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Mapping and Integrating Value Creation Factors with Life-cycle Stages for Sustainable Manufacturing

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Abstract

Instead of implementing each element individually, engineers must be aware of multiple interactions among all major value creation factors and their life-cycle stages. Interactions are analyzed by a set of factors and hierarchical levels within a production system based on empirical observations and described in analytical models. Such analyses and missing information about the current condition of the system and its parts remain limited to addressing specific aspects of interactions among factors and stages for multiple decision making. To build a case-based scope addressing the interactions among a set of factors and life-cycle stages, a comprehensive approach for mapping and integrating relevant elements of sustainable manufacturing is proposed in this paper. By applying the approach, a case study demonstrates how to integrate different levels of factors into various life-cycle stages in order to monitor their condition and provide necessary information for maintenance activities in a service provider company.

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Keywords: Value creation factors; life-cycle stages; sustainable solutions

1. Introduction

Physical and virtual production systems continue to move together closer and closer through emerging information and communication technologies during the last two decades. The fourth industrial revolution, also called Industry 4.0, is driven by new methodologies through the development and implementation of innovative technologies in order to enable real-time availability of information about conditions of several elements of production systems [1]. It has a huge potential to become a key driver for future manufacturing increasing awareness for market needs and entrepreneurial spirit. Increase in productivity due to Industry 4.0 is estimated by 25% only in Germany. This increase can lead to an industrial growth of 200-425 billion Euros by 2025 [2]. How can sustainable development in general, and sustainable manufacturing in particular enabling closed-loop production systems be achieved through increased availability of information about condition at all aggregation levels?

This question is investigated and addressed in this paper. An overview of sustainable value creation in manufacturing is presented in Section 2. Sustainable manufacturing can be applied by using an architecture of value creation factors, their impacts on multiple aggregation levels and life-cycle stages. Methodologies for closed-loop production systems contribute in this context to create value. However, information about interactions among factors, their levels and life-cycle stages as well as current condition of all elements are essential to decide for the right methodology to implement. Engineers must be aware of multiple interactions for multi-criterial decision-making. To build a case-based scope addressing the interactions among a set of factors and life-cycle stages, a comprehensive approach for mapping and integrating these elements is proposed in Section 3. Determination of factors, their levels and life-cycle stages enable the identification of scope as well as exploration of the use of innovative technologies and potential solutions, which support decision-making for sustainable manufacturing.

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By applying the proposed approach, a case study is presented in Section 4. This application highlights the integration of monitoring through sensors into a service provider company to increase the availability, effectiveness and reliability of equipment in a sustainable manner. Section 5 summarizes the major conclusions and future work.

2. An overview of sustainable manufacturing

Parts of production systems are hierarchically mapped to different aggregation levels [3]. Value is a measure of benefits created within the transformation of raw materials or applied services [4]. A value is called *sustainable*, when it benefits the economy, environment and society concurrently. *Sustainable manufacturing* is the creation of manufactured products and services that fulfill their functionality over their entire life-cycle as well as cause a sustainable impact on the environment and society while delivering economic value [5]. The following impacts to economy, environment and society remain relevant for assessing sustainable solutions [6].

Economically, instead of tangible objects, functionality and use-based services should be created and sold, thus achieving more wealth with less resources, and people should act right, having decided on the right action by intense training of balancing impacts and adapting solutions.

Environmentally, non-renewable resources should be processed in multiple life-cycles through 6R methodologies [7] rather than be disposed of after a certain life-cycle, and non-renewables should be substituted by renewables within the natural limitations of renewables regeneration.

Socially, improved living and working standards should be developed to increase equal distribution of global wealth, and people should be well educated and trained to be creative in order to explore new opportunities for innovation and to take initiative for implementation.

2.1. Value creation factors and aggregation levels

Five value creation factors and their interactions constitute and determine a value creation module with a particular scope for a product, service or combination of the two [8]. Value creation modules can be normalized at different levels of aggregation for each factor [3], as illustrated in Fig. 1. All factors can be assessed through their impact to economy, environment and society. They are specified by numerous variables such as type, production depth, capacity and time. An introduction into the five value creation factors and their aggregation levels follows [9].

What should be produced? – *Product* refers to which material, and in what quantity, should be processed through the value creation chain and to achieve the quality required. A product can be a tangible and physical object, a service of completing a task or a combination of two. Products are specified by type, function, geometry and structure [10]. Products are classified into the levels of product portfolio, product, sub-part, workpiece, component and feature [3].

