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A Framework for Material Flow Assessment in Manufacturing

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Abstract Improving material efficiency is widely accepted as one of the key challenges facing manufactures in the future. The increasing consumption of materials, in addition to depleting finite resources, is having detrimental impacts on the environment associated with their extraction, processing and disposal. It is clear that radical improvements in material efficiency are required to avoid further environmental damage and maintain a healthy manufacturing sector. Current material flow analysis and resource management methodologies are used to improve the efficiency of material consumption in economic terms, and environmental assessment methodologies are used to determine environmental impacts, a methodology to effectively assess material efficiency according to both criteria is currently not available. This paper highlights the benefits of considering a broader range of parameters in material flow modelling to support advances in increased material efficiency and proposes a 'material flow assessment' framework that allows greater flexibility in the exploration of material efficiency improvements within manufacturing systems.

1. Introduction

Resource Efficient Manufacturing (REM) is a process that has traditionally been driven by market competition as manufacturers seek to reduce their production costs to maximise profits and increase sales [1]. This generally involved improving efficiencies in labour, materials and energy, whilst increasing output and minimising waste. However, whilst REM has its roots in these traditional economic driven markets, more recently it has been adopted as a sustainability strategy, where the main driver has been resource conservation, 'doing more with less'. With sustainability as the key driver for REM, a greater focus is placed on the use of materials, water and energy, while labour and capital costs are usually secondary considerations. Therefore, whilst many of the past strategies, methods and tools for REM, such as 'Lean Manufacturing and Process Optimization' are still relevant and useful, they are often inadequate for the significant improvements required to meet the sustainable manufacturing challenges of the future.

Manufacturing efficiency driven by cost has largely focused on the key resources with the greatest financial impact. For most manufactures these are materials,

labour, overheads and distribution. Often one particular resource would, for a period of time, be the primary focus of REM initiatives, usually driven by external pressures such as a trend towards offshoring, energy spikes, shortages, inflation, or more recently environmental levies, legislation and waste management. However, with materials on average accounting for around 50% of production cost (as illustrated in Figure 1) [2], one might assume that this particular resource would remain a high priority for most manufacturers.

Scarcity of resources has been identified by the European Factories of the Future Research Association as one of the seven critical trends for manufacturers [3]. The degree of scarcity for a particular resource may be both regionally and seasonally specific, such as with water, or largely 'global demand' driven such as is the case with energy. This view as to which materials are critical or scarce is largely a subjective and dynamic one depending on the industry, country and demand at a given time [4]. In 2010, a list of 14 critical materials were drawn up by the EU, and referred to as the EU-14 [5]. However, this list is as much geopolitically influenced, as it is reflective of a particular materials availability and consumption. One of the problems with classifying materials as a separate resource is that material availability can be intrinsically linked with the other resources such as energy and water. Likewise, energy is mainly generated from materials such as oil or bio-mass which have material applications such as plastics, chemicals and wood. Finite and renewable are terms used to classify material types, but in many respects all materials are finite in terms of an annual supply. In this respect, whilst some materials may be strategically important to economic growth or new technologies, at the primary level the principle of 'doing more with less' should be the main strategic goal of REM across all material types, but with an emphasis on achieving the greatest overall environmental benefit.

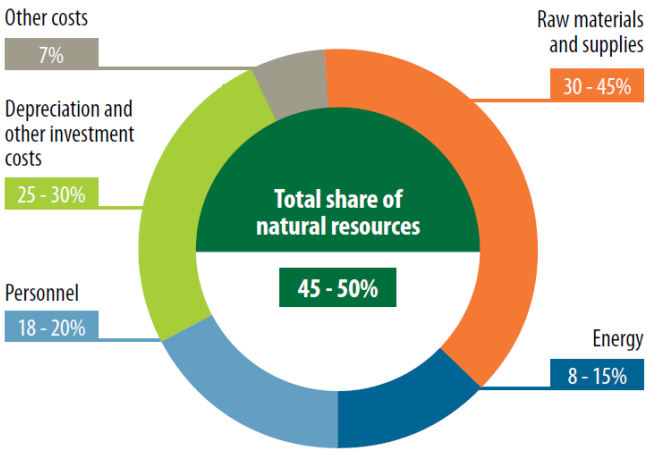

Figure 1: Material as a share of production cost (Greenovate Europe 2012) [2].

