,268.54	250,120.6	26,941,531	39.8	741	91
15	400.67	292,639.98	121,687.74	265,866.86	28,381,225	39.2	824	83
16	420.73	300,763.92	126,823.74	272,086.8	32,701,225	38.6	876	52
17	431.29	313,783.92	135,871.74	285,106.8	34,141,225	37.4	941	65
18	441.33	326,119.92	143,319.6	297,442.8	35,581,225	36.1	1029	88
19	451.41	338,113.92	150,025.2	309,436.8	37,021,225	34.6	1106	77
20	461.49	349,879.92	156,183.6	321,202.8	38,461,225	33.2	1154	48

Table 3 Numerical experiment—the 1st scenario; values of the indicators are presented per order

Order number	Type of product	Order size	LTO	RPC
1	A	20	5993	1.02
2	R	16	5768	1.02
3	A	2	5593	1.19
4	R	5	3123	1.03
5	A	6	9871	1.11
6	R	12	4397	1.02
7	A	4	5710	1.1
8	R	1	3146	1.16
9	A	3	4609	1.1
10	R	28	10,467	1.02
11	A	1	4049	1.27
12	R	7	4589	1.03
13	A	1	4122	1.27
14	R	24	11,680	1.02
…	…	…	…	…
238	A	1	23,132	2.54
239	R	1	8611	1.43
240	A	4	27,285	1.45

Table 4 Numerical experiment—the 2nd scenario; values of the indicators are presented per order

Order number	Type of product	Order size	LTO	RPC
1	A	20	5948	1.02
2	R	16	10,159	1.03
3	A	2	5587	1.19
4	R	5	4608	1.05
5	A	6	9782	1.11
6	R	12	6041	1.03
7	A	4	5783	1.1
8	R	1	3310	1.17
9	A	3	5641	1.13
10	R	28	10,508	1.02
11	A	1	3994	1.27
12	R	7	8615	1.06
13	A	1	4028	1.27
14	R	24	11,680	1.02
…	…	…	…	…
238	A	1	8538	1.43
239	R	1	27,583	1.46
240	A	4	9921	1.12

4 Conclusions

The chapter describes how the simulation modelling approach might be used to test an impact of different variants of organization of a remanufacturing process. The studies on the sustainability assessment of remanufacturing process are limited. Most of the authors analyze the impact of remanufactured products in comparison with new single use products (e.g. Abdul-Kader and Haque 2011; Sutherland et al. 2008; Shau et al. 2011, 2012; Ismail et al. 2014; Abbey et al. 2015). Our focus is placed on the organization of remanufacturing process, not on products' assessment. We implement in the simulation model a set of economic, environmental and social indicators. It allows relatively easy comparison of different configurations of the process with assessing their impacts. For this reason our approach contributes to the body of knowledge on remanufacturing process.

The developed modelling framework is different to the existing build-in "green" simulation tools or life cycle assessment software. The main advantage of the designed solution is its universality. The indicators might be analyzed for particular machine or mean of internal transportation, sub-process (e.g. cleaning) or the whole remanufacturing process. The designed multimodal container significantly simplifies the visualization of the flow of materials through the process. It allows to deal with the probabilistic volume of the materials regarding the dispersion and joining of flow of materials in a remanufacturing process.

The current data sets on sub-processes and machines' variants are rather limited. We have analyzed so far only a remanufacturing process with two product's families. The further research will focus on building more extend process library. We aim to collect more real life data for testing of more advanced configurations of a remanufacturing process. The further work will also include more advanced aggregation procedures of indicators for purpose of the analyses of the sustainability level of the remanufacturing process.

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The Roadmap for Improving Sustainability in Remanufacturing Operations

Paulina Golinska-Dawson, Monika Kosacka
and Karolina Werner-Lewandowska

1 Introduction

Experts are aware of the fact that remanufacturing allows to recover a big proportion of the resources, which were used to produce a product. The environmental and economic benefits of remanufacturing are, as follows:

- It recovers a product to useful life at low cost (up to 85% of the weight of remanufactured products can be reused), thus reducing the price of the product (Ijomah et al. 2004; Sundin and Bras 2005),
- it allows to reduce the raw materials and energy usage compared to primary production(Ijomah et al. 2004; Kerr and Ryan 2001),
- it allows closing the materials loop and reducing landfilling (Seitz and Peattie 2004; Abbey et al. 2014).

Remanufacturing is often perceived as a key strategy to achieve goals of the sustainable development policy (e.g. Ijomah et al. 2004). When proofing the importance of remanufacturing for the sustainable development, the researcher mainly apply the life cycle design and the life cycle engineering approach. There is a research gap regarding the assessment of remanufacturing operational excellence, as far as sustainability issues are concerned. In the previous research we have elaborated qualitative (Golinska and Kübler 2014) and quantitative (Golinska et al. 2015a) method for maturity assessment regarding sustainable usage of resources in a remanufacturing process. We defined three sustainable maturity levels. The assumption was made that small and medium sized remanufacturers (RSMEs) want to perform their operations and used their resources in the most efficient way, regarding economics, environmental and social aspects. Companies can achieve the maturity level, as follows (Golinska et al. 2015a):

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- class k = 1 (in green)—there is an acceptable level of sustainability of remanufacturing operations and no improvement actions are needed;
- class k = 2 (in yellow)—there is a conditionally acceptable level of sustainability of remanufacturing operations, which requires corrective actions, as soon as it is economically and organizationally possible;
- class k = 3 (in red)—there is an unacceptable level of sustainability of remanufacturing operations, which requires corrective actions.

The designed by the authors roadmap provides the guidelines on how to improve the current level of maturity regarding the sustainable usage of resources in remanufacturing operations. It helps to identify the area of operations which need improvements. In the next sections we present the process of creating the roadmap and its application potential.

