

2.3 Ecological analysis of manufacturing systems focusing on the identification of variety-induced non value adding emissions

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Abstract

Today manufacturing companies need to raise their awareness about emissions (e.g. CO₂ equivalents) and their origins within a manufacturing system. The identification of origins of emissions becomes progressively difficult because of the customer and competition driven increase in product and process variants and the corresponding high level of complexity. Therefore, it is necessary to enhance the ecological transparency in manufacturing systems. This paper introduces an assessment methodology which increases the ecological transparency through the identification of variety-induced ecological effects. Furthermore, the developed methodology enables the user to detect starting points for an ecological optimization of a manufacturing system by the use of organizational measures. The effects of influencing variables are presented on the basis of a case study. The obtained results allow manufacturing companies to reveal and reduce variety-induced non value adding emissions.

Keywords:

Ecological analysis, manufacturing systems, CO₂ emissions, variety

1 INTRODUCTION

Nowadays the majority of the manufacturing companies are forced to frequently adapt their manufacturing systems in order to meet the current and future market demands. These demands result from global and long-term economic, social and ecological developments, so-called megatrends, which impact the manufacturing industry and its systems. The most significant trends concerning manufacturing are globalization, diversified customer demands, shorter product life cycles and the shortage of resources. [1]

Especially the diversified customer demands and the shortening of product life cycles lead to an enormous increase in product variety and complexity. The development of the variety in the machinery industry is illustrated in Figure 1.

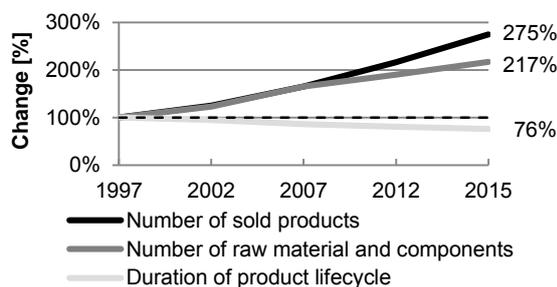


Figure 1: Percentage change of product and component variants and duration of product lifecycles. [2]

This development is one of the main reasons why processes in manufacturing systems are becoming more and more complex and economically as well as ecologically difficult to analyze. [3]

In regards to sustainable manufacturing these different developments have multiple effects and emphasize the

importance of the responsible and careful usage of natural resources in manufacturing systems. On the one hand, companies have the opportunity to reduce their cost by improving their eco-efficiency despite the growing energy and raw material prices. On the other hand, the manufacturing companies can make an effort to regain non-renewable resources in product and material cycles instead of disposing them and ultimately lose their inherent value. Furthermore companies can profit from new developed technologies while purchasing an eco-friendly and carbon neutral manufacturing process. [4] [5]

In this context the global warming effect remains one of the greatest challenges of mankind [4]. The major reason behind global warming is the steadily increasing emission of greenhouse gases e.g. carbon dioxide and methane. Figure 2 illustrates the different shares of global greenhouse gas emissions in CO₂ equivalents (CO₂ eq.) for the Industry and Energy Sector [6].

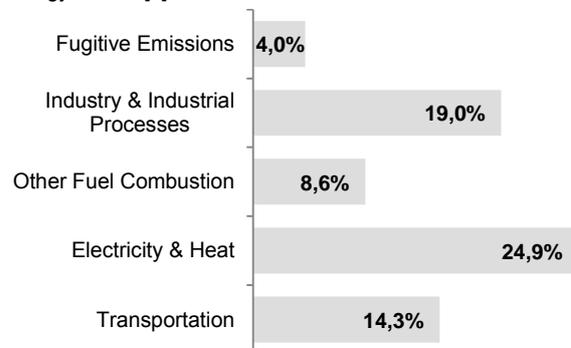


Figure 2: Share of Global Greenhouse Gas Emissions from the Industry and Energy Sector (Total: 31 Gt CO₂ eq.). [6]

The share of 19 % for “Industry & Industrial Processes” contains emissions which were caused by the current used methods, procedures, materials, production schedules and machinery, etc. to plan and control the manufacturing system. The presented numbers also indicate that the emissions in the area of manufacturing are still very high and therefore have a big potential for reduction.

To make use of the potential for reduction, detailed knowledge about the interdependent origins of emissions within manufacturing systems is needed. Since the knowledge about the internal and external drivers for emissions in manufacturing systems is a key element for the ecological target-oriented optimization, the transparency needs to be increased.