2. Material Efficiency Strategies (MES)

A number of different technical strategies exist to improve material efficiency during product design or manufacturing stages. Generally, material efficiency strategies (MES) aim to either provide a product service using less material, or improve yield during production [6]. The former objective is addressed by material minimisation, substitution, elimination and dematerialisation, strategies that are predominantly considered during product design. In the production stage, material efficiency may be improved by reducing yield loss [6]. This is the amount of material lost during manufacturing processes, for example, through subtractive processing or through quality control failures.

Optimisation of individual process efficiencies in terms of yield may be considered as the first measure to improve material efficiency. To go beyond this, the optimisation of an overall production system may have the potential for greater overall efficiency gains [6]. There are a number of existing tools and methodologies that can influence material efficiency in manufacturing and these are described in the following section.

3. Analysis Tools

Material Flow Analysis (MFA) is an established methodology for investigating and quantifying the metabolism of anthropogenic and environmental systems in space and time [7]. MFA is based on the mass balance principle: that matter is conserved in any system, thus input is equal to output mass. Using MFA methodology and quantifying the mass flow of materials within a manufacturing system, it is possible to locate and examine inputs, partitioning, outputs and sources of waste materials. This exercise builds a manufacturing system model and can highlight the material use and losses to waste, to identify point sources of inefficiency. Key MFA definitions relevant to manufacturing include the three types of processes: transformation, transport and storage of materials [7]. The processes and material flow within a manufacturing system can be described using input-output network diagrams, or using simple Sankey diagrams [8].

Some tools designed to support manufacturing efficiency, such as Material Requirements Planning (MRP) systems [9], can also be used to support material efficiency improvements by providing some of the raw data required for material flow analysis. Meanwhile production strategies contained within Lean Manufacturing [10] such as Just In Time (JIT) [11], and Total Quality Management (TQM)[12] can have an influence on material efficiency, by aiming to reduce stocks (material residence time), waste material production or to improve output quality. However, they tend to take a broader manufacturing view, focussing on economic

benefits and do not consider material efficiency in terms of environmental impacts, which may be negative. Lean manufacturing activities have been correlated with reduced waste and emissions [13], however this does not necessarily indicate improved environmental performance; reducing the mass output of one type of waste may result in increased output of a different type that has greater environmental impact overall.

Hicks *et al*. (2004) developed a methodology which aims to model material flow, focussing on broadly characterising process waste according to the waste hierarchy (Lansink's ladder) [14]. This information is plotted against the cumulative value of the materials embedded in each unit product during each process, with the aim of identifying potential value streams associated with waste. Employing this method may have an impact on material efficiency related to improving waste management. However, decisions based on broad characterisation of waste according to the waste hierarchy correlated to economic value may not result in reduced environmental impact.

Although the principle of using the waste hierarchy to drive decisions to reduce environmental impact is conceptually sound in many cases, it does not allow decisions to be made based on empirical evidence. Thus, significant factors may be hidden which may be misleading as to the environmental (or cost) benefit of alternative waste management options. Producing waste that is higher in the waste hierarchy does not necessarily reduce the environmental impact in every case [15][16]. A more systematic approach as used in Life Cycle Assessment (LCA, ISO14040) is to quantify the outputs from a process (emissions) in terms of its quantity, characterisation and allocation to a particular impact type. However, LCA models a functional unit rather than a production system and so is not suitable for dynamic modelling of material flow, or for providing options for material efficiency improvement in the manufacturing context.

4. Research Gap

The previous chapter clearly highlights that there is a lack of support for determining the consequences of implementing material efficiency strategies in the production stage. Furthermore, methods, which may be used to examine material flow and associated environmental impact, are not sufficiently focussed on production to support manufacturer's decision making.

As materials flow through manufacturing processes (transport, storage and transformation), quantitative changes occur which are measureable and accounted for using methods such as MFA, using mass balance approach. Current methods are focussed on analysing quantitative aspects of material use; however, as

materials flow through a system, they are often subject to qualitative changes which have significant impact on material flow and properties, which may define environmental impact. Currently there are no methods that effectively model material flow both in quantitative and qualitative terms. We propose that material flow must be assessed in these terms to comprehend the full complexity of material flow and identify opportunities for ME improvement. In particular, the qualitative changes, which occur during transformation processes, must be fully understood.

A methodology that will allow both dynamic material flow modelling and characterisation of waste generated at different parts of a system through modelling material transformations (in qualitative and quantitative terms), will enable the optimisation of a production system to maximise the material efficiency in terms of its impact according to a range of criteria. Currently models and methodologies that allow materials to be modelled do not characterise materials or waste flow in sufficient detail, while methodologies to assess impacts of material use (qualitative and quantitative) do not allow for effective flow modelling in manufacturing systems.