2 Methodology

The roadmap was developed based on the data collected from small and medium sized Polish automotive parts remanufacturers. The aim was to first identify the drivers and facilitators which help the companies to improve their operations with regard to the sustainability. The roadmap is aiming also to provide some action plan towards implementation of necessary measures.

Roadmap is a useful tool, which is used to capture and communicate the outputs from the strategic planning process towards their implementation (Holmes et al. 2004). Technological roadmap presents the relationship between the market, products and technology parameters and identifies the objectives related to the required effort (Kappel 2001). Phaal et al. (2004) identified 8 purposes for preparing roadmaps:

- Product planning—where roadmaps are used to link planned technology and product development,
- Service/capability planning—where roadmaps focus on how technology supports organizational capabilities. It is mostly used in service–based enterprises,
- Strategic planning—where roadmaps are used to support evaluation of different opportunities and threats,
- Long-range planning—where roadmaps are elaborated at sectorial or national level and act as an radar to discover disruptive technologies and markets,
- Knowledge asset planning—where roadmap links the skills, technologies and competencies required to meet future markets demand,
- Programme planning—where roadmap focuses on implementation of general strategy to particular project development, it shows relationships between technology development and project's milestones,
- Process planning—where roadmap supports new product development by incorporating both technical and commercial aspects,

- Integration planning—this type roadmap focuses on integration and evolution of technology shows how different technologies can be combined to form new technology or system.

In order to create a technology roadmap the two basic dimensions need to be defined, as follows (Phaal et al. 2004): timeframes and amount of layers. The timeframe depends on the industry. For example in case of industries where the technology and market conditions are changing in very short cycles (e.g. electronics), there is no point in building roadmap for 10 years. Phaal and Muller (2009) recommend five main timeframes:

- The past—in this perspective it can be determined which events and factors have led to the current situation. It can be learning point for future actions.
- A short time horizon (now)—this is usually a one year horizon. This is a very important part of the map as it will be converted into real plans and activities, which will influence the future.
- The medium time horizon (plans)—the period between 1 and 3 years (usually), combined with the strategic plan, featuring the main directions and actions affecting the plans and decisions in the short term.
- A long-term perspective (future)—usually a period of between 3 and 10 years, a combination between the average time horizon and the vision and aspirations of the organization. In this horizon should be identified uncertainties and future scenarios, technological changes, the market and the market environment should be identified in order to establish a mechanism radar that can detect and assess certain phenomena that affect current decisions.
- The vision—it is long-time aspirations of the organization, including the definition of the mission.

The layers of the proposed system must be customized and suited to the analysis of the specific organization and problem. The first stage of work on the map is to define the layers and sublayers. Characteristics of the layers is presented in Table 1.

The multi-layer roadmap is presented in Fig. 1. The top layer relates trends and economic, environmental, social drivers with the goal of the roadmap. The middle layer is focused on mechanism through which goals are achieved, like: products, services, performance, requirements, operations (Phaal et al. 2005). The last layer presents resources which are needed to achieve the defined goal.

The literature review has showed that in case of remanufacturing the road map is applied very seldom. The search through databases: Science Direct, Business Source Premier and Google scholar databases were used with criterion "*remanufacturing*" + "*roadmaps*" and "*roadmapping in remanufacturing*", showed very limited results. We grouped the relevant papers into four categories:

- Technology roadmaps for sustainable manufacturing (remanufacturing included marginally) (Mishima and Umeda 2012; Seliger et al. 2008; Valkokari et al. 2014; IMS2020 2010)

Table 1 Characteristics of layers of technology roadmap

Layer	Sub-layer	The main issue	Qualifying question
L1 Market drivers	Market, customers, competition, Environment, business, trends, threats, strategy	The purpose with some factors affecting it	Know—why?
L2 Products/process	Features, functions, performance, services, processes, systems, capabilities	The mechanism of achieving the purpose	Know—what?
L3 Technology/ resources	Technology, competences, knowledge, science, resources, infrastructure, finance, standards, R&D projects	Everything what is required to develop products/services/systems	Know—how?

The own studies based on (Phaal and Muller 2009; Phaal et al. 2005)

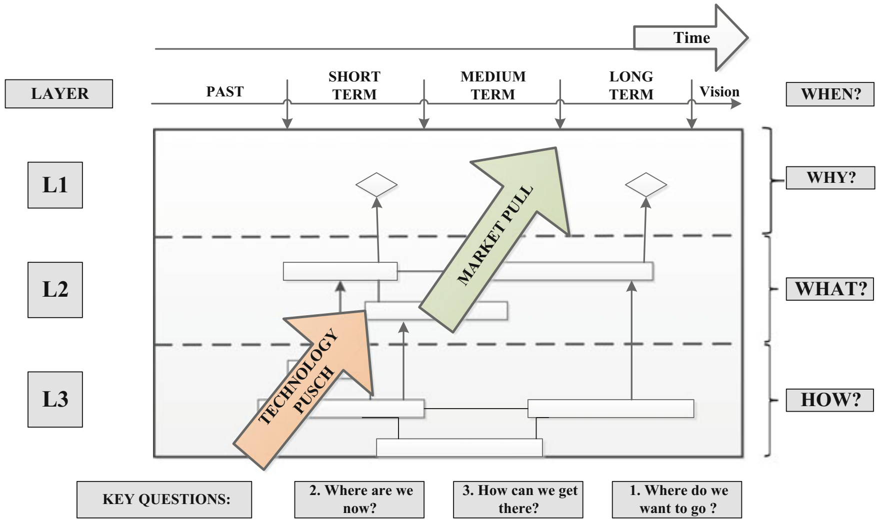

Fig. 1 Multi-layer scheme roadmap. Own study based on Phaal and Muller (2009), Phaal et al. (2005)

- Technology roadmaps for sustainable supply chain (remanufacturing included marginally) (Glenn et al. 2005; Dev and Shankar 2015)
- Technology roadmaps for end-of-life management (Cheung et al. 2015; Wang and Cheng 2013; Juehling et al. 2010)
- Technology roadmaps for design for remanufacturing (Cunha et al. 2011).

