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Integrated analysis of energy, material and time flows in manufacturing systems

Sebastian Thiede[1,3]*, Wen Li[2,3], Sami Kara[2,3], Christoph Herrmann[1,3]

[1]*Chair of Sustainable Manufacturing and Life Cycle Engineering, Institute of Machine Tools and Production Technology (IWF), Technische Universität Braunschweig, Germany*

[2]*Sustainable Manufacturing & Life Cycle Engineering Research Group, School of Mechanical & Manufacturing Engineering, The University of New South Wales, Sydney, NSW 2052 Australia*

[3]*Joint German-Australian Research Group on Sustainable Manufacturing and Life Cycle Engineering*

*Corresponding author. Tel.: +49-531-391-7152; fax: +49-531-391-5842. E-mail address: s.thiede@tu-bs.de

Abstract

Environmental objectives (e.g. energy and resource demand, emissions, waste) become increasingly relevant for manufacturing companies in addition to traditional economic objectives (e.g. throughput time, output). Currently, different methods and tools are available to address those objectives individually, such as value stream mapping (economic), material and energy flow analysis/MEFA as well as Life Cycle Assessment/LCA (environmental). However, there is a lack on approaches that bring together benefits of those tools and allow simultaneous consideration of all objectives. Against this background, a methodology is developed to analyses the energy, material and time flows of manufacturing systems in an integrated manner. The proposed method is exemplary applied to the case of an Australian manufacturing company.

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Keywords: Energy and Material Flow Analysis; Value Stream Mapping; Manufacturing Systems; Integrated Approach

1. Introduction

The economic as well as environmental performance of manufacturing companies is strongly determined by material, energy and time related variables. Manufacturing “transforms raw and auxiliary material inputs into products and wastes using energy inputs” [1], so material and energy consumption are inevitable production factors that have direct cost and environmental impact. In the manufacturing sector, material costs are typically the highest cost portion with a share of about 30-55% on total costs depending on the industrial sector. Energy costs are in a range of 0.5-30% [2]. Besides costs (and quality), time is the third main objective dimension of manufacturing systems [3]. It is reflected in different key performance indicators such as throughput/lead time, output rate or the utilization of machines and labor.

Figure 1 shows the strong interactions between material, energy and time in relation to the economic and environmental impact of a manufacturing company. The connection of energy and time is given per definition since energy demand (e.g. electrical energy in kWh) is a function of energy demand rate (e.g. electrical power in kW) and time. Materials differ regarding the necessary energy for their production and their properties also influence the energy demand of later production steps. Material and time are related through trade-offs between process selection and parameters, e.g. through connected material efficiencies (processes differ in time and material efficiency, e.g. separating vs. shaping) and resulting quality.

While those interdependencies exist, there are no appropriate methods and tools available that allow an assessment of material, energy and time in an integrative manner. Against this background, this paper presents an

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approach that builds a bridge between pure LCA oriented energy and material flow assessment and the consideration of time as critical manufacturing objective.

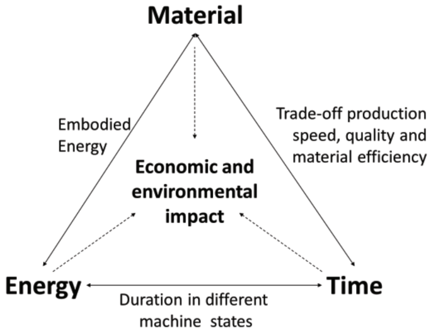

Figure 1: Relations between material, energy and time as production factors

2. Theoretical Background

In this section, necessary background on existing methods and tools for material, energy and time related analysis of manufacturing systems – material and energy flow analysis (MEFA), life cycle assessment (LCA) and (extended) value stream mapping (VSM) - is given.