How should it be produced? – *Process* is defined as the use of one or more physical mechanisms employed to transform and use the shape, form and properties of a material [11]. Processes consider how to create and use products through existing technologies that should be utilized in order to add value. They include discrete and continuous processes in manufacturing.

By what means should it be produced? – *Equipment* relates to machines and tools that are used to run the processes effectively at the required operational conditions, availability and reliability levels. Equipment is classified into the levels of network, factory, site, building, working area, cell, workplace, station, machine, tool and device [3].

When and where should it be produced? – *Organization* deals with the procedural, structural and managerial decisions about when, where and which processes, with which equipment, for which product should be run. It includes the quantitative and capacitive flow of materials, energy, water, finance and information, as well as supply chain management. Organization is leveled in the conceptual design of production systems, value creation modules and factors, factory planning, production planning and control [3].

Who should produce, supervise and manage? – *People* relate the assignment of tasks to stakeholders. Stakeholder satisfaction ensures the accomplishment of success and the achievement of long-term goals. Awareness, qualification and training of decision-makers, employees and operators are required to complete their tasks. Institutions, including people as decision-makers, and workforce are classified in governmental and non-profit institutions, educational and research institutions and private institutions [12].

2.2. Life-cycle stages and methodologies for closed-loops

Economic, environmental and societal impacts of each value creation factor assesses the extent of sustainable value, which is created through implementation and adaptation of methodologies in manufacturing. Sustainable manufacturing closes the loop from cradle-to-cradle with provisions of multiple life-cycles for value creation modules or their tangible factors at the end-of-life. Multiple stages define the *life-cycle* of each value creation factor, which involves integrating any factor into a value creation module, and later a production system, using it and subsequent retirement at the end-of-life for the current life-cycle [13].

Value creation covers all stages of *product life-cycle*: pre-manufacturing, including material extraction, manufacturing, use and post-use [14].

Companies apply mostly new technological processes following the *innovation life-cycle* stages as innovators, early adopters, early or late majority or laggards [15].

The *equipment life-cycle* stages cover the time over which equipment is designed, operated, maintained, decommissioned and disposed of including all methodologies for generating more closed-loop production systems [13].

Life-cycle stages of organizational management involve planning, assessment and improvement.

Stages of education cycle describe the procedure of awareness, motivation, application and transformation for people to decide and act in a sustainable manner [6].

The *6R's* enable closed-loop multiple life-cycles providing comprehensive methodologies [7]. Their overall goal is to protect the environment, conserve resources encouraging economic benefits and to keep in mind social concerns, while reducing pollution and waste. 6R methodologies support the identification of potential solutions to create sustainable value:

Reduce mainly focuses on reduced use of energy, materials and other resources during manufacturing and the mitigation of emissions and wastes during the use stage and increases resource-efficiency.

Reuse refers to the reuse of the product or its components, after its first life-cycle, in subsequent life-cycles to reduce the usage of virgin materials to produce such products and components.

Recycle involves the process of converting end-of-life materials that would otherwise be considered as waste, normally heading to landfills, into new materials for next generation products.

Recover refers to the process of collecting products at the end of the use stage, disassembling, sorting and cleaning for utilization in subsequent life-cycles of the product.

Redesign involves the act of redesigning next generation products, which would use components, residual materials and resources recovered from the previous life-cycle.

Remanufacture involves the re-processing of already used products for restoration to their original state or a like-new form through the reuse of as many components as possible without loss of functionality.

Interactions among value creation factors, their aggregation levels, life-cycle stages and potential solutions through 6Rs are analyzed based on case-based empirical observations Such analyses underline the need for clear definition of scope for the intended application in any case and offer consistency with the structure of value creation.

3. Morphological analysis

Morphology is the study of how elements of a system interact with each other to generate a whole system. A morphological analysis is used in this section to build a case-based scope, which addresses the interactions among a set of factors and life-cycle stages. Fig. 1 presents a comprehensive approach to determine the levels of factors and life-cycle stages in order to explore innovative technologies and potential solutions, while contributing to sustainable manufacturing.

Any selected mix out of Fig. 1 determines a path for value creation and helps to organize information for further investigations. The relevance of 6R methodologies to any path must be specified for each case separately. Innovative technologies based on the Industry 4.0 include sensorial data gathering, scalable data processing and automated knowledge discovery. When integrated holistically to achieve value creation in manufacturing, these technologies usually have a huge impact on the creation of sustainable solutions.

4. Implementation

By applying the new approach in a service provider company, the case study demonstrates how to integrate different levels of factors into various life-cycle stages in order to create sustainable solutions through the application of 6R methodologies and innovative technologies. The goal of the case study is to increase the value, which is created through services by sequencing and scheduling the right maintenance type at the right equipment, and the time and place in a sustainable manner.