The most relevant to our research is the paper of Cunha et al. (2011). The authors applied T-Plan methodology to elaborate technology roadmap in order to identify

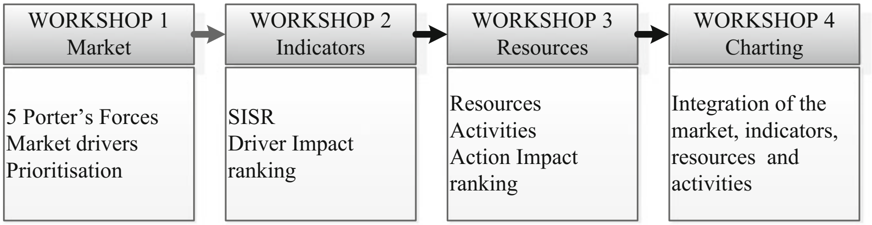

Fig. 2 Research methodology

how to improve the remanufacturing of production equipment, and to develop the new technologies to satisfy the market drivers.

Based on the findings from literature review we decided to also applied the T-plan roadmapping approach. The main advantage of the T-plan is its simplicity, and ability to be used for strategic and tactical planning.

The T-plan methodology recommends to make 4 workshops on: (1) market, (2) product, (3) technology and (4) roadmapping through linking technology resources to the future market opportunities and marking the existing gaps (Phaal et al. 2004).

Our aim was to developed the roadmaps which to guide RSMEs through decision-making process to improve usage of resources in the remanufacturing operations (with focus on automotive parts remanufacturing). We also aimed to link the roadmapinkg with the concepts of the maturity level of sustainable resource utilization. For these reasons we have modified the initial T-plan method as presented in Fig. 2.

In the first workshop (W1), as suggested by Phall et al. (2004) were identified the market drivers, which showed market trends. The second workshop (W2) aimed to identify the links between indicators which were used to described the maturity level of resources utilization (SISR—Sustainability Indicators System for Remanufacturing) and the market drivers. The third workshop (W3) focused on identification of the necessary resources and actions that affected the indicators values. The fourth workshop (W4) aimed to visualize the relationship between the effects of previous workshops, and to show the holistic perspective including the time dimension. The results of the each workshop are discussed in the next section.

3 The Development of the Technology Roadmap for Remanufacturing

3.1 Market Workshop

The main goal of the Market Workshop (W1) was to identify which markets trends are most influential and are driving the development of more sustainable remanufacturing operations in Poland. The basic characteristic of the first workshop is presented in Table 2.

T-Plan methodology recommends a set of tools to perform market drivers analysis. We decided to use common tool for strategic analysis, which was the Porter's five forces analysis. In order to find the drivers which were relevant in the context of sustainability, we examined the dimensions, as follows: suppliers, buyers, substitutes, competitive rivalry, market conditions for potential new entry (as presented in Fig. 3).

In the next stage of the analysis the designated drivers from the Porter's model were assessed. Each driver (d_i) was analyzed from the perspective of its importance level (z) (Table 3). The importance level (z) was evaluated on simple scale, as follows: z = 1—low impact, z = 2—moderate impact, z = 3—high impact.

For the further analysis only drivers with the importance level z = 3 were taken into consideration.

Table 2 Characteristic of the workshop W1

Characteristic	Description
Workshop name	Market
Objective	Identification of the most important market drivers for RSME's
Input data	Market analysis for remanufacturing SME's
Process steps	1. 5 Porter's forces analysis 2. Identification of market drivers 3. Drivers impact ranking 4. Identification of the most powerful drivers

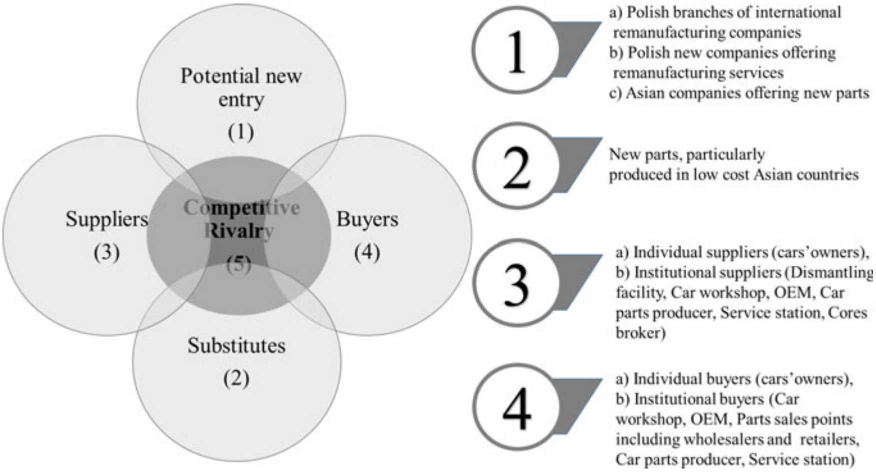

Fig. 3 Porter's model

3.2 Indicators Workshop

In roadmapping the common second step is to assess the influence of the identified markets drivers (from W1) on the product, process or service. In case of our roadmap the second workshop was dedicated to identify the sensitivity levels of the sustainability indicators, which we developed in the previous research. We used so called SISR (Sustainability Indicators System for Remanufacturing). The system is described in detailed in the Chapter Determining the Importance of the Criteria for Assessment of Sustainability in Remanufacturing Companies of this book. These indicators are designed to evaluate the resource utilization of a company taking into consideration 3 dimensions of sustainability. The definitions of each indicator is also presented in work of Golinska et al. (2015a). The basic characteristic of the workshop W2 is presented in Table 4.