The improved characterisation of materials and therefore waste will therefore help to identify sources of significant impacts that must be eliminated preferentially using the best combination of resource efficiency strategies in order to have the most significant reduction of environmental impact. Thus, the methodology will improve on lean manufacturing, which aims to eliminate all waste without discrimination, regardless of positive or negative environmental benefit. It is reasonable to assume that, in most manufacturing processes, there are always inefficiencies and so a certain amount of waste will always be unavoidable. Therefore by modelling the material flow and wastes produced in terms of their environmental impacts will help ensure that the overall impact of all the waste produced is minimised. A framework that uses material flow modelling to assess material efficiency in terms of both economic and environmental impact criteria is therefore proposed, that provides options for improvement that are transparent in terms of cost and environmental benefit.

5. Qualitative Material Flow during Transformation Processes

Quantitative material flow is based on the concept of mass balance, which is derived from the principle of mass conservation, i.e. that matter cannot be destroyed or created, although it may be converted or rearranged in space. In distinction to quantitative changes, which must always be balanced in terms of overall inputs and outputs, the conversion of matter (transformation) can result in the creation or destruction of qualitative material properties. For example, the

material input and output mass quantities for a rubber vulcanising process must always balance; however, certain qualitative properties of the input rubber are destroyed upon the crosslinking of its constituent polymer chains. It can be seen that key area for incorporating qualitative data is at manufacturing process level. The three types of material processes, as defined by MFA are: transformation, transport and storage. We propose that the most important qualitative information and the greatest sources of qualitative variation in materials are associated with transformation processes.

There is a large range of manufacturing processes, with a large variety of associated transformations that may affect different materials in different ways, both quantitatively and qualitatively. A key qualitative aspect of material transformations is the dependencies, which may exist between consecutive transformation processes; one process may not be able to proceed before another has finished. For example, filling a container may not occur before the container itself is produced. In this case, the manufacturing transformation, which produces the correct physical form of the container material, must exist before the following transformation (combination of container and contents) can occur. Dependency is an important aspect of material transformation for the design of manufacturing production configurations. The configuration of consecutive and concurrent individual processes may have an impact on the material efficiency of a production system.

A further key qualitative aspect of certain transformations is their reversibility. Referring again to the rubber vulcanisation process, this transformation can currently be described as irreversible. Reversibility is not an absolute term however, as all transformation processes may theoretically be reversible, provided the knowledge, technology and resources exist to carry out the process. Hence, reversibility may be described as a relative term, referring to the practical methods by which it may be carried out. For example, a coating transformation process (Figure 2) involving the combination of two materials may be described as reversible *via* a range of methods, such as the dissolution (a transformation process which alters the physical state of the coating), or mechanical scraping to remove the coating material. Qualitatively, the reversal of a coating transformation may only be applicable to one of the two materials, i.e. the coated material is returned to its original form, however, the coating material is further transformed by dissolution or scraping and is not returned to its original form.

The reversibility of transformations is particularly important when considering the characteristics and management of waste materials; the reversibility can dictate the possible options for waste flow. A fully reversible transformation may allow wasted material to be reused, following reversal of the transformation. An irreversible

transformation may result in waste material that is not reusable or recyclable, with limited potential for recovery of constituent reusable materials.