2.1. Material and energy flow analysis (MEFA)

Material flow analysis (MFA) and – through addition of energy flows – material and energy flow analysis (MEFA) is a comprehensive and systematic method for quantifying flows and inventories/stocks within defined space and time boundaries [4]. It focuses input/output relations of processes and systems and is based on the law of the conservation of matter (input and outputs of a process or system need to be in balance). The groundwork for an application in economics was laid by Leontief [5] who developed input-output tables as a method to quantify interrelationships within economic sectors or single production systems. MEFA specifies material and energy flows and stocks in standardized and defined terms and presents the results in a meaningful and reproducible manner. For handling of huge amounts of data and better visualization (e.g. Sankey diagram), several software tools are available to facilitate the work, e. g. Umberto from IFU Hamburg GmbH [4].

2.2. Life Cycle Assessment (LCA)

Life cycle assessment is the most detailed and thorough method available to evaluate the environmental impacts a certain product (goods or services) induces over its entire life from resource extraction to disposal or recycling. As this, it is highly integrated and can be used as part of general product life cycle management [6][7]. Common goals of an LCA are the comparison between products, the comparison between different life cycles for one product and the identification of improvement opportunities over the life of the specific product [8]. Through ISO Norm 14040 LCA is well standardized into four different steps (1) goal and scope definition (e.g. definition of functional unit), (2) inventory analysis (quantifying material and energy flows over life cycle), (3) impact assessment (assigning material and energy flows to defined impact categories, e.g. global warming potential, land use, resource depletion) and (4) interpretation [9]. LCA is well established and used in research and industrial practices. For supporting application dedicated software tools for the LCA studies (Umberto, GaBi, SimaPro, Open LCA) and supporting LCI/LCIA databases (e.g. GaBi, EcoInvent) are already available. One strength of the LCA methodology is the holistic perspective over the life cycle thus preventing wrong conclusions due to missing aspects. However, three major challenges for application are typically mentioned. First, LCAs are very data intensive and missing and/or estimated data can limit the accuracy as well as leading to high uncertainties within the results of the study. Second, even within the standardized LCA method, a study is still based on several methodological preferences like allocations or time limits [10]. Thirdly, the interpretation with different impact categories is not trivial. While LCA can provide transparency, the decision (e.g. is climate change more important than land use?) needs to be done by the user. Single indicators (e.g. Eco Indicator 99) combining different impact categories or just using selected impact categories (e.g. carbon foot printing as method just focusing on the Global Warming Potential) are used but also strongly discussed in literature.

2.3. Value Stream Mapping

Value stream mapping (VSM) can be defined as a team-based approach of analyzing a process from its beginning to end by splitting it up into individual value-adding and non-value-adding steps in the viewpoint of the customer. In a second step, a plan to improve the process is developed by removing the non-value-adding elements, i. e. waste, and straightening the value flow [11]. It is thus closely related to the five principles of lean as it starts with value, focuses on the value stream itself, and facilitates the transfer towards flow, pull, and in the end, perfection [12].

VSM is an easy applicable paper-and-pencil approach; all gathered information is combined in a drawing – the value stream map - using standardized symbols [12]. Besides the material and information flows with their performance characteristics, a time line is commonly added on the bottom of the map, indicating the total lead time and the total value-added time of the process [12][13]. Associated benefits are a thorough understanding of the value generation and the links between the process steps by all participating employees, an improved decision-making process, the development of a common language and potentially quick improvements [11].

As a major drawback, VSM only provides a static picture of a limited product range. It is therefore usually not able to handle multiple products or general dynamics and uncertainties occurring in industrial practice which hinders continuous application. Further developments towards multi-product VSM and combination with simulation techniques aim to overcome those issues. Since VSM in its original form focuses on time and inventory as major key performance indicators, other extensions (e.g. energy value stream mapping) include energy [14][15] and partly material flows [16] [17].