We made assumption that companies use their resources efficiently and in more sustainable way when they achieve higher level of remanufacturing process maturity (Golinska and Kübler 2014). The company maturity level assessment results from the value of the 15 indicators in SISR. We created the matrix of influence (see Table 5) to find out which indicators values are most sensitive to changes of the most important market drivers (from W1). Every participant of the workshops W2 graded each factor with the following scale:

- i = 0—no effect;
- i = 1—low impact;
- i = 2—moderate impact;
- i = 3—large impact;
- i = 4—a very big impact.

The summary of the assessment process is presented in Table 5. In order to identify the most sensitive indicators to changes in the market driver the results were normalized by scaling between 0 and 1. The most sensitive (results over 0.75) are indicators: Overall out of stock (OOS), Employment, Overall equipment effectiveness (OEE) and Material recovery rate (MRR). This findings corresponds with the results of our previous survey on group of over 40 RSMEs in automotive sector in Poland (see Golinska et al. 2015b). The majority of respondents there stated (87.5%) that they struggle to reach lot size bigger 1 piece. The very high variety of products variants make impossible to automate most of the operations in the remanufacturing process. The manual operations required advanced technical skills of employees. The respondents were complaining about the difficulty to find suitable employees because of the demographics trends and also shift on the job market towards service and high-tech industries. Lack of economy of scale also negatively influence the overall equipment effectiveness. The respondents also stated that the constant flow of cheap automotive parts from emerging markets (e.g. China) negatively influence the availability of cores for remanufacturing (impact on OOS value).

Table 3 Identification of drivers with the use of Porter's five forces analysis

No	Driver (d_i)	z	Dimension of the Porter's model
1.1	New technologies are relatively rarely used by the RMEs (mainly manual work – relatively low equipment's cost)	3	1. Threat of new entry
1.2	The companies are very similar in their structure and business model	1	
1.3	Increasing importance of sustainable purchasing models	3	
1.4	Similar products portfolio (most of the RMEs provide services for others so brand identity is low)	1	
1.5	Difficulties to achieve economy of scale	2	
1.6.	Global companies (including OEMs) entering the market	3	
2.1.	Low price of new parts from Asian markets	2	2. Threat of substitutes
2.2.	Frequent changes of products' version (shorter lifecycles and models' proliferation)	2	
3.1.	Trend for closing material loops (the purchaser of new products, as well as the remanufacturing) become suppliers for remanufacturers (e.g. repair services, car owners)	2	3. Bargaining power of suppliers
3.2.	Mismatch between supply and demand	1	
3.3.	Insufficient quality and quantity of cores	3	
3.4	Grey zone extinction—because of more strict laws and better databases (e.g. central register of vehicles) and growing environmental awareness it will be more difficult to operate in the grey zone (e.g. unauthorized vehicle dismantling). The disappearance of the grey zone should increase the input stream to the remanufacturing process	3	
4.1.	Dispersion of buyers	1	4. Bargaining power of customers
4.2.	Insufficient scale of purchases	1	
4.3.	Growing products' standardization	3	
4.4	More sustainable utilization model	3	
4.5	PULL paradigm—the buyer starts the process, since in RMSEs mainly remanufacture-to-order (buyer after delivery of the core starts the process)	3	
4.6	Growing environmental awareness of buyers	2	
5.1.	More restrict and common end of life laws	3	5. Competitive rivalry
5.2.	Increasing environmental awareness of society	1	
5.3	Certification of remanufacturing processes and products —it means that workers are trained and processes are well described, which brings benefits to enterprises (including less defects—fewer complaints) The process requires lower materials and energy consumption, which also translates into lower labor intensity resulting in greater comfort of employees	3	

(continued)

Table 3 (continued)

No	Driver (d_i)	z	Dimension of the Porter's model
5.4	Increasing importance of design for remanufacturing	3	
5.5	Growing remanufactured products' attractiveness	3	
5.6	Shortage of qualified staff for highly manual remanufacturing operations	3	

Table 4 Characteristic of the workshop W2

Characteristic	Description
Workshop name	Indicators
Objective	Identification the sensitivity level of the indicators (s)
Input data	• SISR • Market Drivers with the highest importance (from W1)
Process steps	1. Evaluation of the impact of market drivers on indicators 2. Creating the matrix of influence 3. Normalization of the results 4. Identification of the most sensitive indicators to changes in the market

Source Own elaboration

The sensitivity level analysis shows which indicators are most exposed to change their values when the market conditions might change. For this reason they should be monitored more carefully. The actions taken in case of the positive change of the market conditions, should result in the improvement of the maturity level of the remanufacturing process and more efficient use of resources.

3.3 Resources Workshop

In T-plan methodology usually the third Workshop (W3) focused on technology. In case of our roadmap the focus was placed on more sustainable utilization of resources. During W3 we reviewed the results from the market and indictors workshops. After the brainstorming session on how resources can be used more sustainable in remanufacturing process we created a list of potential actions which might be taken to improve the values of the SISR in order to achieve a higher level of remanufacturing process maturity. We made classification of the activities according to their impact on sustainability indicators. Finally we were able to identify the most influential actions for increasing maturity level of sustainable recourse utilization. The basic characteristic of the workshop is presented in Table 6.

