

## Abstract: Sustainable manufacturing through material efficiency management

Material efficiency contributes to reduced industrial waste volumes, reduced extraction and consumption of virgin raw materials, increased waste segregation, decreased energy demand, and reduced carbon emissions, thereby generally mitigating the environmental impact of the manufacturing industry. However, the area of material efficiency in manufacturing is under-researched, and related knowledge is limited particularly at individual manufacturing sites and lower levels. These levels are crucial to achieve improved material efficiency, as a great amount of material is consumed and waste flows are generated on manufacturing shop floors. There are still gaps in both literature and industrial practice regarding material efficiency in manufacturing, where materials are consumed to make products and great volumes of waste are generated simultaneously.

The research objective of this dissertation is to contribute to existing knowledge on management and improvement of material efficiency in manufacturing. To achieve this objective, three research questions were formulated to investigate material efficiency barriers, material efficiency tools and strategies, and material efficiency performance measurement. The results are supported by four structured and extensive literature reviews and also by five empirical case studies conducted at a total of fourteen Swedish global manufacturing companies. These empirical studies entail observations, interviews, waste stream mapping, waste sorting analyses, environmental report reviews, and company walkthroughs.

A number of material efficiency barriers in manufacturing were identified, categorized and clustered to facilitate an understanding of material efficiency to effectively mitigate the barriers. The clustered barriers cited most often in the literature are budgetary, information, technology, management, vision and culture, uncertainty, engineering, and employees. In the empirical studies, vision and culture, technology, and uncertainty were replaced by communication. Most of the material efficiency barriers identified appear to be internal and are dependent on the manufacturing company's characteristics.

A number of tools and strategies were identified and some were used to assess, manage, and improve material efficiency in the manufacturing companies studied. Empirical studies indicated that certain criteria are necessary to select and use operational tools. These criteria include being hands-on, time efficient, based on lean principles, easy to use and learn, visualized, promoting engagement, and being connected to a predetermined goal. These criteria are essential for mutual understanding, intra-organizational communication, performance improvement, and becoming a learning organization.

A model for a material efficiency performance measurement system was proposed that included the most common material efficiency-related key performance indicators from literature and empirical findings. The model divides material and waste flows into four main categories: productive input materials, auxiliary input materials, products, and residual output materials. The four main categories should be measured equally to realize material efficiency performance improvements in an operation.

This research contributes to the research area of material efficiency and sheds light on different inter-connected aspects, which affect one another and contribute to assess, manage and improve material efficiency in a manufacturing context. The studied conducted and the results are presented in five appended papers.