2 NEED FOR ECOLOGICAL TRANSPARENCY IN MANUFACTURING SYSTEMS

As previously stated, the customer demands and other global long-term developments result in a high number of product variants. The additional effort to maintain an efficient manufacturing system rises with each product variant and leads to more complex system since the complexity of these systems is directly related to the number of different product variants [7]. Within a specified system the term complexity is defined by the amount and variety of elements, their relationships and their temporal variability [8]. Based on studies, the costs for product and process complexity in manufacturing companies are up to 25 % of the total costs [9]. Additionally, 30 to 40 % of the complexity-caused costs can be linked to the manufacturing process itself [10] and the doubling of product variants can raise the costs of a product up to 30 % [11].

In terms of sustainable manufacturing not only economic but also environmental issues like emissions should be considered. The integration of environmental aspects like energy and material consumption into the planning and control of manufacturing systems offers high potentials [1], but detailed knowledge about drivers of emissions in a more and more complex environment is needed.

A specifically focused approach for the identification of variety-induced emissions in manufacturing systems does not exist so far, but several methods to assess environmental impacts of products and manufacturing processes are available, which can be adapted for the identification of variety-induced emissions in manufacturing systems.

The method Life Cycle Assessment (LCA) according to ISO 14040 and 14044 [12] has become widely-used and represents the actual state of science in the area of environmental assessment. A LCA evaluates the environmental impact of any system (e.g. product) by considering all inputs and outputs (energy and material). Normally the creation of a LCA is supported by special LCA software (e.g. SimaPro or GaBi) and the use of environmental databases (e.g. Ecolnvent). Usually a LCA assesses the environmental impact of a product life cycle (cradle to grave) [13]. In order to ecologically analyze a manufacturing system and to identify variety-induced emissions a product-related cradle-to-grave approach is not applicable. Nevertheless the ISO 14040 (goal and scope definition, inventory analysis, impact assessment, interpretation) represents a suitable framework, which has to be adapted to the specific requirements [14].

Environmental impacts can be measured in several categories (acidification potential, eutrophication potential, etc.) and evaluated by the use of different evaluation methods [15]. This paper will focus on the global warming potential, which is measured in CO₂ equivalents and has become quite popular over the last years [13]. Nevertheless, the presented methodology could also be adapted for the quantification of other environmental impact categories.

3 IDENTIFICATION OF VARIETY-INDUCED EMISSIONS

3.1 Scope of assessment and system understanding

The elements (e.g. processes or machines) of a manufacturing system can be generalized as process modules (Figure 3). Each process module is characterized by several input and output variables and aims to transform an input into a specific output. In a manufacturing system a number of process modules are coupled to a process chain. The coupling of process modules in more complex systems is identified through multiple input and output connections (e.g. parallel process chains or network structures).

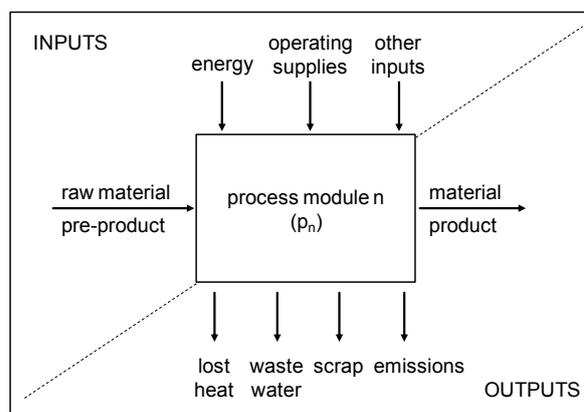


Figure 3: Generic process module [16]

The manufacturing system considered in this paper is a linear process chain, which mainly focuses on the ecological analysis of the inputs and outputs of the coupled process modules. Moreover the ecological effects of variety within the manufacturing system need to be identified in order to make the actual drivers of emissions visible.

In manufacturing systems production machinery is responsible for a major part of the emissions. The environmental impact of production machinery is mainly caused by electric energy consumption of the machine and the peripheral units. For instance, the electric energy consumption of an elementary flow of a milling process accounts for more than 95 % of the CO₂ emissions [14].

Besides the machinery other factory equipment e.g. lighting equipment or technical building equipment cause emissions as well. The latter ones do not significantly alternate with production volumes [14] and therefore are not taken into consideration in the assessment of emissions.