Table 5 Evaluation of the impact of the drivers on the indicators SISR

Indicator	Market drivers							
	1. New technology	2. Sustain able purchasing model	3. Competition in the sector	4. Cores' supplies	5. Grey zone extinction	6. Products' standardization	7. Sustainable utilization model	8. PULL Paradigm
1. Over equipment effectiveness (OEE)	4	2	3	2	2	4	3	4
2. Remanufacturing process flow (RPF)	2	2	2	2	2	4	3	4
3. Planning adequacy (PA)	2	2	2	2	2	4	3	3
4. Availability of machines & tools (AMT)	4	2	2	2	2	3	3	3
5. Service level (SL)	1	4	2	4	4	2	3	2
6. Overall out of stock (OOS)	1	4	4	4	4	2	4	4
7. Energy consumption level (ECL)	3	2	2	2	2	3	3	2
8. Waste generation level (WGE)	3	2	2	3	3	3	3	2
9. Material recovery rate (MRR)	2	2	2	4	4	3	4	4
10. Generated emissions level (GEL)	4	2	2	2	2	3	3	2
11. Employment (E)	4	4	4	3	3	2	2	3
12. Staff Training (ST)	2	2	4	2	2	3	3	2
13. Harmfulness of the remanufacturing process (HRP)	3	1	2	2	2	2	2	2
14. Average level of comfort at work (AVC)	3	2	3	3	3	3	3	3
15. Innovation level (I)	2	1	2	2	2	3	2	2

(continued)

Table 5 (continued)

Indicator	Market drivers					
	9. End of life laws	10. Certification of processes & products	11. Design for remanufacturing	12. Products' attractiveness	13. Shortage of qualified staff	Results (sensitivity levels)
1. Over equipment effectiveness (OEE)	1	3	4	3	3	0.75
2. Remanufacturing process flow (RPF)	1	4	3	2	3	0.50
3. Planning adequacy (PA)	1	2	3	3	3	0.38
4. Availability of machines & tools (AMT)	1	3	2	2	1	0.25
5. Service level (SL)	1	4	3	3	1	0.50
6. Overall out of stock (OOS)	4	2	4	4	1	1.00
7. Energy consumption level (ECL)	4	4	3	2	1	0.44
8. Waste generation level (WGE)	4	3	4	3	1	0.63
9. Material recovery rate (MRR)	2	2	4	4	1	0.75
10. Generated emissions level (GEL)	4	4	3	2	1	0.50
11. Employment (E)	3	2	2	3	4	0.81
12. Staff Training (ST)	1	4	2	2	3	0.38
13. Harmfulness of the remanufacturing process (HRP)	3	3	2	2	3	0.19
14. Average level of comfort at work (AVC)	2	3	4	3	2	0.69
15. Innovation level (I)	2	3	1	2	2	0.00

Table 6 Characteristic of the workshop W3

Characteristic	Description
Workshop name	Resources
Objective	Identification of the actions which should be taken in order to achieve a higher level of remanufacturing process maturity in terms of sustainability
Input data	Case study results using RPA method (rapid plant assessment) Results of the conducted ReMC analysis (remanufacturing operations muda checklist) Sensitivity level of each indicator (from W2)
Process steps	1. Resource identification 2. Resource categorization 3. Definition of improvement actions in remanufacturing (providing higher process maturity level) 4. Linking actions with resources 5. Ranking the impact of each action on each indicator (influence matrix) 6. Normalization of the results 7. Classification of the activities according to the greatest impact on sustainability indicators 8. Identification of the most influential activities for increasing maturity level of sustainability

Table 7 Categorization of improvement actions

Resource category	Subcategory				
	Availability (A)	Standardization (S)	Effectiveness		
			Eco	Econ	Soc
Materials (M)	M–A	M–S	M–Eco	M–Econ	M–Soc
Information (I)	I–A	I–S	I–Eco	I–Econ	I–Soc
Employee (E)	E–A	E–S	E–Eco	E–Econ	E–Soc
Machines and tools (MT)	MT–A	MT–S	MT–Eco	MT–Eco	MT–Soc

The resources used in the remanufacturing process in small and medium sized enterprises were divided into four categories: materials, information, employee, machines and tools.

During the brainstorming sessions we created list of the 64 actions which contributing to the more sustainable resources utilization in remanufacturing process. Then they were allocated to subcategories, depending whether they might focus on improving availability, standardization or effectiveness of the resources (see Table 7). The list of actions is presented in Table 8.

The distribution of the improvement actions between the subcategories is presented Fig. 4.

In case of resources, like materials and information most of the suggested improvements actions focused on standardization. The remanufacturing process in small and medium sized enterprises is “difficult to standardize partly due to the

Table 8 Identified actions and their classification

No.	Actions	Category
1	Simplifying dismantling operations	E–S
2	Creating information feedback mechanism between the RSMEs and OEMS	I–Econ
3	Creating system of measurement and reporting of energy consumption for remanufacturing process	MT–Eco
4	Reducing idling time and setups	MT–A
5	Optimizing layout	E–A
6	Designating of places of storage of the waste and the works in progress	M–Econ
7	Isolating of equipment and surfaces in order to minimize heat loss	MT–Eco
8	Using air filters	MT–Eco
9	Applying of water soluble cleaners	MT–Eco
10	Optimizing parameters and the temperature of the washing and the choice of suitable cleaners	MT–Eco
11	Monitoring of the lighting levels	E–Soc
12	Job scheduling in advance	MT–A
13	Optimizing the lot size	MT–A
14	Reducing friction in machines	MT–A
15	Optimizing times and temperature of drying	MT–Eco
16	Eliminating the storage of materials in the production hall	M–A
17	Implementing ISO standards	I–S
18	Creating work stand's instructions and working standards for each operations	E–S
19	Implementing 5S	E–S
20	Limiting the number of operations performed in a standing position	E–Soc
21	Implementing tools for demand forecasting	M–A
22	Implementation of the plan of preventive maintenance	MT–A
23	Improving machine setups (SMED)	MT–A
24	Establishing a system of clear orders' marking and monitoring of their movement through the process	M–S
25	Introducing of Checklist for the proper verification of the quality of the core at the entrance to the process (disassembly checklist)	M–S
26	Introducing of the principles of maintenance tools and periodic quality control of tools	MT–S
27	Introducing idea boxes	E–Soc
28	Paying incentives for employees, who improvements are implemented	E–Soc
29	Internal training (e.g. relating to the complaint, the quality issues)	E–Soc
30	Verifying of complaints in order to prevent future shortcomings	P–Econ
31	Limiting distances between workstations (line system if possible)	E–A
32	Describing the operational goals & providing their transparent measuring system	I–S
33	Job rotation	E–Soc
34	Active participation in the practical training of future employees (training options for pupils on site)	E–Soc

