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Management tool design for eco-efficiency improvements in manufacturing – a case study

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Abstract

As the worldwide GDP is forecasted to double by 2035, the energy demand globally is expected to increase by 34%. The industrial sector is also expected to account for more than 30% of the primary energy demand by 2040. These projections make manufacturing operations even more complicated when combined with predicted long-term inflation of raw material prices and increasingly stringent environmental regulations. Therefore, it has become increasingly more challenging for practitioners in manufacturing to improve their eco-efficiency or to "do more with less". Traditional manufacturing management tools based on lean principles such as Value Stream Mapping have not been designed to facilitate eco-efficiency improvements. On the other hand, environmental management tools such as Life-Cycle Analysis focus more on improving environmental impacts rather than financial sustainability. This paper addresses the design gap between these tools and proposes an integrated toolkit for eco-efficiency improvements. The toolkit development process and design principles are described through a case study in the flooring industry. Results from each module are validated and the overall output is used to propose a range of applicable solutions to the manufacturer.

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Keywords: tool design; eco-efficiency; value stream mapping; life-cycle analyis

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1. Introduction and research objectives

As natural resources scarcity and environmental concerns become more and more urgent on the world scene, manufacturing emerges as a key area to address environmental pollution and usage of raw materials [1]–[3]. Aligned to the World Business Council for Sustainable Development (WBCSD), this study falls under the working area of eco-efficiency or as it is generically defined "doing more with less" [4]. Within this subject area, various frameworks have been proposed that intend to operationalise eco-efficiency at manufacturing level. The focus in this work is the design of tools that may facilitate and accelerate eco-efficiency improvements.

Nomenclature

LCA	Life Cycle Assessment
SVSM	Sustainable Value Stream Mapping
EVSM	Environmental Value Stream Map
ERFMI	European Resilient Flooring Manufacturers Institute

2. Literature review and research gap

The authors observe a trend in literature to combine existing tools that enhance productivity with tools that enhance environmental performance [5, 6]. Verrier, Rose and Caillaud [7] analysed the most effective "Lean and Green" tools: Value Stream Mapping (VSM), Visual Management

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and Key Performance Indicators. The attractiveness of application of the VSM tool to analyse environmental wastes is a recent research endeavour as the first attempt was undertaken in 2002 [8] by Simons and Mason who proposed a method named Sustainable Value Stream Mapping (SVSM). In that study, the authors aimed at reducing the green-house gas emissions in a supply chain but did not include other important environmental indicators such as water, material and energy usage. In 2007, the United States Environmental Protection Agency [9], aimed to standardise the use of the SVSM in a toolkit which integrates Lean and Environment practices in order to facilitate the identification and measurement of environmental wastes. The study includes material and water usage and provides several industrial cases but does not cover energy consumption. Acknowledging this gap the US EPA proposed a second toolkit aiming at integrating energy goals in the SVSM.

Fearne and Norton [10] enhanced the methodology developed by Simons and Mason to analyse the waste in the UK chilled food sector adding indicators regarding material waste, Green House Gases (GHG) emissions and water use. The same authors also used the methods indicated in the LCA procedure by Guinee to attribute values when the allocation was uncertain. The study used the energy as a mean to calculate the CO2 emissions but failed to not take into consideration the environmental impacts of the raw materials production. Moving forward, Faulkner et al. [11] applied SVSM at a satellite-dish manufacturer, for the first time separating the amount of energy used in processes from the one used in distribution. The study was then taken up and enhanced by Brown, Amundson and Badurdeen [12] as they successfully applied the framework in three different manufacturing systems in terms of volume and product range. However, the authors focused on validating the method of Faulkner et al. [11] without taking further the energy mapping. The energy mapping was improved by Müller, Stock and Schillig [13] as they aim at optimizing the value-stream on two levels:

- Machine level: include rump up, production and idle time.
- Transportation: include the inbound and outbound transportations.

Their study fails to provide a real case study for the application of the extended transportations value-stream. Instead, Bogdanski et al. [14] and Schlechtendahl et al. [15] concentrate solely on the machine levels. Lastly, Alvandi et al [16] use discrete event simulation to model multi product environment and overcome the static nature of the VSM. With regards to the use of additional tools combined with VSM, Paju et al [17] indicate the use of life-cycle analysis (LCA) and discrete even simulation that could feed the map with more data. Vinodh, Ben Ruben and Asokan [18] use LCA to complement the mapping of automotive component process with the environmental impacts of the various process steps.