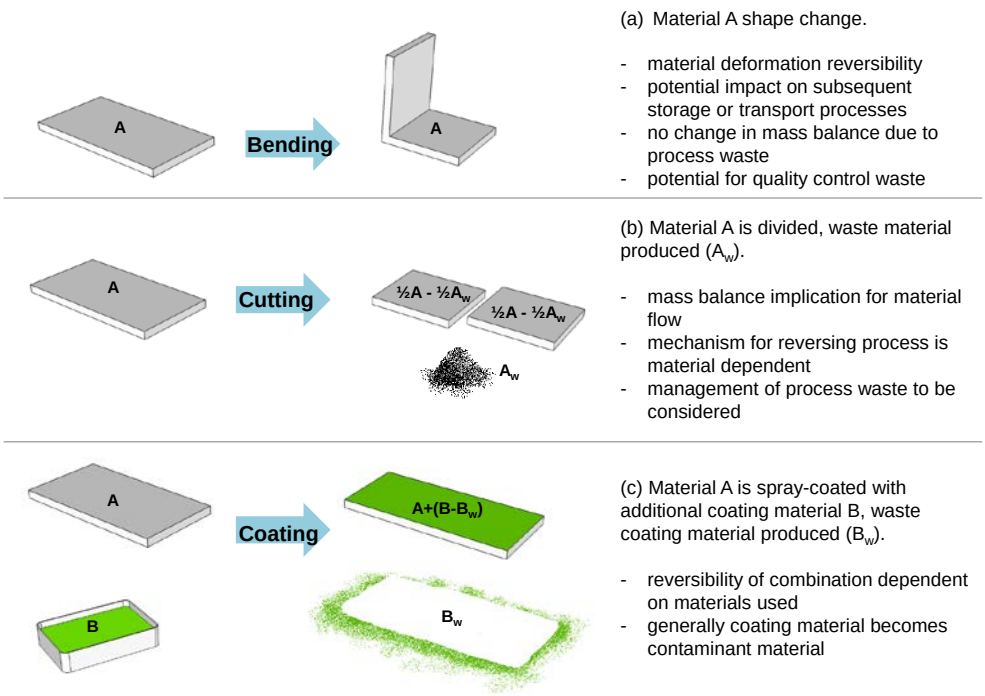

Figure 2: Examples of material transformation processes (bending, cutting and coating) and the implications to material flow.

In modelling the qualitative and quantitative aspects of material transformations this allows us to model highly complex systems which cannot be optimised by simple observations alone. However, the following simple example aims to describe the application of some of the concepts and methods described in the following framework.

A simple example of a product bottling system involves the following processes: bottle moulding, filling, capping and finally labelling. The dependencies resulting from the various transformations dictate that filling and labelling must follow moulding and that capping must follow filling. The reversibility of processes dictate that a moulded bottle may be recovered and remoulded, the material filling is not recoverable due to potential contamination

In this scenario, labelling has significantly lower process efficiency than the other processes: it is the greatest source of waste through rejected products. If labelling is the final process in the sequence, it contributes the greatest number of rejects with the greatest mass contribution per reject (bottle, drink, cap and label). In this example, a modified configuration could improve material efficiency by placing labelling closer to the start of the process, where each product has less mass (less materials combined). This is possible because the labelling transformation (material combination) is dependent only on the moulding process. Labelling immediately after moulding would provide the minimised waste mass (bottle and label are wasted only), leading to significantly reduced cumulative waste per batch of product. A further benefit of this configuration is that the greatest source of rejects has minimised material combination (two materials) with the highest potential for reversibility and therefore the impact of the most inefficient transformation is minimised.

It is not currently possible to model qualitative changes in material flow. To address this we have developed a framework for material flow assessment, which incorporates both quantitative and qualitative information. This will form a comprehensive material flow accounting and assessment method to inform mechanisms which may be used to generate and assess alternative strategies for improving material efficiency in manufacturing.

6. Framework

6.1 Framework specification

The material flow assessment framework is to be used as a basis for investigation of the material efficiency in the manufacture of a product. The assessment of material efficiency is based on the objectives of using less material to produce a unit product, to improve production yield and to reduce the environmental impact of material processing. Thus, it is intended to assist decision making to improve design at product, process and production levels. The framework must facilitate the analysis of material flow through static and deterministic modelling to identify locations of inefficient material flow, measured against a range of parameters. In addition, material flow simulation (stochastic modelling) of alternative production strategies must be facilitated to determine if material efficiency is improved. Many of the terms defined in MFA (substance, good, material, process, activity, flow and flux etc.) are used with equivalent definition in this framework.

6.2 Framework Phases

The framework for the material flow assessment consists of five phases, which follow a largely sequential but potentially iterative progression of phases 1-4 but with the interpretation 'fifth' phase providing a reflective mechanism for each, as shown in Figure 3.

Phase one: This is the first phase in the material flow assessment and involves the definition of the system boundaries. This includes defining both the specific product being manufactured and the production system (e.g. factory) that is being examined. Thus a subject-specific system boundary is created. Information relating to the product should include the design and statement of the product function and service, including the activity or activities to which it is associated (to nourish, clean, transport and communicate, etc.). The inventory of materials and their quantities embedded in a unit product, in addition to a description of associated qualitative or semi-quantitative factors. The fundamental descriptors of each material should be included such as the substances, which it is comprised of, its primary functional parameters (physical, mechanical, aesthetic, etc.), hazard information and storage information. Other inherent descriptive factors relating to waste management and environmental impact should be stated such as waste management options, material recyclability and options for recycling, or if a material is from recycled feedstock. Factors, which are time variable such as material scarcity, criticality and economic value or cost, may include predictions for future trends. For material inputs included in product sub-components that are pre-assembled outside of the manufacturer's zone of influence in terms of production, the contribution of these materials towards the product mass balance must be stated. This inventory process serves as a database of key qualitative and quantitative parameters for the materials flowing through the system.