(continued)

Table 8 (continued)

No.	Actions	Category
35	Using exclusively the waterborne paints and varnishes	MT–Eco
36	Using safe spraying booths	MT–Eco
37	Creating instructions for separating waste	M–S
38	Determining of safe storage of waste in the production hall	M–S
39	Using mainly reusable transport containers (both internal and external)	M–S
40	Applying KANBAN	M–S
41	Applying FMEA	M–S
42	Analysis and elimination of waste using Muda checklists	M–S
43	Applying ISO 140001	MT–Eco
44	Use mainly materials suitable for recycling or other reuse options	M–Eco
45	Avoiding/reducing usage of toxic substances	M–Eco
46	Local sourcing	M–Econ
47	Creating manuals for operators to facilitate components' substitution.	I–S
48	Creating system of transparency orders and components indexing	I–S
49	Creating visual data base for easy products' types identification	I–S
50	Networking with other RSMEs	I–S
51	Periodic reviews of the cores' inventory and establishing guidelines to scrap them	M–S
52	Verifying the cores at the process entrance for assessment of the potential profitability (gatekeeping)	M–Econ
53	Creating guidelines for verifying the cores after disassembly to assess the usage rate of particular components	M–Econ
54	Designating clear and undistributed transportation ways at the production hall	MT–S
55	Setting system for transparent work monitoring	P–S
56	Training employees to multi tasks work (a minimum of 2 workstation)	E–Soc
57	Training of workers to self-control of quality	E–Soc
58	Rationalizing of the material needs	M–A
59	Eliminating of unnecessary movements while working	E–Soc
60	Elaboration of principles of the materials feeding for each workplace	I–S
61	Standardizing of production documents (for example, production order)	I–S
62	Monitoring of the training needs of employees	E–Soc
63	Noise monitoring and reduction	MT–Eco
64	Products' portfolio optimizing	M–Econ

variability of components parts, products and processes" (Guidat et al. 2015). The Polish small remanufacturers suffer from very high variability of products variants, which influence the profitability of their operations and limits the application of more efficient organization and resources utilization (Golinska et al. 2015b). The standardization of operations, the information exchange and work routines help to reach better utilization level of resources.

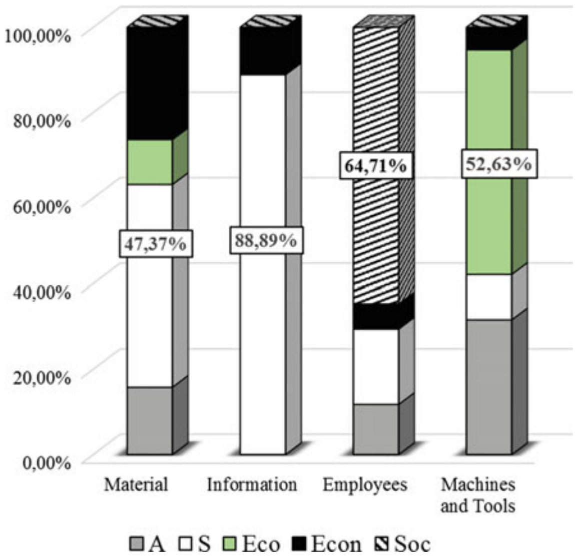

Fig. 4 Sectional activity analysis

In the case of human resources most of the actions (over 60%) focus on improving the effectiveness by creating more friendly and safe work environment.

The actions which focus on improvements of usage of Machines and Tools are aiming on improving of the ecological effectiveness. However about 30% of proposed actions also include introduction of standardization procedures.

After the actions were linked with appropriate resources then we ranked the impact of each action on each indicator from SISR (influence matrix). The Influence matrix is presented in Table 9. The numbering of the actions respond to those presented in Table 8, and numbering of the indicators responds to those presented in Table 5. At the intersection of the column (indicators) and line (action) is analyzed the impact of the actions on the indicators and are presented the evaluation according to the previously described scale (i = {0, 1, 2, 3, 4}). The results (last column) were normalized by scaling between 0 and 1 to facilitate comparisons of the scores. In the result there is obtained the answer for the previous question about the most desirable actions which have the greatest impact on sustainability indicators.

Authors divided all actions into 7 classes according to the normalized results (Table 10).

Class boundaries were estimated with the use of the statistics method. Authors made calculations with the different class number from 3 till 7. The best results were achieved when dividing actions into 7 classes. The analysis showed that there were 13 actions, which had a high impact on the SISR.

These were the actions no: 5, 10, 12, 13, 14, 16, 23, 24, 25, 26, 43, 45, 47, which accounts for about 20% of all relevant activities. There can be applied Pareto rule that 20% of all actions may cause 80% effect in sustainability improvement.