3.2 Assessment of variety-induced non-value adding emissions

For the assessment of variety-induced emissions of a manufacturing system only the output of process modules, which produce good parts, are considered value adding. Different output is assumed to be non-value adding and needs to be identified. Through this identification and separation of variety-induced value adding and non-value adding emissions the ecological evaluation and transparency of a manufacturing system can be improved.

Concerning a single process module within a manufacturing system the energy consumption - the main driver for CO₂ emissions - is characterized by different operating states [17]. This characteristic sequence of operating states (power profile) is schematically illustrated in Figure 4.

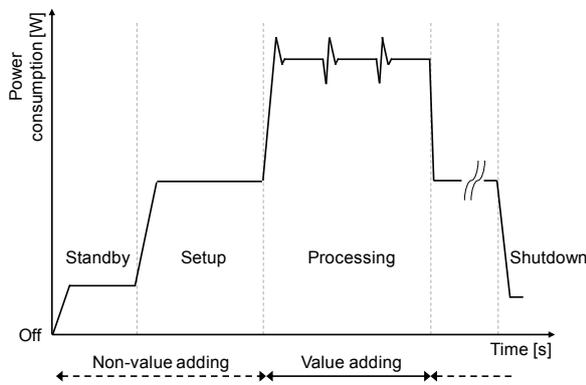


Figure 4: Power profile of manufacturing equipment with different operating states

The operating states differ from power consumption and duration. The duration of the operating state "Processing" for example is influenced by the product specification as well as the lot size, i.e. the number of equal products that are produced between two setup operations. As mentioned before, the operating states can be generally separated into value adding states (Processing) and non-value adding states (Setup, Standby, Shutdown). The ratio between value adding and non-value adding operating states is highly determined by lead times, setup times, lot sizes and the production program. This strong relation also applies for the number of product variants since the majority of these influencing variables are very closely related to the product variants.

Besides the operating states other non-value adding operations in manufacturing systems, e.g. production of process scrap and setup scrap, have to be taken into account as well. As described before, only the production of good parts is considered value adding. As a result of this, processing operations of a process module, which result in scrap later on, are considered non-value adding as well. The same applies to setup scrap, which increases with more frequent setup operations. An overview of value adding and non-value adding outputs of a process module is shown in Table 1.

Table 1 : Classification of value adding (va) and non-value adding (nva) outputs of process modules

Operating state	Output of process module (product)	Classification	
		va	nva
Standby	--		x
Setup	--		x
Processing	Product (good part)	x	
Processing	Process scrap		x
Processing	Setup scrap		x

In order to assess the environmental impact (CO₂ eq.) of a production program and the ecological effects of product variants, the emissions of each operating state (of each process module and product variant) have to be modeled by the use of LCA software and stored in databases as CO₂ data sets. For a discrete manufacturing process the functional unit of the environmental impact of the operating state "Processing" is one part, i.e. the amount of CO₂ equivalents caused by the processing of one specific product variant on one specific machine. The classification whether a processing operation is value adding or non-value adding depends on the output of the process module and is therefore considered later on. The functional unit of setup (as well as standby) operations is one second as the amount of emissions is related to the duration of the setup operation.

By the use of this CO₂ data sets and the classification (value adding vs. non-value adding) the ecological effects of a higher number of product variants (and therefore the production program) can be assessed and be made more transparent.

4 CASE STUDY RESULTS

4.1 Model

The manufacturing system considered in this paper consists of three generic process modules (Figure 3) which are arranged in a linear manner. The first process module is a turning machine which processes the cast parts for further machining. The two following process modules represent two sequenced milling operations on two different machines with separate characteristics e.g. specific inputs and outputs.

For purposes of the case study and especially for the evaluation of the described assessment methodology, the described manufacturing system is prototypically modeled in the discrete event simulation software Plant Simulation. On the one hand, the discrete event approach enables the consideration and detailed evaluation of different general aspects (e.g. production program) for the entire manufacturing system and its elements (e.g. machines and processed parts). On the other hand, it is also possible to factor the ecological traceability of the processed parts into the processing steps by assigning specific attributes (e.g. variant type and environmental impact) to these objects. The possibility of assigning specific attributes to certain objects and the findings of this basic model are going to be of particular interest for further examinations regarding ecological uncertainties and effects of more complex manufacturing systems (or supply chains) and its processes.

