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Multidimensional analysis of process chains regarding the resource-efficient manufacturing of hybrid structures

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Abstract

One of the leading topics in the automotive industry as well as in the aircraft and aerospace sector is the use of lightweight structures for weight reduction. For this purpose, hybrid materials, e.g. metal-plastic structures, are of essential importance. Despite the high technological challenge, the manufacturing techniques still provide versatile development potential. Especially the integration of separate production techniques in one single tool opens new possibilities of successfully designing a resource-efficient process chain for hybrid components, suitable for series production.
Within the Cluster of Excellence “MERGE Technologies for Multifunctional Lightweight Structures”, a modelling approach for the resource-efficient process design of the manufacturing of hybrid structures, which is based on a multidimensional analysis, will be developed. Besides the technical optimisation, the energy efficiency, the cost-effectiveness, the robustness of process chains as well as the maturity regarding series production will be considered during the entire development process. The paper will present main features of this modelling approach including a proposal for a systematic and structured procedure of a multidimensional analysis.

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Keywords: cost-effectiveness; energy efficiency; hybrid components; maturity analysis; resource-efficient process chain; robustness

1. Introduction

Current studies predict a 40 to 50 % increase in energy, food and water consumption by 2030 [1]. Rising prices are a consequence of this increasing demand for resources; hence, their efficient management and use play an important role. Here, energy efficiency is a starting point. In 2007, the member states of the European Community agreed upon common energy efficiency guidelines that were renewed in 2011. The target of the directive is to achieve an increase in energy efficiency of approximately 20 % by 2020 [2].

The term “sustainability” is frequently mentioned in this context. In its original sense, “sustainable” refers to an effect that lasts for a long time. At present, sustainability is always understood as the principle of not consuming more than can regrow, regenerated or made available again in the future [3]. Sustainable development can be related to product optimisation, that is, an increase in the energy and resource efficiency of products, and process optimisation, that is, procedural reduction of energy and resource consumption, including intelligent controls. The presented modelling approach refers primarily to the process optimisation, but also the option to integrate product-related decisions is provided.

The Federal Cluster of Excellence “MERGE Technologies for Multifunctional Lightweight Structures”, which was constituted in November 2012, deals with the key issue of “Resource-efficient manufacturing technologies for resource-efficient components”. It is aimed at a sustainable fusion of technologies enabling savings of energy and material in production of lightweight structures. These structures, in turn, are characterised by a reduction in energy and material consumption and diminished CO2 emissions in mobile

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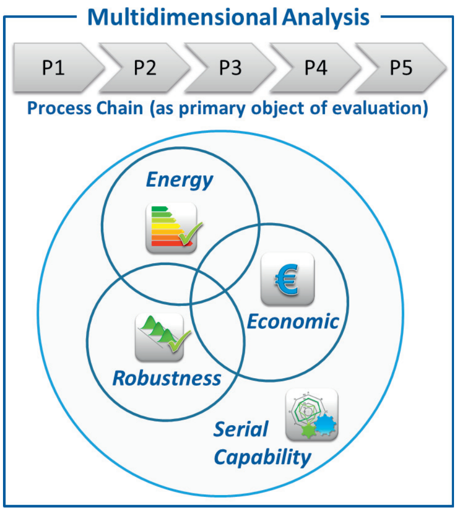

Fig. 1. Perspectives of multidimensional analysis

applications. The fusion of technologies describes the combination of basic technologies in textile, plastic and metal processing to manufacture hybrid components. A hybrid component is a net-shaped structure of multiple materials, which is produced without the use of hot or cold bonding or joining techniques. In doing so, the different materials will be connected only using forming or casting technology, where the connection can be form-fitting as well as firmly bonded [4].

To meet the demands of a sustainable production, the implementation of appropriate methods for the early and holistic assessment of process chains is required. In this context it is important that not only energy and costs are taken into account but also robustness and maturity for series production are considered (see Fig. 1).

An approach which enables the assessment from different subject-specific perspectives is very demanding. For this purpose, the following questions have to be answered:

- How can a model that is generally valid be formulated?
- How can the process or process chain to be assessed be represented, so as to guarantee that all information for evaluation is included?
- How can information be recorded to ensure clarity and avoid redundancy?

The aim of this paper is to outline an approach to meet these challenges.