Table 9 Influence matrix: activity—indicators

Sensitivity (s)	0.75	0.50	0.38	0.25	0.50	1.00	0.44	0.63	0.75	0.50	0.81	0.38	0.19	0.69	0.00	Result	Normalized result
Indicator No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15		
Activity																	
1	1	1	1	1	1	1	1	1	3	1	2	2	4	4	3	13.06	0.01
2	3	2	3	3	2	2	1	1	2	1	1	1	1	1	1	19.81	0.38
3	2	2	2	3	1	1	4	2	1	4	1	1	2	1	1	15.75	0.16
4	4	3	3	3	1	1	2	2	2	2	1	1	1	1	1	15.69	0.16
5	3	3	2	2	1	1	3	2	1	3	1	1	1	4	1	26.13	0.73
6	3	3	2	3	2	4	1	4	2	1	1	1	2	2	1	19.69	0.38
7	2	2	1	2	1	1	4	2	1	4	1	1	2	2	1	23.81	0.60
8	2	2	1	2	1	1	4	2	1	4	1	1	2	2	1	15.81	0.16
9	2	2	1	2	1	1	3	2	1	4	1	1	2	2	1	23.81	0.60
10	2	2	1	2	1	1	4	2	1	4	1	1	2	2	1	27.81	0.89
11	2	2	1	2	1	1	4	2	2	3	1	1	4	4	1	25.81	0.83
12	4	4	4	4	2	2	3	2	2	3	2	1	1	3	1	31.00	1.00
13	4	4	4	4	2	2	3	2	2	3	2	1	1	3	1	31.00	1.00
14	4	3	2	4	2	2	4	3	3	3	2	1	1	2	1	30.44	0.98
15	2	2	1	2	1	1	4	2	1	4	1	1	2	2	1	23.81	0.76
16	3	4	2	2	2	4	2	3	2	2	1	1	1	3	1	26.31	0.84
17	2	2	2	2	2	2	2	2	2	2	2	4	2	2	2	23.38	0.75
18	3	3	3	3	3	2	2	2	2	2	2	3	3	4	3	22.94	0.73
19	3	3	3	3	3	2	2	2	2	2	2	3	3	4	3	22.94	0.73
20	1	1	1	1	2	1	1	2	2	1	2	3	3	4	3	15.19	0.47
21	3	4	3	2	2	4	2	3	2	2	2	2	1	3	1	23.88	0.76
22	4	4	3	4	2	3	3	3	3	3	2	2	3	3	1	24.75	0.79

(continued)

Table 9 (continued)

Sensitivity (s)	0.75	0.50	0.38	0.25	0.50	1.00	0.44	0.63	0.75	0.50	0.81	0.38	0.19	0.69	0.00	Result	Normalized result
Indicator No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15		
Activity																	
23	4	4	3	4	2	3	3	3	3	3	2	2	3	3	1	27.75	0.89
24	3	4	3	2	2	3	3	3	3	2	2	2	2	2	2	28.13	0.90
25	3	4	4	2	3	3	3	4	4	2	2	2	2	2	2	30.38	0.98
26	4	4	3	4	2	3	3	3	3	3	2	2	3	3	1	30.75	0.99
27	2	2	2	2	2	2	2	2	2	2	2	3	2	3	4	21.69	0.69
28	2	2	2	2	2	2	2	2	2	2	2	3	2	3	4	21.69	0.69
29	2	2	2	2	2	2	2	2	2	2	3	3	2	3	4	20.50	0.65
30	2	2	2	2	4	2	2	2	3	2	2	2	2	2	2	20.38	0.65
31	4	4	3	3	2	3	2	2	2	2	2	2	2	2	1	22.75	0.73
32	3	2	4	3	3	2	2	2	3	2	2	2	2	2	2	21.63	0.69
33	3	2	2	4	2	2	2	2	2	2	3	3	3	4	3	22.63	0.72
34	2	2	2	2	2	2	2	2	2	2	4	3	1	3	3	21.13	0.67
35	1	1	1	1	1	1	3	3	3	4	1	1	3	3	1	19.31	0.61
36	1	1	1	1	1	1	3	3	3	4	1	1	3	3	1	19.31	0.61
37	1	1	1	1	1	1	3	4	3	3	1	1	2	3	1	22.25	0.71
38	1	1	1	1	1	1	3	4	3	3	1	1	4	3	1	22.63	0.72
39	1	3	1	1	1	3	2	2	3	2	1	1	2	3	1	20.50	0.65
40	2	3	1	1	4	3	2	2	3	2	1	2	2	3	1	23.13	0.74
41	2	3	1	2	3	2	2	2	3	2	1	2	3	3	2	20.06	0.64
42	4	3	3	3	3	3	2	2	3	2	1	2	3	4	3	24.25	0.78
43	2	2	1	2	4	2	4	4	3	4	1	3	3	3	2	26.69	0.86
44	2	2	1	1	2	3	3	4	3	4	1	1	3	3	2	23.69	0.76

(continued)

Table 9 (continued)

Sensitivity (s)	0.75	0.50	0.38	0.25	0.50	1.00	0.44	0.63	0.75	0.50	0.81	0.38	0.19	0.69	0.00	Result	Normalized result
Indicator No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15		
Activity																	
45	2	2	1	1	2	3	3	4	2	4	1	1	4	3	2	29.13	0.94
46	3	3	3	1	3	4	2	2	2	2	2	2	2	2	1	24.50	0.78
47	3	3	3	2	4	4	2	2	2	2	2	2	2	3	1	25.94	0.83
48	3	3	3	2	4	4	2	2	2	2	2	2	2	3	1	23.94	0.76
49	3	3	3	2	4	4	2	2	2	2	3	3	2	3	3	25.13	0.80
50	2	2	2	2	3	3	2	2	2	2	3	4	2	3	3	22.38	0.71
51	2	3	3	2	3	4	2	3	4	2	2	2	2	2	2	24.13	0.77
52	2	3	3	2	3	4	2	3	4	2	2	2	2	2	2	24.13	0.77
53	2	3	3	2	3	4	2	3	4	2	2	2	2	2	2	24.13	0.77
54	4	3	3	2	3	3	2	2	2	2	2	2	3	4	1	24.06	0.77
55	4	3	4	3	3	2	2	2	2	2	2	2	2	4	1	23.50	0.75
56	3	2	2	4	2	2	2	2	2	2	3	3	2	3	3	21.75	0.69
57	4	2	2	2	4	2	2	3	2	2	2	3	2	3	2	22.81	0.73
58	4	3	3	3	3	4	2	3	1	1	1	1	1	1	1	21.06	0.67
59	3	1	1	1	1	1	1	1	1	1	2	2	3	4	2	14.44	0.45
60	4	3	3	3	2	4	2	2	2	2	2	2	2	3	1	23.94	0.76
61	1	3	3	3	2	4	2	2	2	2	2	3	2	4	2	20.75	0.66
62	1	1	1	1	1	1	1	1	1	1	2	4	2	3	1	12.81	0.39
63	1	1	1	1	1	1	1	1	1	2	2	1	4	4	1	13.25	0.41
64	3	3	3	3	3	2	2	2	2	2	2	1	1	3	1	19.13	0.60