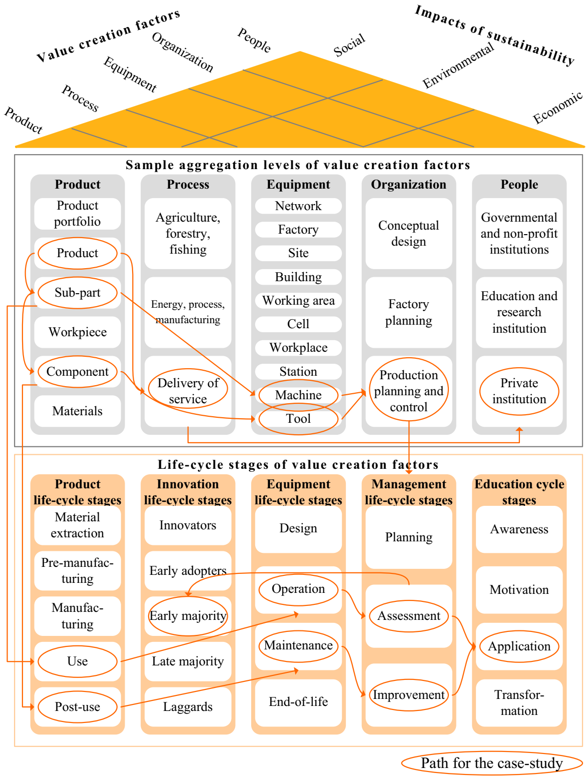

Fig. 1. Mapping of value creation factors, aggregations levels and life-cycle stages

4.1. Mapping

The mapping, as proposed in Fig. 1, presents how to relate value creation factors with various aggregation levels and life-cycle stages to maintain sustainably. The path for this case study is highlighted with a red line, the specific relations among factors, levels and stages are presented by red arrows in Fig. 1 and the mapped elements are written in **bold** letters below.

The selection of an appropriate methodology and time to maintain are crucial for (1) increasing the availability, effectiveness and reliability of the equipment in the **operation** stage, (2) decreasing maintenance duration and costs in the **maintenance** stage, and (3) keeping the equipment or its parts longer in life-cycles and **improving** their functionality in all stages. The first two aspects point on the equipment life-cycle stages.

The proposed approach is applied by a **private service provider company**. A brief introduction into the *value* *creation factors* (VCF) from a higher aggregation level is described as follows: Recycling and cleaning of waste is a **service**, which is provided in the **post-use** stage of tangible vehicles, which demonstrate $VCF_1 = \boldsymbol{product}$. Technological processes for cleaning and recycling of waste present $VCF_2 = process$. Various **tools** and **machines** can be applied as $VCF_3 = \boldsymbol{equipment}$ including **vehicles** to collect waste and complete these processes. Scheduling, logistics and performance measurement regarding all processes using IT tools form $VCF_4 = \boldsymbol{organization}$ in **planning, control and assessment** of all value creation activities. Workforce including operators, service providers, designers and managers represent $VCF_5 = \boldsymbol{people}$, who apply their capabilities to run the service-based system [6].

A brief introduction on the lower level into the production system is necessary to analyze value creation for maintaining the right vehicle or component of a vehicle, time and place in a sustainable manner. The VDI 3963 standards is **applied** to classify failures, their frequency and distribution over the **use** stage of single components of various vehicles types [16]. A challenge of classification is the unknown failure frequency of components in a vehicle and fuzziness of the duration and distribution of life-cycle stages on component level.

4.2. Analysis

The failure analysis with the following code numbers is used to investigate the service based system, as presented in Fig. 2.

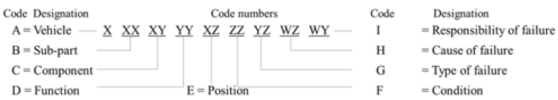

Fig. 2. Failure analysis

The service provider company owns about 1,800 **vehicles** with the following aggregation levels in different life-cycle stages. Vehicle X as a **product** in the **use** stage must be reliable, effective and available for any required service as an **equipment** in the **operation** stage. Vehicle X is equipped with multiple sub-parts such as **sub-part** XX. To ensure the required service, all sub-parts must function also reliable, effective and available in their **operation** stage. Each vehicle has about 200 sub-parts, each with 3-17 components. A Pareto analysis is conducted to identify components, which cause almost 80% of failures and account for around 20% of failure types. **Component** XY in the **post-use** stage is selected as a part of sub-part XX in this sample to maintain enabling the required service after the **maintenance stage** as an **equipment**.