2. Procedure model for process chain and product evaluation

An early and holistic assessment of process chains as well as an evaluation of alternative process chain designs can be a very complex task. This complexity arises from several facts: Process chains are usually a composition of various processes, consisting of different sub-processes and activities. Furthermore, impacts on the produced product(s) as well as a huge number of heterogeneous influencing factors have to be taken into account [5]. A further challenge will be the relevance of multiple target figures – here energy efficiency, cost-effectiveness, robustness and serial capability. Finally, a lot of necessary data can only be forecasted with considerable uncertainty.

To handle this complexity, a procedure model particularly focusing process chains for manufacturing hybrid components was conceptualized within MERGE. In the following, this procedure model will be briefly presented (for more details see [6, 7]).

The model systematically divides the evaluation task into subtasks. It is hierarchically structured into different levels with subtasks such as the assessment of highly relevant processes or the forecast of dominant influencing factors on the lower levels. Hence, it enables a structured evaluation of and decision-making about process chains. If decisions about process chains for manufacturing hybrid components are interrelated with component- or even product-related decisions, bundles of products/components and process chains have to be assessed by using the procedure model. For enabling such an evaluation, a process-related as well as a material object-related dimension is included in the procedure model.[1] The process-related dimension refers to the process chain as a whole, processes, sub-processes, and activities. Similarly, the material object-related dimension represents products, components, parts, equipment, etc.

The evaluation at each level as well as for each dimension consists of different steps connected by feed forward and feedback loops. The structure of these steps is derived from decision theory. Most of these steps refer to a single basic element of decision models: target figures and preference relations, alternatives, environmental factors, result functions, and their outcomes [8]. After defining the system boundaries that are relevant for evaluation, target figures, and preference relations have to be defined. Subsequently, (alternative) process chains are preselected, analysed, and modelled as well as environmental factors identified, analysed and forecasted. This serves as a basis for determining result functions. The result functions, in turn, are applied to calculate intermediate results as well as the outcome of the target figure. Afterwards, methods of multi-criteria decision-making can be used to derive decision values from the relevant target figure outcomes and, hence, to support decision-making. In addition, sensitivity analysis can be performed to account for uncertainty.

3. Input-Throughput-Output model

In order to design an optimal and balanced process chain, a detailed analysis of the relevant processes within a process chain is first required. For this purpose, different models and methods are available. Within the MERGE project, the Input-Throughput-Output model (ITO model) is used as the basis for the structural analysis and the process and process chain

[1] Note: Other dimensions, e.g. for life cycle phases, influencing factors or result functions can also be introduced [6].

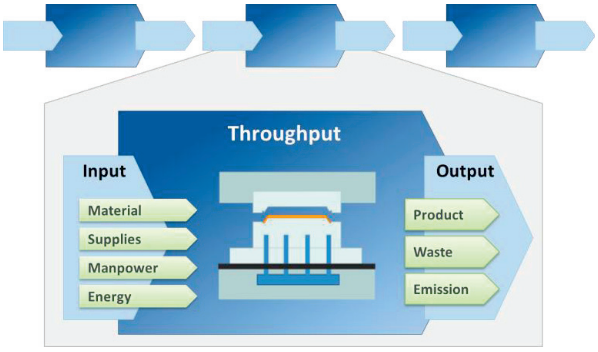

Fig. 2. Input-Throughput-Output model (ITO model)

modelling. The ITO model describes the flow of the input and the output of a process in dependence of each other and of the parameters of the process operation (throughput) [9].

In the ITO model (see Fig. 2), input can be defined as material or immaterial objects provided for a system to be transformed in its operation to achieve an output. The output is the resulting object of a transformation which can be the input for another transformation or the final output of a system. The throughput represents the transformation process, whereby not only technical aspects are considered but also the flow of resources. It focusses on the structure of the production system and its influencing factors [10].

Based on the information accumulated in the ITO model, the system function of each sub-process can be detected. By the derived suitable input-output relations, inferences concerning cause and effect can be drawn [11].

Referring to the procedure model, after defining the system boundaries it is necessary to build a fundamental framework for the multidimensional analysis. Its four perspectives (energy, economic, robustness, serial capability) seem to be very different to each other, at first. However, the comparison of the required process data has shown that there is a large overlap in the data basis, which is used for the respective analyses. The ITO model was chosen to acquire the relevant process data in terms of technical, ecological and economical relevant flows. Material and energy flows are more essential for the ecological and economic analysis, while production-related or performance-related flows are of particular interest for the robustness but also the economic evaluation. Yet, to some extent the observed flows are equally important for all perspectives (e.g. raw material and energy use) [12].