2.4. Discussion and research demand

Table 1 gives an overview and relative comparison of the methods discussed above. It is based on criteria selected with regard to the applicability in manufacturing companies. Material and energy flow analysis can be well applied in production through its clear methodology, supporting IT tools and transparent decision support, e.g. through Sankey visualization. LCA has an extensive perspective over the whole life cycle which increases data requirements and efforts as well as expertise (e.g. allocation issues) for modeling. Both methods clearly focus on material and energy. In contrast to that, value stream mapping originally focuses time and inventory related issues and is of course well applicable in production. VSM is relatively easy to apply and provides standardized visualization. Some methodological questions (e.g. multi-product environments), energy and specifically material related considerations as well as IT support for continuous applicability are challenges. Altogether, there is a need for a seamless integration of all three methods while balancing benefits and drawbacks. It should support an intuitive modeling and visualization within appropriate IT tools and should also allow life cycle oriented analyses.

Table 1: Relative comparison of methods.

Legend: [x]: considered [+/o/-] better/worse criterion fulfillment than the other methods (relative comparison)	**M(E)FA**	**LCA**	**(Advanced) VSM**
Material	X	X	(X)
Energy	(X)	X	(X)
Time			X
Data requirements	o	-	o
Modelling effort and expertise	o	-	+
Clarity and ease of visualization	+	o	o
IT support for continuous applicability	+	+	-
Production context	+	o	+
Life cycle perspective	-	+	-

3. Methodology

Figure 2 shows the conceptual framework of the method. The general procedure is related to the four phases as defined in ISO 14040 for LCA. As known from MEFA, for modeling a standardized petri-net based logic with places and transitions is used. Transitions calculate inputs and outputs according to certain rules, which are usually inserted as user-defined functions. Besides manufacturing processes also technical building services (TBS), e.g. compressed air generation, heating/cooling etc. are considered. For practical implementation, the software Umberto was used which also eases environmental impact assessment through integration of Ecoinvent as LCI database.

Similar to LCA procedure within the goal and scope definition, the system boundaries and terms of space and time as well as a functional unit need to be defined.

The core idea of this method - the consistent integration of extended material, energy and time studies within one modeling framework – is embedded within the inventory analysis and modelling phase.

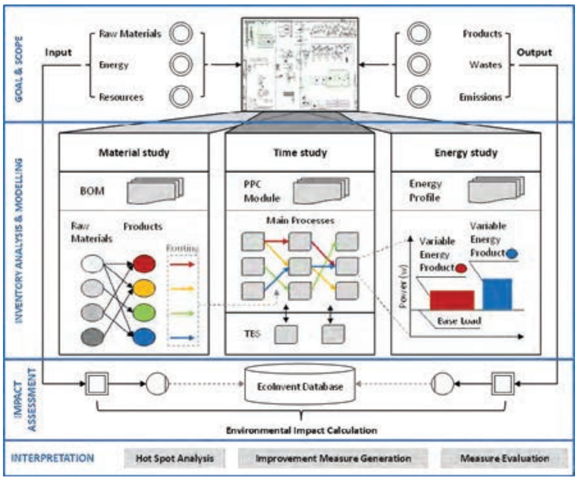

Figure 2: Conceptual Framework.

The *material study* is done as usual in MEFA based on the bill of materials (BOM) of all products which are in the scope of the analysis.

For the *time study* significant extensions had to be done since - as indicated above - time is typically not really considered in MEFA and LCA. For example, Umberto as a typical software in this field does not provide support features for time related studies like value stream mapping in particular. Thus, VSM functionality can only be included by adapting the available flow framework in a meaningful manner. Within a production planning and control (PPC) module for each product the related individual manufacturing process chain with involved machines and relevant machine parameters are integrated and aggregated to machine related data for the period of investigation. Sankey diagrams can be used well to visualize the findings and in line with material and energy studies. For example, regarding the machine characteristics it is possible to show the utilization over time in form of Sankey arrows as shown in Figure 3.