The following analysis is necessary to **plan** and **control** the **organizational** handling of component XY. Manufacturer of component XY provides information about the duration of a life-cycle, delivery times, price and the cost for stock-keeping by replacement or lost production costs by failures in general. Further information is extracted for the purpose of use within the vehicle X in the specific situation of the service provider company. Function YY specifies the type, role and purpose of component XY within sub-part XX for any necessary activities in the operation stage. Position XZ specifies the place, geometry and structure of component XY within sub-part XX for any necessary activities such as disassembly and cleaning in the maintenance stage. Condition ZZ is essential to logistically organize any maintenance activities in the planning stage. Type YZ, cause WZ and responsibility WY of a failure are determined in the **assessment** stage to decide if component XY can be **improved** in terms of reuse without any changes, maintenance or replacement.

Assumptions are made before the analysis of company requirements and derivation of potential solutions according to the sample mapping in Fig. 1: Three types of vehicles with more than 65 sample vehicles are selected as **early majority** at the first aggregation level. Six types of sub-parts with more than 46 sample sub-parts are selected as **early majority** at the second aggregation level. A single component of each sub-part is considered for further analysis. Methodologies such as reuse, maintenance and replacement of components run perfectly that a component is equal to a new one in terms of availability, effectiveness and reliability after implementation of the selected methodology. Environmental and social impacts of maintenance can be reduced significantly by allowing a minor increase in economic costs.

An analysis for the selected six components is performed according to these assumptions, and the annual report of the service provider company in 2014. The analysis results are presented in Table 1. Each maintenance order is classified as only inspection and service, only repair or a combination of the two. Each order leads to a failure, which means not operating time for the vehicle and a change from **use to post-use** for **assessment** or from **operation to maintenance** for **improvement** stage. Each change conducts multiple activities to ensure the required service of the vehicle. Waiting time indicates that a spare part or other information or material is missing to continue working on the necessary activities. Cumulative costs of orders and lost production costs of waiting times are included in Table 1.

Table 1. Analysis of indicators

Indicators		Number of failures	Number of activities	Costs
Total of maintenance orders		988	12,402	901,565 EUR
Type	Only inspection and service	169	6,458	539,122 EUR
Type	Only repair	146	1,155	143,678 EUR
Waiting time		657	4,764	217,119 EUR

Weibull distribution is used commonly for time to failure analysis. A two parameter Weibull reliability function with probability density function is adopted for this case study according to Equation (1), where b is the shape parameter and T is the scale parameter:

$$f(t) = \frac{b}{T} \cdot \frac{t}{T}^{b-1} e^{-\left(\frac{t}{T}\right)^{b}} \tag{1}$$

A vehicle type is selected to demonstrate the failure probability in order to calculate the life-cycle duration for selected components. Component XY is selected to present the results in this case study due to the space limitations of the paper. Fig. 3 shows the Weibull distribution plots of the failure probability for component XY. The straight line in Fig. 3a confirms that the shape parameter chosen is appropriate.

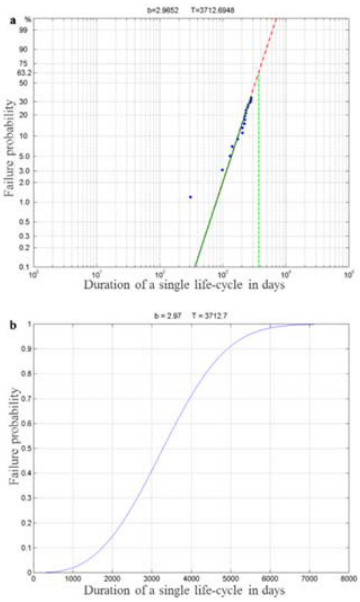

Fig. 3. Failure probability for component XY

4.3. Improvement

The path in Fig. 1 demonstrates relations among value creation factors, their aggregation levels and life-cycle stages, which are used by the proposed approach to derivate potential solutions and to discuss with stakeholders including the service provider company. Existing monitoring infrastructure for vehicle X is provided by the vehicle manufacturer and is not available at the component levels. Real-time monitoring on component level through sensors as an element of Industry 4.0 is identified as a high potential solution, which increases data availability across life-cycle stage operation and maintenance of multiple components [1]. Monitoring of component's condition provides measured values for the decision if a component can be reused or recovered. The goals of the proposed solution are to (1) address the challenge of fuzzy failure duration and distributions, (2) increase availability and reliability of components in single life-cycle stages, (3) keep components longer in single life-cycle stages and (4) decrease maintenance duration and costs.

