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A multi-criteria approach for assessing resilience, sustainability and efficiency measures in manufacturing companies

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Abstract

In recent years, manufacturing companies have been increasingly confronted with rising demands relating to their production, uncertain conditions in their environment and volatile markets. To fulfil the diversified customers' demands and rapidly changing markets, manufacturing companies need to achieve and maintain high productivity and quality. This requires fast responses, sufficient flexibility and short lead times. Therefore, flexible, resilient and customer-oriented production processes are becoming more and more important. Current optimization measures of industrial environments focus primarily on increasing efficiency while reducing costs. The reliance on other factors, such as a resilient as well as economically, ecologically and socially sustainable manufacturing system, has not been sufficiently taken into account yet. Bridging the gap between research and practice, this paper proposes a holistic approach that assesses resilience, sustainability and efficiency measures of manufacturing companies. A multi-criteria assessment model is developed to stabilize qualitative and quantitative measures within these dimensions. Furthermore, the model is tested in an Austrian small and medium-sized (SME) enterprise in the wood processing industry. The targeted groups are SMEs and multinational companies.

Keywords: production optimization; resilience; sustainability; efficiency; assessment model

1. Introduction

The need for continuous improvements towards higher efficiency and performance, the increasing complexity of customer and market requirements, as well as increasing digitalization, are forcing production systems towards an ever-increasing level of complexity. [1, 2]. Furthermore, the increasing significance of sustainability in manufacturing is fueled by factors such as rising environmental awareness, social responsibility, and economic advantages imposing further requirements for manufacturing enterprises [3]. Demographic change is also bringing issues such as the shortage of skilled workers and the resulting need for more human-centered design into focus [4, 5]. Moreover, the increasing resilience of value systems has become a key optimization objective [6, 7].

In the past, optimization efforts of manufacturing companies typically prioritized a single objective, such as cost reduction or service level improvement, without considering the interactions with other objectives [8]. This can have negative effects, for example on resilience, that are not immediately apparent [9, 10]. To ensure the long-term success of manufacturing companies, it is essential to take a holistic view and optimize strategic goals [11].

To address these challenges, this paper proposes a structured approach that integrates existing assessment models to provide a multi-criteria approach to assess resilience, sustainability, and efficiency measures in manufacturing companies. The aim of

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this paper is to enable a multi-criteria optimization across the entire value chain and to provide a basic framework for future research.

The paper is structured as follows. The second chapter provides a literature overview of existing frameworks and approaches on measuring digital competences resulting in our research methodology. Section three and four describe the research approach, model development and the resulting assessment model. The last two sections contain industrial use cases for validation as well as conclusions and future research steps.

2. State-of-the-art

Several publications and articles provide approaches to optimizing the aforementioned factors. However, there is an evident lack of knowledge to understand and measure them qualitatively and quantitatively in the overall context of manufacturing companies. This issue is briefly discussed in this section through a review of state-of-the-art approaches.

2.1. Assessment models in manufacturing companies

Recent literature in the field of sustainable, resilient, and economic production optimization can be divided into two basic streams: (i) theoretical approaches that deal with the definition and establishment of assessment models for a prospective design and (ii) publications that propose tools for qualitative or quantitative measurement of one or two of these factors. The literature review includes scientific papers from both directions, which are combined in this paper, as they aim at a holistic assessment of the factors from different areas of a company.

One identified model from the literature is the ESSENZ method [12], which enables an assessment of the resource efficiency of products, processes, and services. In addition to the quantities used, the potential risk of limited availability and the potential environmental impacts are also considered. Furthermore, the social acceptance of the materials used in the product is estimated with regard to compliance with social and

The model of Oehlinger et al. [13] provides companies with a tool to evaluate their own resilience maturity. The systematic identification of possible shock and stress factors in a company forms the basis for avoiding unplanned production downtimes as far as possible. In the first step of the process model, the current situation is assessed using a two-stage questionnaire based on qualitative variables. The application of the model depends on the industry, the competitive situation and the individual requirements of the company's production system. However, there are no special restrictions for manufacturing companies.

In recent decades, maintenance management has become an increasingly important lever for industrial companies to influence their profitability. Therefore, the concept of Lean Smart Maintenance (LSM) was developed to improve corporate profitability and efficiency [14]. Schmeidbauer et al. [15] evolve the Lean Smart Maintenance Maturity Model towards Industry 4.0 and how it can help manage the complexity of asset and maintenance management in the manufacturing industry. The model assesses qualitative and quantitative measures and focuses primarily on maintenance processes.