Torres and Gati [19] recognised the need to combine the SVSM with additional tools to analyse alternatives and future scenarios. Following up from this study, the authors observed that the referenced VSM-based studies do do not follow a tool design approach for the tool development phase. Little attention is also paid to the way that the tool can be used by practitioners and how practitioners can generate and prioritise improvements. According to Ilevbare et al., the creation of a business tool takes place in two stages: an initial framework or sketch of the intended tool and what key outputs are expected from the tool (figure 1)[20].

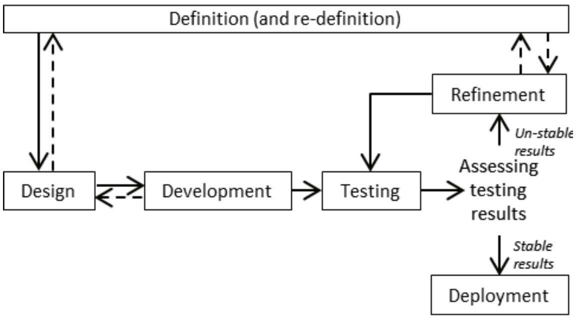

Fig 1. Management tool design process according to Ilevbare et al. [20]

Ilevbare et al. [20], suggest that the tool needs to be efficient for the user (e.g. an SME as opposed to a multinational) and satisfy two principle conditions:

1. *"On the one hand, this means that it can be successfully applied within the capabilities and resources available to the target user group.*
2. *On the other hand, the tool should be sufficiently sophisticated to align itself with the level and breadth of analysis that is seen as the norm for such a business (e.g. the use of simulation software in a multinational versus the use of simple charts and templates in a micro-sized firm)*".

In this study, the process by Ilevbare is followed to develop a type of SVSM that can map energy and material usage (more than time) applied in the case of a flooring manufacturer in the UK. The authors produce a sketch of the tool's internal functions and propose a way of using it through the case study. The novelty of this work lies in the internal functions of the tool. Ways to inform the tool with existing data are described as well as ways of prioritising improvements.

Finally, the authors argue that tools such as VSM and LCA are designed to drive economic and environmental performance respectively. By further expanding the utility of VSM, as illustrated by other authors, with environmental management capabilities, companies can reach higher eco-efficiency levels [21]. Nevertheless, the design principles that need to be obeyed are subject to review in this work.

3. Case study and tool development

The company where this study took place is a leading flooring manufacturer in the United Kingdom. It is a large size company with worldwide presence that offers a diverse portfolio of PVC-based products (floor and wall coverings). Three years prior to the case study, the company initiated lean and green improvement efforts and aims to a six-fold revenue growth in by 2035. The aim of the improvement strategy was to support the 2035 vision but also to further reduce its environmental impacts. One of the key challenges had been to understand what areas of improvement should attract their immediate attention and also how to keep track of the changes in the system. Value stream mapping (VSM) was used as a starting ground for this work. The sustainability manager intended to generate a detailed overview of the existing manufacturing system and further use the output of this work to target improvements. The case study is presented here in steps so that other practitioners and academics can follow the process to build a custom environmental value stream map (EVSM). The following steps do not need to be followed in the same order and it is assumed that a VSM already exists. The output for other practitioners is a conceptual tool design to support eco-efficiency improvements.

3.1 Process mapping

The first step of the process was the clarification of the manufacturing process steps that can to be examined. Ideally, all main processes need to be identified and be scoped but due to technical and time limitations, this step may be subject to availability of data. For example, in figure 2, "in-line mixing" occurs twice within the linear coating process but energy usage data was not available for both "in-line mixing" processes. As mixing occurs in parallel to the process in two discrete steps and energy data were available for mixing overall, the authors chose to represent this as one step in the overall process (figure 2). Measurements of time energy, materials and waste are necessary in this work.

The key processes that fall within the scope of this work are shown in figure 2. A flowchart can be simplified to reflect the availability of data.

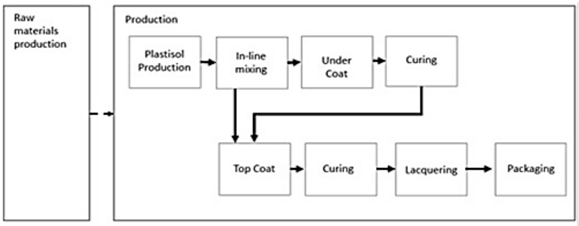

Fig 2. The main process steps that fall in-scope in this work.