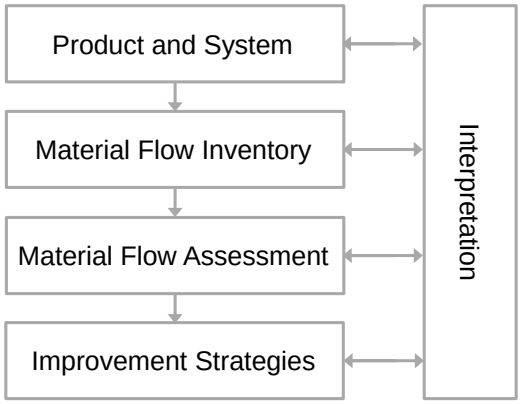

Figure 3: Five phases of the material flow assessment framework.

The manufacturing system is defined in terms of its spatial and temporal system boundaries. This is similar to defining the system boundary in MFA methodology. Here, the manufacturing processes and grouping or zoning of processes; the level of subdivision and smallest, fundamental process units are defined and the physical connectivity between processes (input and output connections) including cyclic systems are established. The temporal system boundary includes information such as production scheduling and batch processing. The control system boundaries are defined, including location of process monitoring equipment or sensors and the frequency of data acquisition. The locations and description of control personnel should also be described.

In addition, a description of scope for system improvement could include process information such as scope for technology or equipment updates, the use of legacy equipment (locked into use), the economic value of equipment and the cost of decommissioning and commissioning equipment. Within the product definition and production system boundary definition, any assumptions should be included where information or data is unknown, is not available or practicably collected.

Phase 2: The next phase involves defining the material flow inventory, by defining the inputs and outputs for each process in the system. This phase creates a material flow model based on mass balance through the system by detailing quantitative flow within individual transformation, transport and storage processes. The physical connectivity of process inputs and outputs are assembled to complete the system model, giving the overall product and waste outputs in qualitative and quantitative terms.

Phase 3: The Material Flow Assessment phase includes steps to examine the material flow according to various performance measures. By applying different performance assessment criteria, the material flow can be assessed based on a range of useful metrics in addition to mass flow.

Phase 4: The selection and testing of potential improvement strategies takes place in the penultimate phase. This involves simulation modelling the strategy implementation to assess their impact and define potential benefits to material efficiency according to a range of performance metrics. At this stage the information collected and organised by the framework is entered into tools designed to simulate the implementation of improvement strategies, such as production optimisation. Depending on the strategy under examination, a separate, modified model of the system will be created (modifying the product and system and also the material flow inventory). This will create a new model with altered qualitative and quantitative material flow, which can then be assessed and compared according to the material flow assessment phase.

Phase 5: Interpretation is the final phase of material flow assessment, in which the findings from the material flow inventory and assessment are considered alongside results from improvement strategy simulations and assessments. In this phase it is determined how best to improve material efficiency in the manufacture of a product. The findings of this interpretation take the form of detailed assessment, breaking down the material flow efficiency and material processing impacts, to inform decision making towards improved material efficiency and environmental impact.

7. Conclusions

This paper describes a framework for material flow assessment within the manufacturing facility. This uses a combined quantitative and qualitative approach to model and assess the material transformation processes and the economic and environmental impacts of those transformations. This will facilitate dynamic modelling, to identify opportunities for improved material efficiency within the production system boundaries without impacting the product in terms of its design.

The material flow assessment framework described here will provide the basis for development of a material flow assessment methodology and support tool which will facilitate:

- Optimisation of process sequencing to maximise the environmental and economic material efficiency of the overall production system.
- Individual process optimisation, assessed in terms of the overall system impact.
- Process substitution, which may or may not include material substitution (product design change), depending on the product-system boundary.

Decision making support will be provided through the generation of optimum solutions described using a range of parameters and KPIs relating to sustainability; providing economic and environmental evidence to build a business case for change. This novel and progressive approach to material flow modelling will allow for a step change improvements in manufacturing material efficiency.

Further work involves the development of a decision support tool, to facilitate the modelling of large production systems. Also due to the volume and complexity of the data, the modelling algorithms and the automated generation of improvement options, it is concluded that a computerised aided tool would be most appropriate for the implementation of this material flow assessment framework.

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