Other approaches, such as the principle of LARG management (Lean, Agile, Resilient and Green) [16], consider multiple interrelationships between the lean, agile, resilient and green paradigms. The goal is to achieve efficient process design within an organization from the holistic perspective of a sustainable company and the associated competitive advantages. The approach includes qualitative and quantitative paradigms of business models without a method to measure and evaluate them.

The LGAMS method (Lean, Green, Agile Manufacturing System) [17], aims at a holistic view of the perspectives of lean, green and agile measures in manufacturing systems. The introduction of lean manufacturing in the supply chain is intended to increase profit by reducing costs, while agile manufacturing is intended to maximize profit at the same time through close customer orientation in production. Additionally, the point of sustainable and environmentally friendly guidelines in green manufacturing is to be considered in the fulfilment. The method provides qualitative and quantitative lean, green and agile aspects. However, it does not include an approach that makes the variables measurable and optimizes them.

Another approach about green recovery in the mature manufacturing industry [18] provides how sustainability-driven strategic innovation can create a competitive advantage for manufacturing firms. It presents a qualitative framework that places sustainability as the business approach that represents the greenest means for a future society based on shared social values.

2.2. Research gap and contribution

Yet, all of the identified approaches lack practical applicability and tool availability. Thus, the topic of optimizing manufacturing enterprises has mostly relied on theoretical frameworks and isolated attempts with little practical relevance. Despite existing approaches to optimize sustainability, resilience or efficiency, there is a lack of comprehensive understanding of the causal relationships, with sometimes conflicting statements.

In addition, existing models are mostly superficial or cover companies in general and do not address manufacturing companies. There are also no approaches that allow for a combined qualitative and quantitative assessment of the three factors. Likewise, some approaches have been identified that focus on the framework and aspects for qualitative assessment of sustainability and resilience. However, there is no model that identifies and quantifies them.

Nevertheless, sustainability is mainly seen in the context of green energy and low resource consumption [19]. However, this also requires social aspects in conjunction with sustainable working practices and people-centredness to tackle the ongoing and growing demand for skilled labour [20].

A multi-criteria approach for assessing resilience, sustainability and efficiency measures in manufacturing companies both qualitative and quantitative could lead to precise recommendations for manufacturing companies and, if successfully implemented to significant savings in overall production costs. The presented approach should enable the stabilization of the three factors to ensure the overall sustainable, resilient, and economic competitiveness of companies in the future.

In this context, the contribution of this paper consists in the development of the so-called ORSE-framework (Optimization of Resilience, Sustainability and Efficiency), a holistic assessment model for measuring resilience, sustainability and efficiency of production systems by determining qualitative and quantitative measures, as well as the application in a practical setting. This approach makes it possible to bring together the divergent target systems of all business units, as well as to control and sustainably stabilize the achieved state.

3. Methodology for model development

The approach in this paper combines scientific and practical elements. For the development of a scientific-based model, the methodology is built on the step-by-step approach of Becker et al. [21]. Becker's approach adopts Hevner's Design Science guidelines [22] for developing assessment models. For this approach, the methodology is divided into the scientific and practical part. The first part includes the development of a scientifically sound model and the development of the holistic, practically applicable ORSE-framework. The second part includes the practical application, and the validation of the framework through a pilot test in practice.

The Design Science framework and Becker's procedure model lead to the following five-step development methodology (see Fig. 1).

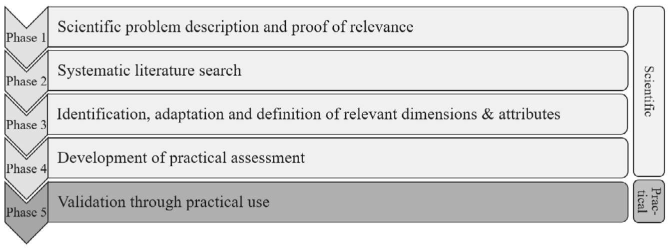

Fig. 1: Development methodology ORSE-framework

Phase 1 outlines the problem statement and the scientific relevance, described in Section 1. The systematic literature review, Phase 2, was conducted in addition to the state-of-the-art research focusing on existing concepts and structures in the field of assessment approaches, cf. Section 2. The collection of validated models in related fields serves as the basis for the developments. Model designs and structures from existing developments were considered. Phase 3 leads through the development of the structure and content of the ORSE-framework. For this purpose, all dimensions and attributes from selected literature were captured using an explorative concept mapping approach. The concept mapping started with existing designs and structures of existing assessment models and was exploratively developed towards other areas of model applications.