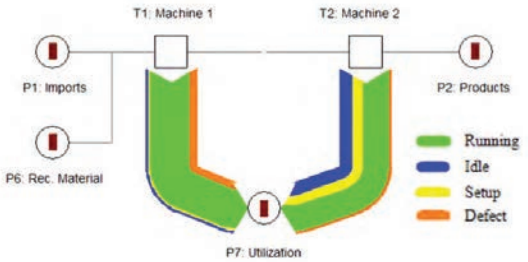

Figure 3: Sankey visualization of machine states and utilization.

This is done by using parameters like cycle time, changeover time, and down times in combination with the production data and general statistics like overall working hours and breaks to dynamically compute the time shares for production, changeover, maintenance, and standing idle. These shares are modeled as time inflows and outflows so that they can be selected in the visualization. Other time related results can be computed and visualized similarly. Another good example is the display of the increasing lead time as shown in Figure 4. Similar to material and energy flows, lead time is depicted as Sankey diagram. In every process step, the average cycle time and waiting time for a part is added on top of the lead time of the foregoing step. Thus, the diagram shows directly how long a part would take from any step in the process until it reaches the end. While the cycle time is taken from the collected data, the waiting time is calculated from the inventory data, the daily running time and the cycle time (assuming a first in, first out inventory organization, FIFO). By showing both components in different colors, high inventories and bad flow balancing can be spotted with one sight.

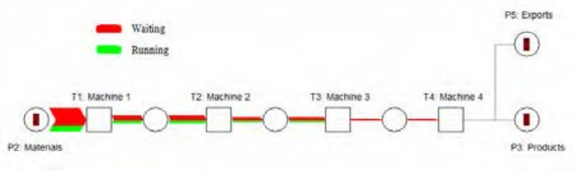

Figure 4: Sankey visualization of lead times.

For the *energy study*, it shall be possible to consider different energy demand levels – e.g. for machine processing and idling – since this potentially bears significant saving potentials. However, Umberto's basic input-output transition specification allows only the use of energy intensities. Therewith energy flows are determined through coefficients, thereby locking in the ratio between input and output. If this linear relation does not represent the real setting sufficiently, user functions can be used to fill the gap. To distinguish between idle and processing energy demands, the combination with time study variables is beneficial. As an easy example, a global parameter specifying the total time the factory is running can be defined and multiplied with machine specific parameters for utilization and energy demand rate for processing/idling. Thus, depending on all time related aspects as described above also energy demand can be calculated significantly more correct and value as well as non-value adding demands can be identified. In a similar manner, more complicated functions or subnets can be employed to determine the demand in more detail.

The impact assessment as the third phase of the methodology is carried out through a company specific cost model (economic) and the connection to Ecoinvent database for LCI data on upstream processes for material and energy generation (environmental). Based on LCI data, the environmental impact can be (as usual) calculated within different impact categories. Finally, within the phase interpretation hot spots in terms of material, energy and time demand are identified and potential measures for improvement are derived and evaluated.

4. Case Study

The case study has been conducted in an Australian company that produces break blocks and pads for trains and other railway vehicles. In total, every year about 100 different parts are being produced and exported, as the different breaking systems used in railway transportation throughout the world require different shapes, thicknesses and material compositions. The different raw materials are weighed and mixed before being loosely pressed into rectangular block called "biscuit" (biscuiting). Next, the biscuits are molded, i. e. they are heated up and pressed into shape. In this step, a steel plate is added at the back of the part too, which is used to fasten the break block to the train later on. Many of these steel back plates are also manufactured in-house in a separate area. Finally, the molded products are baked in a curing oven to reach the special material composition necessary for their intended breaking function. The above described production processes are supported by several technical building services. Among these are for example four different dust collectors, which are connected to most machines via a ramified pipe network to clean the air and recycle lost material. The dust collectors as well as several other machines also need compressed air to function properly, so that an air compressor and the corresponding pipes have been installed in the factory as well. Finally, the heaters need a cooling system to function safely. An overview of processes and TBS is given in Table 2.