In general, the ITO model is a very flexible model, which can be adapted to different fields of application and system boundaries. Furthermore, all relevant input and output flows can be captured as well as their quantitative values. It is not only possible to analyse material resources, but also human resources and further data of the production system within one model. Accordingly, all perspectives of the multidimensional analysis can be included. Using one model for all perspectives also implies synergy effects. Therefore, for every perspective a larger process data base is available and no data redundancy occurs.

The generated framework (based on ITO models) within MERGE is the basis for the multidimensional analysis which combines all process data in one model. The interconnection of all perspectives favours an analysis with respect to sustainability. The following section explains in more detail which target variables are relevant for the multidimensional analysis.

4. Multidimensional analysis

The multidimensional analysis combines the individual analyses of process chains for lightweight products. Thereby, a multi-criteria decision making is supported and the relevant objectives for lightweight constructions are taken into account. The results of the multidimensional analysis can be used to assist the design engineer in its decision making process regarding the design of hybrid components and the related process chains. On the one hand, different product and process related alternatives can be compared. On the other hand, problems of the process chain can be identified by means of the analysis and subsequently improvements can be initiated.

4.1. Energy evaluation

Climate change, resource scarcity, and global political events have demanded a shift in thinking concerning the management and use of energy and raw materials for some time now. In this context, considerations focussing on energy efficiency are of essential importance. The term “efficiency” is a very general one that can be understood in different ways. The standard ISO 9000:2008 describes efficiency as the ratio of the achieved result and the resources used to achieve it [13]. In energy assessment, energy efficiency $\eta_{process}$ is calculated as the ratio of the ideal process energy $E_{ideal,\ process}$ and the real process energy $E_{real,\ process}$.

For energy efficiency assessment of hybrid structures, a method was generated based on the approaches to determine the holistic efficiency of processes and process chains according to Stiens and the cumulative energy demand [14]. The method elaborated represents a systematic approach to energy assessment of processes and process chains. The

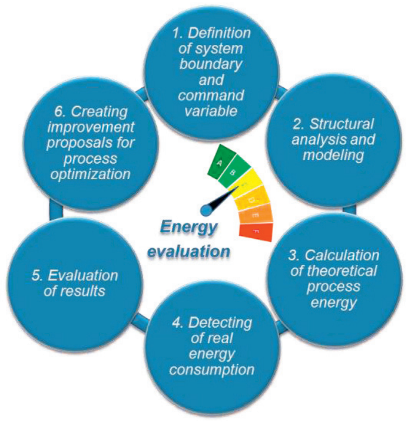

Fig. 3. Method for energy evaluation (MEE)

method is subdivided into six individual steps as shown in Fig. 3.

The first step defines the system boundary and the command variable of the considered process chain. The second step comprises the accomplishment of a structural analysis and modelling of the system. Here, the ITO model can be implemented. In the third step, the theoretical process energy is calculated. This calculation needs different parameters which can be difficult to determine. In the fourth step, the real energy consumption is measured. For this purpose, digital electricity measurement technique is used to determine the instantaneous power (P) over a specific time period. The results obtained in the third and fourth steps are subsequently evaluated in the fifth step. For the evaluation of the target variable, the cycle efficiency $\eta_{process}$ is calculated and is then ranked by category of efficiency. Then, the cycle efficiency is compared with the variable defined in the first step. Finally, improvement proposals for the process optimization based on energy balancing will be created in the last step.

4.2. Economic evaluation

To ensure resource-efficiency and sustainability of process chains for manufacturing hybrid components, also the cost-effectiveness of (alternative) process chains configurations has to be taken into account. Hence, an economic evaluation has to be performed as well. Within MERGE, this refers to the comparison of traditional process chain configurations for manufacturing hybrid components with the “new” ones based on technology fusion. For this purpose, the procedure model outlined in section 2 with its levels, dimensions, and steps can be used as a basis.

In a lot of situations, the costs of the process chain are an appropriate economic target figure for the assessment of process chains. Thus, they are focused here. Fig. 4 represents a calculation scheme for these costs which is based on the method of Overhead Percentage Calculation combined with a

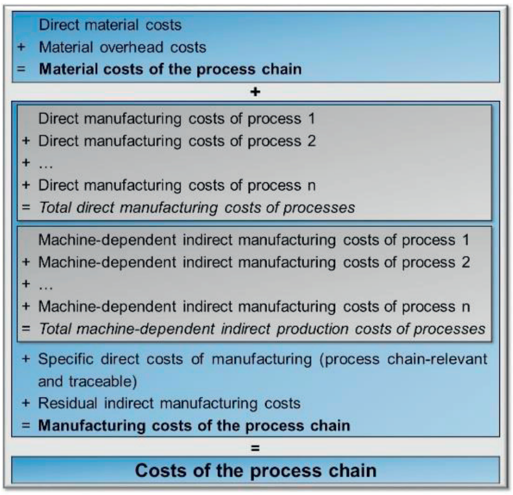

Fig. 4. Calculation scheme of costs of process chains [15]