Transferring abstract models within the three categories resilience, sustainability and efficiency into operationally measurable attributes, the ORSE-framework results in 59 attributes grouped in 15 dimensions.

Phase 4 is an iterative approach that translates the dimensions and attributes into operationally measurable attributes to transform the framework into a practical tool. It should be noted that an assessment should be conducted by employees across all occupational groups and levels in order to minimize bias and obtain consistent results.

In Phase 5, the ORSE-framework is tested in a real industrial environment to validate the framework and to further increase the relevance and comprehensibility of the attributes by including feedback from practitioners.

4. Resulting assessment model: ORSE-framework

The main areas of the ORSE-framework, corresponding to the target variables of resilience, sustainability and efficiency were supplemented by the cross-sectional dimension of costs, which has an influence on all three factors and was thus included as a separate dimension, pictured in Fig. 2.

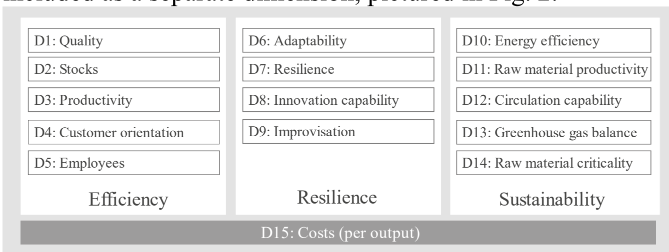

Fig. 2: Defined dimensions of the ORSE-framework

Each dimension consists of 3 or 4 attributes. Table 1 lists the attributes for the efficiency variable, dimensions 1 to 5, as an example. The first and last attributes of each dimension follow the same scheme, asking for the definition and the question of an indicator system, as well as assessing individual key performance indicators of the respective dimension.

Table 1. ORSE-framework dimensions and attributes of the area efficiency

	Dimen-sion	Attribute number	Attribute naming
Quality	D1	D1.01	Definition and indicator system
	D1	D1.02	Quality management system
	D1	D1.03	Quality deviation
	D1	D1.04	Key performance indicators
Stocks	D2	D2.01	Definition and indicator system
	D2	D2.02	Transparency on work in progress & stock
	D2	D2.03	Spare parts warehouse
	D2	D2.04	Key performance indicators
Productivity	D3	D3.01	Definition and indicator system
	D3	D3.02	Data collection and data processing
	D3	D3.03	Process transparency
	D3	D3.04	Key performance indicators
Customer orientation	D4	D3.01	Definition and indicator system
	D4	D3.02	Customer focus
	D4	D3.03	Adaptability& flexibility of customer changes
	D4	D3.04	Key performance indicators
Employees	D5	D3.01	Definition and indicator system
	D5	D3.02	Promotion, qualification & development
	D5	D3.03	Fluctuation - employee loyalty
	D5	D3.04	Key performance indicators

The developed framework measures the assessed maturity level (ORSE-level) within the dimensions using a quantitative rating

scale from 1 to 6, where 1 corresponds to the lowest level and 6 to the highest level.
The evaluation attributes consist of the title, the evaluation questions, a specification for easy evaluation by the participants, six evaluation levels including a description, and an evaluation of the relevance of the content of the attribute for implementation in the company. The maturity levels are composed of two parts, the name of the level (e.g., level 1-2) and some examples for a better interpretation of the maturity level. This detailed description of six maturity levels individually for each attribute considerably increases self-sufficient application in industrial companies (example – see Fig. 3).

Attribute D3.02	Data collection and data processing
Are you able to collect production data from your machines and systems (current operating status, sensor technology, retrofitting, connection to a MES system, automated production planning etc.)?	
Level rating categories	
1-2	• There is no connection to a Manufacturing Execution System (MES) or similar and hardly any communication between the machines and systems. • No data is collected about processes/work steps. • The productivity of the plant cannot be determined/can only be determined with manual effort.
3-4	• As much data as possible from the processes/work steps is collected, but not actively used to optimize productivity. • Some of the machines/systems are networked with each other or connected to a MES system or similar - the potential is not yet fully exploited.
5-6	• Machines/systems communicate independently with each other and with a MES system or similar - and can allocate and execute jobs automatically. • Available data of the processes/work steps is collected and processed to optimize productivity. • Regular checks are carried out to keep the equipment up to date with the latest technology.
Attribute very irrelevant / Attribute quite irrelevant / Attribute moderate relevant / Attribute rather relevant / Attribute very relevant	