Table 2: Results of inventory analysis in relative values (100% is maximum per KPI)

KPI / **processes**	**Time** takt time [sec]	**Material** material loss [tons]	**Energy** energy demand [MWh]	average (equal weighting)
Weigh up	50%	3%	11%	21%
Mixing	19%	2%	19%	13%
Biscuiting	63%	100%	30%	64%
Back plate	25%	73%	12%	37%
Moulding	50%	95%	100%	82%
Curing	100%	0%	90%	63%
TBS (sum)	0%	0%	75%	25%

4.1. Goal and scope definition

The main goal of the analysis is the investigation of material and energy efficiency potentials throughout the factory while avoiding any consequences on production performance, e.g. delivery capacity. Regarding the scope, the study is focusing the operations inside the factory except for the environmental study, in which the effects of the upstream raw material production incorporated. The analysis focuses on data of one year which means over 100 different products made out of about 60 different raw materials. The functional unit has generally been chosen to 1 kg of processed friction material, as it is the only constant measure throughout the process – thus, most allocations and evaluations took place on a mass basis.

4.2. Inventory Analysis

For inventory analysis the necessary detail data for all products and related processes was collected and processed. For each dimension a best representing key performance indicator was identified and calculated for the defined period of investigation: takt time (dimension time), material loss (dimension material), and energy demand (dimension energy). The results are shown in Table 2, for reasons of confidentiality just in relative values.

The relevance of machines differs significantly based on the KPI used. Priorities for further actions can be clearly identified from both single (per KPI and/or process) or integrated perspective. As an example Figure 5 shows the Sankey diagrams within the factory layout for material (A), energy (B) and lead time (C). Therewith all dimensions can be depicted within one consistent graphical framework and support decisions through full transparency on factory level. The diagrams also underline the significant differences of flows which might also lead to different priorities for further actions.

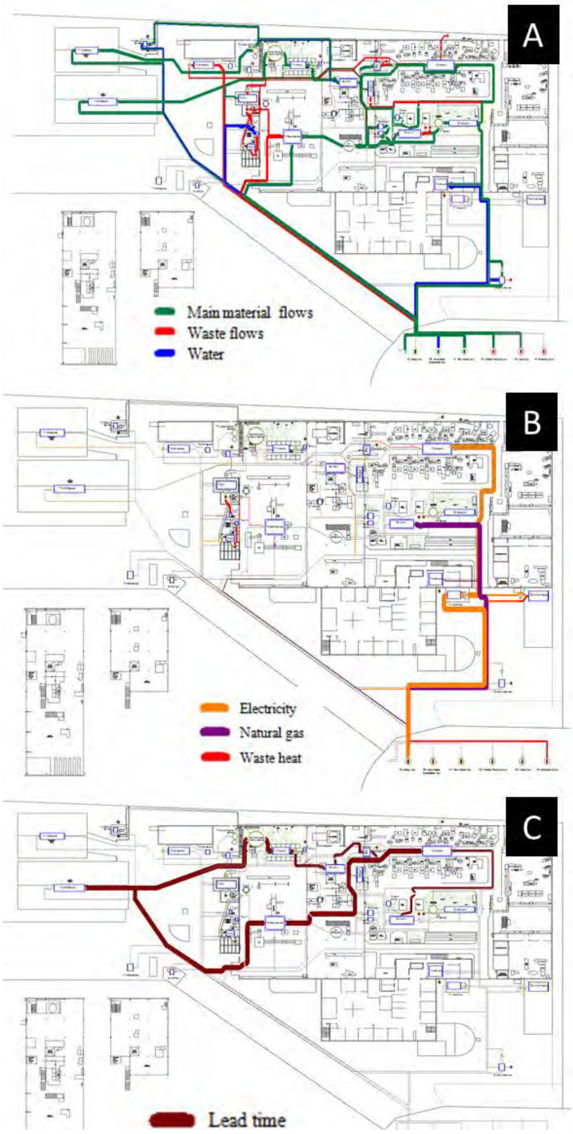

Figure 5: Sankey visualization of material, energy and time flows.