Calculation of Machine-dependent Costs. The costs of the process chain comprise its manufacturing costs which in turn consist of the costs of all manufacturing processes within the determined system boundaries. To calculate the costs of these processes, for each process direct manufacturing costs as well as machine dependent costs and their items have to be determined. This can be accomplished at the process level – a subordinated level of the procedure model. At the process chain level, these costs are aggregated.. Furthermore, also material costs should be included at this level. Finally, specific direct costs of manufacturing or residual indirect manufacturing costs have to be taken into account, if they are relevant for decision-making. Hence, by means of calculating the costs of process chain configurations these can be compared and the most profitable one can be identified [7, 15]. Additionally, by systematically analysing the cost and their drivers saving potentials can be revealed. Especially for this purpose, the approach of Flow Cost Accounting, focusing on the costs of unintended outputs, can be applied alternatively (see [9, 16]).

However, since little available data exists, the identification and classification of relevant cost items and influencing factors of innovative processes, sub-processes and activities is a specific challenge. To handle this challenge, ITO models ([9], see also section 3) and methods of development-concurrent calculation [17] seem to be useful.

The fusion of manufacturing technologies also can have effects on hybrid component characteristics and, thus, may influence the product-usage, product-disposal, and/or recycling requirements and efforts. In that case, the design or improvement and the evaluation of process chains should have a long-term focus. In addition, the implementation of new or modified process chains usually requires investments. To include these long-term effects explicitly and in an appropriate manner, the short-term oriented cost calculation should be extended to a long-term (life cycle-oriented) one. Then, instead of period-related costs, the life cycle costs or even the life cycle profit should be chosen as target figure. They can be calculated by means of the net present value method and using cash flows that are derived from the costs [5, 6]. Concluding, a further potential way of extension shall be mentioned: It is possible to integrate economic, ecological and other target figures into sustainability ratios (see, e.g. [18]).

4.3. Robustness evaluation

The focus on sustainability often aims at savings, whether of materials, energy, weight, or $CO2$ emissions. The relation of robustness with sustainability is therefore initially difficult to detect. Nevertheless it is reflected in the original sense of the term “sustainability”. There, the product or process properties durability, reliability and a long service life were focused on.

The term “robustness” as applied to technical systems refers to the property to counter unforeseen changes without any adjustment to the original process settings. Within MERGE, a process is called robust, if it is controlled and capable at the same time [7]. Therefore, a process for

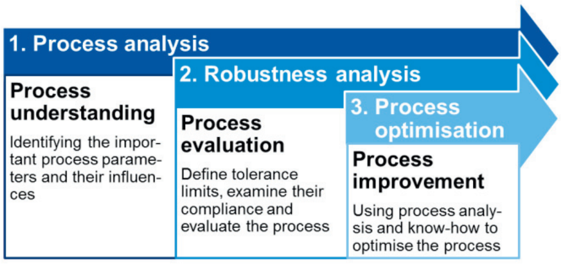

Fig. 5. Steps of robustness evaluation

manufacturing hybrid structures is robust, if it is repeatable and predictable as well as the achieved product quality meets the defined tolerance limits completely.

An increased product or process robustness can be achieved through the use of high-quality materials and advanced manufacturing. Therefore, new materials and alternative designs must be developed. An improvement in the manufacturing process can also contribute to sustainability. A robust design can result in a reduced consumption. This includes the reduction of material input for production and the reduction of waste produced during manufacturing. Nevertheless, the balance between robustness and energy efficiency as well as cost-effectiveness should not be disregarded. Possible additional costs in the phase of manufacturing should always be compared with the benefits and the savings generated in the phase of usage.

To perform a robustness evaluation for a manufacturing process three main steps need to be carried out (see Fig. 5). Similar to the other perspectives, the process analysis is performed, at first. Here, the ITO model is used to identify important process parameters as well as their effects and interactions (supported by DoE). Knowing the process or process chain in more detail, the actual robustness analysis can be carried out in the second step. As a result, the robustness indicator visualises in form of a traffic light system whether the process can be classified as robust or non-robust [7]. The robustness indicator itself consists of individually defined quality criteria with a predetermined weighting. The quality criteria in turn are calculated by a function of key figures. If a process has proven to be non-robust at the end of the second step, then a process optimisation can be carried out in the third step to improve the process.