Fig. 3: Exemplary attribute description

Consistently over all attributes, the lowest maturity level (level 1) describes the lack of implementation of each attribute, in the previous example, a lack of data collection and data processing. The highest level (level 6) describes a state of completed development compared to the current state-of-the-art.
The attribute structure, including a maturity level rating and a relevance rating enables the calculation of a so-called Development-Need-Index (DNI) [20, 23] for each attribute. The development needs of the assessment attributes indicate the extent to which there is a need for action for the respective attribute. The EBI is a key figure that results from the gap between the assessed maturity level of the attribute and the maximum achievable maturity level in combination with the relevance rating of the attribute. The index is expressed in values between 0 (no action required) and 100 (high action required) and is calculated from the maturity level and relevance. A low ORSE level with high relevance implies a high DNI, a high ORSE level with low relevance implies a low DNI. The index is expressed in values between 0 (no need for action) and 100 (high need for action) and is calculated using the maturity level and relevance. A low ORSE-level with a high relevance implies a high DNI, and a high ORSE-level with a low relevance implies a low DNI.

Besides the maturity model, we defined a 4-step procedure for ORSE-measurement in practice (see Fig. 4).

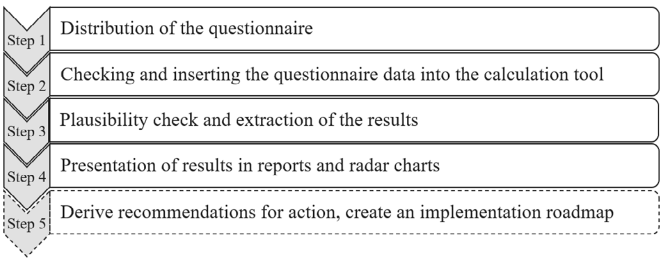

Fig. 4: Development methodology ORSE-framework

This procedure is currently carried out semi-automated, whereby the distribution of the questionnaire in Step 2, as well as the data quality check in Step 3, are carried out manually. The transfer of collected assessment data into the developed calculation tool is carried out fully automated using pre-defined software templates and calculation logics in the software package Tableau™ in combination with MS-Excel™. In Step 4, the resulting dashboards, reports and radar chats, including the ORSE-level and the Development-Need-Index allow to prioritize areas that require development at the attribute, dimension or overall company level. The final step is to derive recommendations for action and create a roadmap for their implementation. For the practical application in Section 5, this last step is still pending.

5. Practical model application

The following section provides the results of assessing the ORSE-framework exemplary for the target area efficiency (see Fig. 5). The validation of the ORSE-framework regarding content, structure and applicability was done by a practical application in an Austrian SME in the wood processing industry according to Phase 4 in Fig. 1.

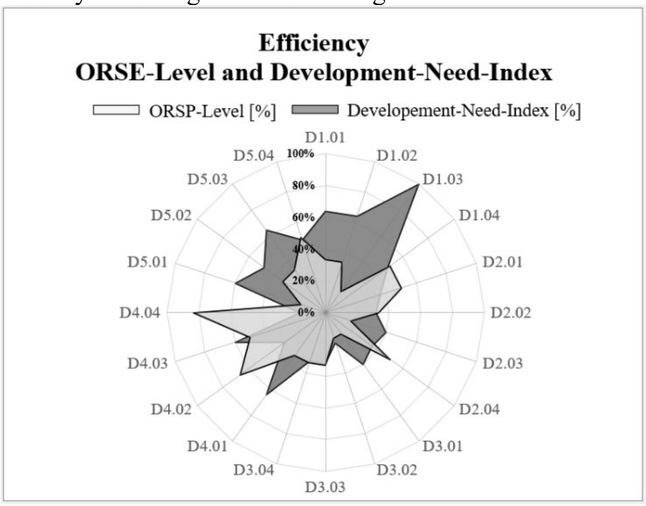

Fig. 5: ORSE-level and DNI exemplary for the area efficiency

Therefore, the ORSE-level and the DNI, calculated from the assessed maturity level and the respective relevance surveyed, were normalized between 0 and 100 percent and represented across the attributes of the five dimensions. Attribute D4.04 shows the highest ORSE-level, just above 80%. All other attributes show far lower levels. On the other hand, the DNI shows overall higher results with values up to 100%. The highest DNI shows attribute D1.03. The exception is shown by the attributes D2.01, D2.04, D4.02 and D4.04, which have a substantially lower DNI than ORSE-level. That means that the following attributes are already more developed than it is relevant for the company. That means that the following attributes are already more developed than it is relevant for the company and thus do not require further optimization measures. For those attributes with a high DNI, optimization measures are required to increase the maturity in the long term.

