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Procedia CIRP 48 (2016) 200 – 205

www.elsevier.com/locate/procedia

23rd CIRP Conference on Life Cycle Engineering

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

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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.

Peer-review under responsibility of the scientific committee of the 23rd CIRP Conference on Life Cycle Engineering

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

Peer-review under responsibility of the scientific committee of the 23rd CIRP Conference on Life Cycle Engineering
doi:10.1016/j.procir.2016.03.248

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

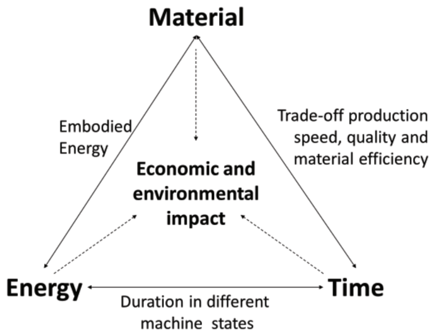

Figure 1: Relations between material, energy and time as production factors

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