4.4. Serial capability

The fundamental production methods that form the basis of the research in MERGE are characterised by mass-production compatibility, whereas the production of hybrid components (e.g. metal-plastic compounds) is limited to niche applications due to the high technical claim. To ensure that the developed technologies are suitable for resource-efficient series production of lightweight structures, it is necessary to identify risks and deficits as well as potentials during the entire origination process. To facilitate this, a methodology for the maturity analysis has been evolved [19]. Maturity is generally understood as the assessed development status of an object (technology, product or process) at a specific time by characteristic indicators in relation to phase-dependent requirements on them [20]. The determination of the maturity level provides a quantitative basis which increases the transparency of the development status. Thus, a goal-oriented approach is made possible and the operational decision-making process is supported.

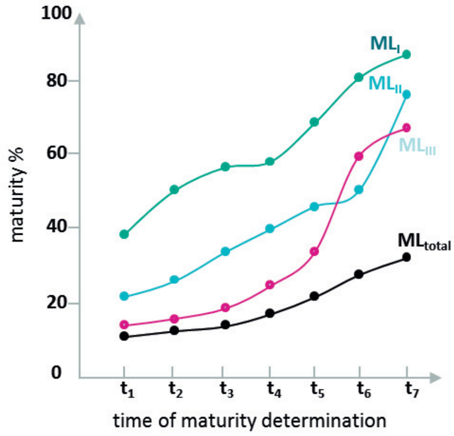

Fig. 6. Dynamic of maturity for each development phase

The developed methodology is based on the concept of the Technology and Manufacturing Readiness Levels (TRL and MRL) [21, 22] and consists of the three parts initialisation, conception and realisation which are described in more detail in [19]. In the initialization phase, the requirements for the technology regarding their application in series production need to be set. Here, in addition to technical, economic and operational also environmental target values are considered. These include amongst others the consumed raw materials and supplies required for production.

In contrast to the TRL and MRL which only provide a one-dimensional result, it was of particular importance to establish the possibility of a multidimensional evaluation. Therefore several target figures in different levels of consideration have to be defined.

To accomplish this, data and information will be analysed and qualified, so that quantitative rateable and machine-readable variables V_q ($q \in \{1,\dots, m\}$; $m \in \mathbb{N}$) can be formed and assigned to the corresponding development phases of a technology. Based on these variables as well as the results from the energetic, economic and robustness evaluations a certain amount of criteria C_{ij} for each development phase can be defined. After the determination of all criteria, the maturity for each development level ML_i and the overall maturity ML_{total} can be calculated by using the calculation rules in [7]. As a result, several target figures are available for the evaluation.

For identifying risks and deficits, the overall maturity ML_{total}, which only clarifies the achieved percentage of the objective, is insufficient. But the ML_i of each development phase is more meaningful. To ensure that important aspects are not neglected, for example, the progress in the different development phases, as shown in Fig. 6, can be evaluated.

The results of the phase-specific criteria can also be used for the evaluation. For example, Kiviat diagrams provide a possibility to highlight the thematic priorities which have been sufficiently taken into account and which have significant gaps.

5. Conclusions and Outlook

The paper presents an approach to meet the challenges of a multidimensional analysis of process chains for hybrid structures. At first, the procedure model which was conceptualised for an early and holistic process chain evaluation is briefly described. The procedure model enables a simultaneous examination of process- and material object-related dimensions as well as at different linked levels. Thus, process, product and equipment as well as different target figures can be considered. Afterwards, the Input-Throughput-Output (ITO) model is presented. It includes all information for each perspective of the multidimensional analysis. That means, the ITO model combines all process data within one model, so that synergy effects can be exploited and redundancies are avoided. In the last part of the paper, the various perspectives (energy, economic, robustness and serial capability) of the multidimensional analysis including the different target figures are described in more detail.

In further research activities the procedure model should be enhanced with the aim of realising additional synergy effects between the different perspectives of the multidimensional analysis and to create a consistent evaluation base. Besides, also target figures and evaluation methods for other ecological or even social aspects, referring to the dimensions of sustainability, can be taken into account [18]. In doing so, possible synergy effects should be focussed again. For example, a sophisticated integration of Life Cycle Assessment, which addresses ecological effects and Life Cycle Costing for determining the long-term economic success, may contribute generating a significant and consistent evaluation base [23].

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