4.3. Impact Assessment

For assessing the current and potential future states of the manufacturing system four KPI – energy per part, raw material per part, global warming potential (GWP) per part, longest lead time - were selected and calculated based on the material, energy and time network in Umberto. Climate change with GWP as characterization factor was selected as environmental impact category in this case. Figure 6 shows the relative distribution of GWP. Energy demand is the main driver with a share of about 54% followed by material with about 42%.

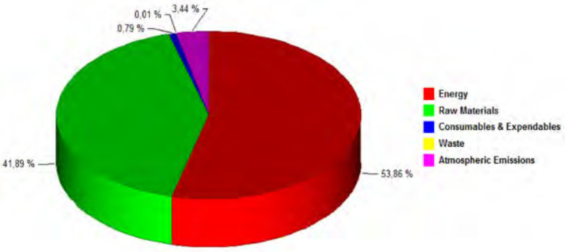

Figure 6: Composition of GWP.

4.4. Interpretation

Table 2 already gave an overview regarding the most relevant processes and a good indication regarding most beneficial directions of improvement. Based on those prioritized fields of action, Table 3 shows selected measures that have been derived through workshops with (internal and external) experts and further technical analyses.

Table 3: Scenario descriptions

Scenario 1
- Boiler insulation - Back plate inventory reduction - Recycling rate increase - Automatic shutdowns air compressor - Reduced water consumption for irrigation
Scenario 2
- Improved settings air conditioning - Automatic switch-off of facility lighting - Improved molding press insulation during idle mode - Constructional measures to reduce dust creation
Scenario 3
- Automatic shutdowns dust collectors - Waste reduction stirrup production - Improved planning and forecasting

They are grouped into three different scenarios depending on saving potentials and applicability whereas those scenarios build up on each other (e.g. scenario 3 includes measures of both other scenarios already). All measures were virtually implemented in the Umberto model and the resulting KPI were calculated. Figure 7 shows the relative improvements with the current state given as 100% value. It can be stated that material and energy demand could be significantly reduced. The lead time was not compromised but could be even decreased as well.

5. Summary and Outlook

Material, energy and time are all strongly interacting factors that influence the economic and environmental performance of manufacturing companies. For different purposes and stakeholders, methods and tools are available to address those objectives individually, e. g. value stream mapping (economic), material and energy flow analysis as well as Life Cycle Assessment (environmental). To enable a simultaneous and seamless consideration, a consistent modelling framework was presented in the paper. Based on established MEFA and LCA procedures, extensions on time studies and more realistic energy studies were done. Therewith, significant progress could be made and all relations between material, energy and time as depicted in Figure 1 can be taken into account. This fosters a systematic improvement focusing on most relevant aspects and also avoids environmental improvements at the expense of economic drawbacks. Benefits and drawbacks of MEFA, LCA and VSM could be balanced within one approach. Without a question, as for the other methods data availability is still an issue. Due to utilization of standard IT tools with interfaces to LCI databases (external or internal process libraries) and potentially companies' IT systems (enterprise resource planning/ERP, manufacturing execution system/MES – streaming of most recent data) this issue can be improved in the future. For considering dynamic interactions and stochastic nature of manufacturing systems, a combination with material and energy flow oriented simulation approaches [18] is promising.

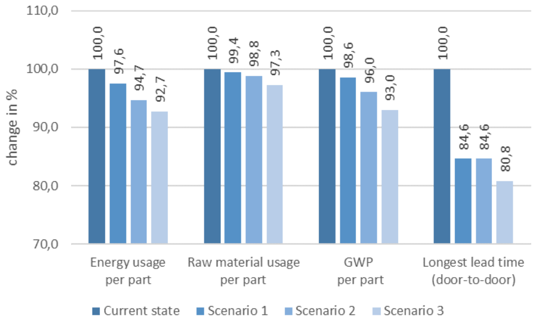

Figure 7: Case study results for improvement scenarios.

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