Potential solutions for waste collector vehicle X, hydraulic part XX to create a more sustainable value through monitoring, as presented in Fig. 4, are (1) particle counter monitoring impurity of hydraulic fluid, (2) monitoring of hydraulic lubrication level, (3) position sensor for monitoring of loading process, (4) pressure transducer for monitoring of hydraulic fluid, (5) current clamp monitoring battery charge condition and (6) data transmission via bluetooth, radio or wireless local area network.

These solutions require cooperation with the vehicle or sub-part manufacturers, and if necessary, change of suppliers for spare parts to retrofit the vehicles integrating the identified sensors.

Requirements for achieving the goals are analyzed based on annual reports of the service provider company, specification sheets of vehicle X provided by its manufacturer as supplier of the service provider, maintenance orders, knowledge and experience of the workforce. Following requirements are identified as relevant: (1) function of the components with regard to the availability of the vehicle, (2) failure frequency of the components with regard to the reliability of the vehicle, and (3) duration, required workforce and costs for maintenance activities with regard to the effectiveness of the vehicle.

The company requirements focus mainly on time-based economic impacts due to their large impact in cost-benefit analysis to convince the service provider company.

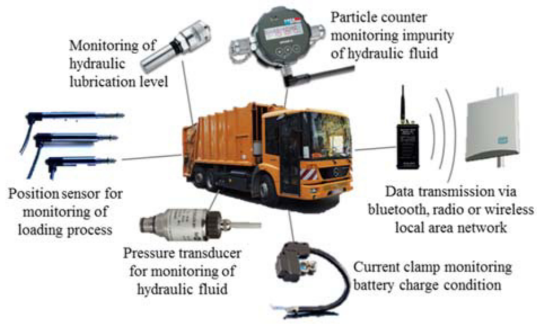

Fig. 4. Potential solutions through monitoring

Table 2 presents an overview of how to develop weightings and assign measures to the following requirements through monitoring.

Table 2. Requirements

Requirement		Relative weighting	Absolute weighting
Functionality	25%		
	Potential failure	33.33%	8.25%
	Following damage	33.33%	8.25%
	Detection possibility	33.33%	8.25%
Failure frequency	40%		
	Frequency per component	25%	10%
	Frequency of inspection	35%	14%
	Frequency of failure	30%	12%
	Frequency of tests	10%	4%
Costs	35%		
	Duration	50%	17.5%
	Costs per maintenance activity	50%	17.5%

Implementing methodologies to reuse component XY and recover the functionality changes the distribution of failures and duration of life-cycle stages. The integration of identified sensors for component XY is tested on 15 vehicles with on-field experiments in 2015.

Fig. 5 plots the Weibull distribution of the failure probability for component XY after the sensory data gathering, and it indicates that the duration of operation stage is extended through continuous monitoring and automated knowledge discovery about the component's condition. Maintenance costs are reduced by about 4% for component XY during the on-field experiments. The implementation of the potential solutions for further components should also decrease duration of further life-cycle stages such as maintenance with positive environmental and social impacts. The longer a life-cycle stage is, the more the resources in a component are kept in circular economy and the less efforts of the workforce are needed.

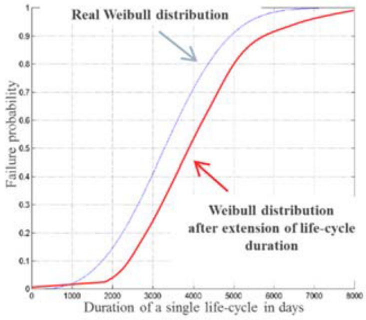

Fig. 5. Failure probability for component XY with real and extended life-cycle duration

5. Conclusions and future work

An approach for sustainable manufacturing consisting of 6R methodologies and value creation factors for multiple aggregation levels with different life-cycle stages are presented as closed-loop production systems. The proposed approach is based on state-of-the-art methodologies to morphologically map and integrate the factors at different levels and life-cycle stages. An example of how to apply 6R methodologies with a case-based scope through the integration is presented. The case-study demonstrates how to identify a sustainable path for operating and maintaining a vehicle and its components in a service provider company. Multiple sensors for process-condition and component's monitoring are used for an improved maintenance scheduling and troubleshooting capability. On-field experiments result in longer duration of operation stages with shortened maintenance time, thus saving resources in terms of time, capacity and workforce load, maintenance costs. Further research should investigate how Industry 4.0 can drive sustainable manufacturing through real-time available information about process- and component-conditions in all aggregation and hierarchical decision levels of production systems.

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