The assessment results of the Austrian enterprise over all 15 dimensions (named in Fig. 2) are shown in Fig. 6. For the outcomes, the mean value of all attributes within the respective dimension was formed.

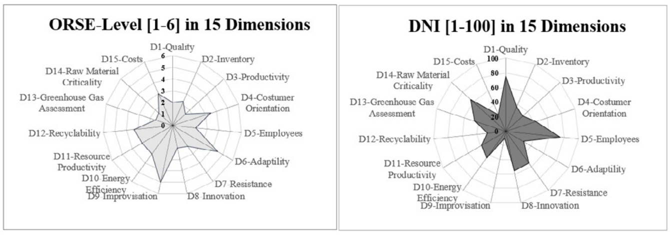

Fig. 6: (a) ORSE-level and (b) DNI within all 15 dimensions

The first picture shows the ORSE-level within the 15 dimensions on a scale of 1-6. The second picture shows the DNI within the 15 dimensions scaled from 0 to 100. The wood processing company exhibits high maturity levels in dimension 4 (customer orientation), dimension 6 (adaptability) and dimension 9 (improvisation). The DNI of dimension 1 (quality) and dimension 5 (employees) is significantly higher than of the other dimension. Therefore, appropriate measures must be derived to optimize dimensions 1 (quality) and 5 (employees) without affecting the other areas.

To address the development needs of the wood processing company, suitable methods must be identified. These, in return, must lead to optimization measures for a long-term, holistic improvement of the required attributes, the further development of the dimensions. The focus is on those attributes and dimensions that have the largest gaps between the assessed ORSE-level and relevance, leading to a high resulting DNI. These correspond to the company's greatest weaknesses in terms of achieving the goal of a sustainable, economical and resilient production company.

6. Conclusion and future research agenda

In this paper, a novel multi-criteria model is presented to assess and evaluate resilience, sustainability and efficiency indicators of manufacturing companies. The development methodology followed a multi-method approach based on Design Science. The model was transferred into a practically applicable tool, the so-called ORSE-framework, and created the tools required for self-reported maturity assessment in practical settings. Overall, the 59 attributes within 15 dimensions for measuring resilience, sustainability and efficiency values in 6 levels proved to be suitable, and the tool provided was perceived by practitioners as understandable and easy to use.

The intimate next steps in the development of the model are the automated evaluation of the ORSE-framework questions and the evaluation through extensive practical applications. This should also make it possible to derive a benchmark for industry comparisons of manufacturing companies.

In the future, methods for identifying potentials in production systems regarding the measures presented in the ORSE-framework will be identified based on the dimensions and attributes developed. Based on these identified methods, well-founded measurements can be selected and implemented that lead to an optimization of the system with regard to the objectives of the ORSE-framework. Therefore, as a follow-up activity of the developed ORSE-framework, an ORSE-toolbox of methods has to be developed. This enables the selection of individual methods for each practical application and, as a result, the determination of targeted measurements for holistic optimization, see Fig. 7.

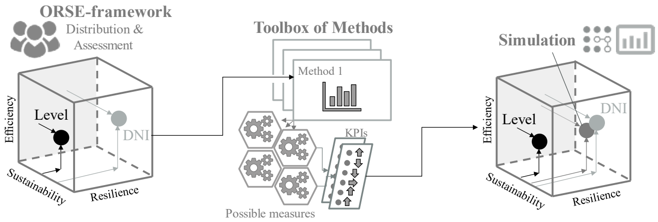

Fig. 7: Big picture ORSE-framework and future research agenda

Often, the simultaneous implementation of several measurements (so-called measurement packages) leads to complex interactions that are not or only partially comprehensible for operational and strategic planning. The implementation of measurements on complex production systems can appear to make sense a priori, but in retrospect, lead to strongly deviating results and unplanned effects. For example, packages of measurements for system optimization successively led to changes in other elements due to interdependencies of the system elements, which can only be understood with a high level of understanding of the system. To visualize the influence of measurements on the target values of all ORSE-framework's dimensions, it is useful to abstract and model interdependencies. Already during the planning of the measurements to be performed, a supporting tool should be used to improve the understanding of the system and the derivation of measurements based on it. Therefore, in the last step of this research project, a simulation, the ORSE simulation, is planned to model the system interrelationships on an abstract level in order to illustrate the dynamic influence of disturbance variables and measurements on the system behavior (see Fig. 7, right).

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