Table 10 Class intervals for actions

Class	Impact on SISR	Class boundaries		Frequency	Frequency accumulated	Percentage share (%)
1	Low	<0.000	0.143)	5	5	7.81
2	Low	<0.143	0.286)	3	8	12.50
3	Medium	<0.286	0.429)	8	16	25.00
4	Medium	<0.429	0.571)	17	33	51.56
5	Medium	<0.571	0.714)	18	51	79.69
6	High	<0.714	0.857)	7	58	90.63
7	High	<0.857	1.000)	6	64	100.00

Table 11 Characteristic of the workshop W4

Characteristic	Description
Workshop name	Charting
Objective	Roadmap for remanufacturing SME's
Input data	• Market Drivers with the highest importance (from W1) • SISR • Activities categorized from the perspective of the resources in remanufacturing company (from W3)
Process steps	1. Layers definition 2. Determination relationship between Market drivers and SISR 3. Linking relationships 4. Determination relationship between actions and SISR 5. Linking relationships 6. Visualization of the roadmap for remanufacturing 7. Establishment of the implementation plan

It can be assumed with high probability that when a company takes such actions, it will improve the SISR indicators values to such an extent that it would reach a higher maturity level of a remanufacturing process in terms of sustainability and would benefit from market-based drivers.

3.4 Charting Workshop

During the last workshop we reviewed the results from previous workshops. Then we focused on the layers definition and determination of the relations between market drivers and SISR. In the next step the actions were linked to the indicators. All the links were visualized in the roadmap The basic characteristic of the workshop W4 is presented in Table 11.

The prepared roadmap aims to help companies to implement actions which will result in more sustainable resources utilization in RSMEs and operations higher maturity level. According to the presented methodology a company has a long road to achieve that target. Firstly, a company has to know how do the market drivers influence the indicators (SISR). Moreover the resources should be identify (what is available, what is the resources' quality). In the result company is able to select proper set of actions leading to higher resources utilization (Fig. 5).

In Fig. 6 are presented the layers, which were identified in the previous workshops, namely: market drivers, indicators, resources. The next step was to establish links between layers. The result of the linking layers in the roadmap is illustrated in Fig. 6.

Fig. 5 Concept of the technology roadmap for remanufacturing

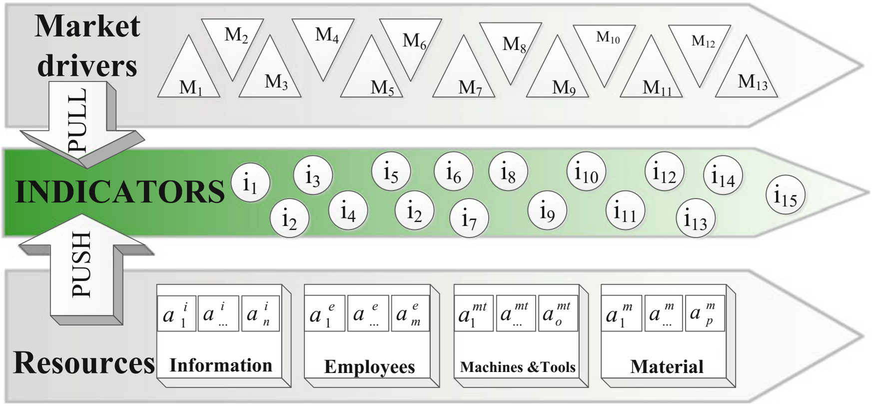

Fig. 6 Roadmap

In the proposed approach the relevant market drivers (M_1–M_{13}) have a direct impact on indicators (i) (PULL). The middle layer contained indicators, which are affected by the resources (PUSH).

Resources are divided into four groups including: information (I), employees (E), machines (M), tools and material (MT). In each appropriate activities according to the formula:

$$a_z^y \tag{1}$$

where

- y—resource group, $y \in \{$i (information); e (employees), mt (machines & tools), m (material)$\}$,
- z—number of activity in the resource group.

By taking appropriate measures the company can improve the value of the indicators. Map shows the relationship and direction of influence between the resources and indicators.

4 Conclusions

The aim of the chapter was to present the process of elaboration of the roadmap for improving the resources utilization in the remanufacturing operations. In the process of the roadmap construction were identified the relations among the market drivers, process indicators and resources in the RSMEs. The map provides a decision support for small and medium sized enterprises in the remanufacturing sector. It visualizes the relations between actions which might be taken and their effects on resources utilization in long term perspective. It presents the actions which can be taken in order to achieve a higher level of maturity in the remanufacturing process.

The study has some limitations. The proposed actions are rather general. Due the fact that each company can be initially at different levels of maturity of remanufacturing process in terms of sustainable resources utilization, therefore timeframe was not included in this roadmap. The chapter rather provides a framework and guidelines for detailed roadmap elaboration in a RSME.

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