Figure 5 illustrates the schematic structure of the model as well as the three specific databases for each process module

and the general database for the entire manufacturing system. The manufacturing system's database includes the product program which mainly controls the number of products and variants as well as the size and sequence of the generated lots. Furthermore the information about the point of variant creation is stored in this database. Since the variety-induced emissions are of particular interest in this paper, the following two variety-related boundary conditions are imposed:

- The product program consists of maximum five products in maximum three different product variants.
- Only when the point of variant creation is reached the corresponding process generates the number of assigned variants according to the manufacturing database.

These two boundary conditions lead to a variety maximum of 15 different product variants. Within these boundaries the model enables the user to change the numbers of variants and the point of creation.

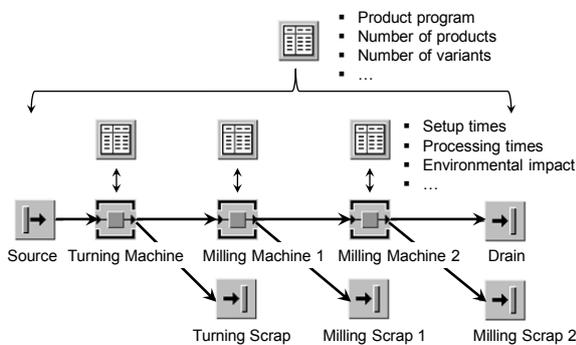


Figure 5 : Schematic figure of the manufacturing system in Plant Simulation with inputs, outputs and databases

The three specific databases for each process module combine manufacturing information (e.g. process time, setup time, scrap rates) as well as ecological information (e.g. CO₂ data sets). Concerning the ecological information the databases contain precise information about the caused emissions depending on the processing of one specific product variant on one specific machine. This ecological information can be changed by the three following influencing variables:

- Process scrap rate: This number represents a factor which influences the total number of scraped parts for the machinery.
- Setup scrap: This number represents the total amount of processed parts which are scraped during one setup operation of the machine.
- Setup time: This number represents a factor which increases or decreases the required time for setting up the machine for a new product variant.

The presented structure of the model and the discrete event approach makes it also possible to include even more influencing variables (e.g. machine failures), focus on further ecological aspects in combination with economic key performance indicators and to enlarge the scope of the

considered manufacturing system e.g. by adding more complex structure of process modules.

4.2 Results of the case study

The above presented model of the manufacturing system and its corresponding influencing variables are applied in a case example. The range of the examined values of the variables and their value in the initial situation are described in Table 2.

Table 2 : Values of influencing variables and initial situation

Name of Variables	Used Values of Variables	Initial Situation
Point of variant creation	1 – 2 – 3	2
Numbers of variants	5 – 10 – 15	10
Process scrap rate	0.5 – 1 – 2	1
Setup scrap rate	0 – 1 – 2	1
Setup time	0.5 – 1 – 2	1

The initial situation serves as basis for the comparison of the sensitivity of the influencing variables in different scenarios. During the sensitivity examination of this simulation model only one variable at a time was changed in order to evaluate the sensitivity of this variable for the ecological impact of the entire manufacturing system. In the following course of the analysis the ecological impact is distinguished in value-adding and non-value adding shares. The calculation of the different shares is based on the already described CO₂ data sets for different operating states which are collected and stored in the three specific databases of the process modules.

In order to make the absolute emissions comparable to the initial situation each scenario contains a total input of 1,500 parts. For each scenario the size of the lots is based on the number of variants, equally distributed and sequentially manufactured. In Figure 6 the ecological impact in kg CO₂ eq. of three different scenarios is presented.

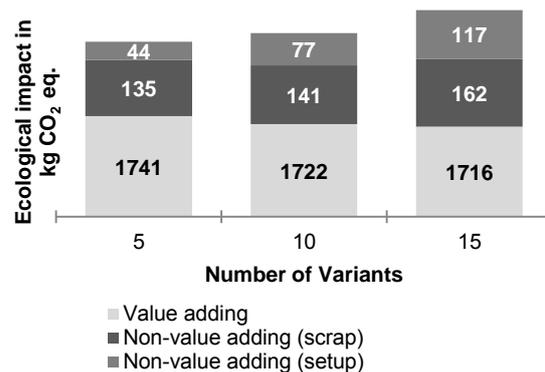


Figure 6 : Ecological impact in kg CO₂ eq. of three different scenarios of number of variants (5, 10 and 15)

The scenario in Figure 6 represents a variable configuration in which only the number of variants differs from the initial situation. The value-adding share remains approximately constant whereas the non-value adding emissions increase with a higher number of variants. In this particular case (initial number of variants: 10) the non-value adding emissions for five product variants decrease by 18 %. For 15 product

variants the change is approximately a 28 % increase in non-value adding emissions.

For the further assessment of the influencing variables two different values for each defined variable are considered in comparison to the initial situation. Figure 7 and Figure 8 show the result of the sensitivity analysis for the influencing variables process scrap rate, point of variant creation, setup scrap rate and setup time for a total of 1,500 input parts and 10 different product variants. During the change of one variable all other variables maintain their initially assigned value (Table 2).

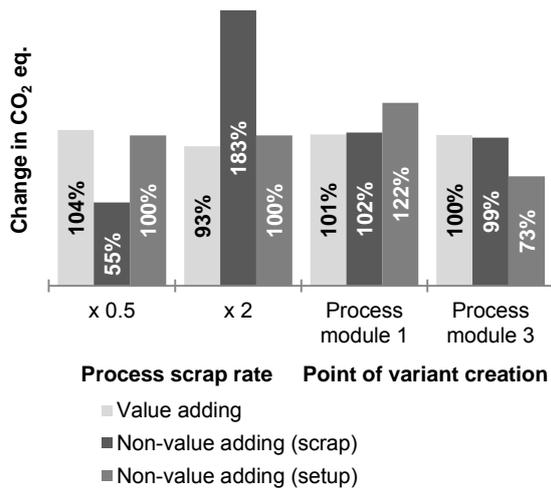


Figure 7 : Percentage change of ecological impact in CO₂ eq. for the variables process scrap rate and point of variant creation in comparison to the initial situation

The halving or doubling of the process scrap rate leads to a significant decrease (55 %) respectively an even more increase (183 %) of the non-value adding processing share. The most recognizable change in the differentiation of the point of variant creation is the variation of the non-value adding setup time. This effect can be explained by the fewer amount of setup operations in the upstream process modules.

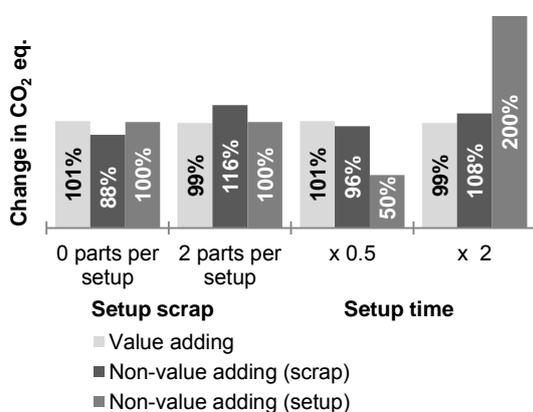


Figure 8 : Percentage change of ecological impact in CO₂ eq. for the variables setup scrap rate and setup time in comparison to the initial situation

In Figure 8 the results of the examination of the final two influencing variables are shown. The ecological effect of the setup scrap rate is based on the same origin (scrap) but slightly weaker than the process scrap rate in Figure 7. The drastic change of the ecological impact caused by the alternation of setup time can be explained by the direct impact of the setup time factor in all process modules and for each single setup operation.

5 CONCLUSION AND OUTLOOK

This paper presented an assessment methodology which increases the ecological transparency in a manufacturing system. The methodology focuses on the identification and quantification of variety-induced ecological effects. The effects of five different variables (point of variant creation, numbers of variants, process scrap rate, setup scrap rate and setup time) are examined and distinguished in value and non-value adding emissions. Especially the non-value adding emissions are highly affected by the variety-related variables (e.g. number of product variants).

The methodological approach was prototypically implemented in a discrete event simulation model. The implementation allows the examination of different scenarios through the alternation of influencing variables. Furthermore it is possible to trace single object (products) and measure their ecological contribution to single process modules as well as to the entire manufacturing system. The sensitivity of the influencing variables and their ecological contributions and effects were also verified.

As part of further research the presented model and its structure should be examined in a more complex situation. This includes the extension of the system boundaries and complexity (e.g. number of processes, interactions and uncertainties of process modules and number and variety of products) of the manufacturing system itself. Moreover further influencing variables e.g. machines failures, lot sizing and production scheduling could be considered as well. In addition to the presented sensitivity analysis detailed analysis of interdependencies between influencing variables have to be carried out in further research activities.

The further research topics also include the combined ecological and economic assessment of variety-induced effects in manufacturing systems as well as the deduction of courses of action and their evaluation in the context of traditional goals of production planning and control.

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