3.2. LCA-VCM scope clarification and alignment

The second step in developing the tool is the alignment of scope between VSM and LCA. The LCA software used was GABI® by Thinkstep. It is important to use the same manufacturing stages in both tools. Therefore a cradle-to-gate approach was used in Gabi®. The descriptions follow a typical production pattern for this industry (see www.erfmi.com). Elements that are within the scope of this project are:

- Raw Material Supply, Transport and Manufacturing life cycle stages.
- Energy consumptions of manufacturing processes, in plant transportations, Technical Building Services (TBS) (compressed air and shop floor lighting) and offices.

Elements that are outside the scope of this project are:

- Construction process, "Use" and "End of life" phases of the product life cycle (according to ISO14040:2006).
- Social and economic impacts.
- Manufacturing system water consumptions.
- Detailed analysis of the machines consumption

One of the main reasons for the exclusions was the limited availability of data for the "use" and "end-of-life" phases for VSM. Practitioners need to make sure that both VSM and LCA use the same manufacturing stages and this can be a limiting factor for a comprehensive tool development.

For each manufacturing stage, table 1 clarifies what parameters and dimensions of performance are in/out of scope for the VSM/LCA.

Table 1. In and out of scope processes for this study.

Process	**In scope**	**Out of scope**	**Reason for exclusion**
Process inputs	All the materials used in the processes list in figure.	Water consumption	Water is not a product ingredient. It is used for cooling parts of the process. The company implemented water preservation activities 15 years ago, reducing fresh water demand by 99%.
Internal transports	Any non-manual transport on the shop floor.	Manual transport of color pigments.	Manual process no data available.
Upstream transportation	Plasticisers, Aggregates, Additives, Filler, Scrim	Transportation of any other material not specified.	Constituting less than 1% of the end product. See section 3.3.
Energy	Electricity and natural gas.	Ultraviolet lights for curing process.	Estimated impact less than 5% on the electricity bill. Limited data accuracy/availability.
Infrastructure	Shop floor lighting and offices heating.	Offices lighting	Estimated use: 5% of overall electricity usage.
Process		Recycling unit	Intermittent operation. can be considered an independent operation to main activities in fig2.
Buffers		Silos room, tank farm, holding tanks, warehouse	Difficult to estimate the cost of buffers in this manufacturing site in terms of energy use or time and cost of storage. Bottlenecks and wasted energy and materials were calculated for continuous flow.
Raw material supply	Subject to data available in the GABI inventory.	Processes occurring in the upstream supply chain	The study is limited to a cradle-to-gate assessment. More upstream data are necessary for a cradle-to-cradle assessment.

3.3. Life-cycle analysis and validation through benchmarking

Third step in this development is the modelling of the environmental impacts within the product life-cycle from cradle to factory gate (aligned to the scope of the tool and to ISO14040:2006 principles [22]). In the case study, the authors relied on the use of the bill of materials for a typical 2mm thick product (most popular, based on sales). At this point a level of experience using/testing the LCA software and its parameters accelerates the overall process. Key considerations and assumptions for using the software were found to be:

- Estimating the energy and material discharges produced by the manufacturing system which are then linked back to the potential effect on the environment via classification and characterisation.
- Inserting energy and transportation data.
- Assume no production breakdowns.
- The analysis was conducted to estimate only the consumptions during production time. Consequently, the power factor for all the line machines was assumed to be 100%. For the machines out of the line, the power factor estimated was 100% on load and 25% off load.
- Standard roll surface:40 m2

In table 2, the results of the LCA are compared to the European industry performance levels (online in ERFMI website).

Table 2. Example of LCA output and comparison with industry performance levels

Impact category	Unit	This study	ERFMI levels
Global warming potential (GWP) 100a	Kg C02 Eq.	7.48	9.5
Acidification potential	Kg SO2 Eq.	1.95e-02	2e-02
Eutrophication potential (EP)	Kg Phosphate Eq.	4.25e-03	2.7e-03
Photochemical ozone creation potential	Kg Ethene Eq.	7.80e-03	6.9e-03
Abiotic depletion potential fossil (ADPF)	MJ	1.39e02	2.1e02
Ozone layer depletion steady state (ODP)	Kg CFC 11 Eq.	3.63e-08	1.9e-08

By combining the data from the sensitivity and gravity tests in GABI®, it was concluded that the difference between the results produced by the LCA model and the EFRMI in the GWP and ADPF categories could be due to the PVC quantities used. The difference in the EP, however, is due to the emissions during the curing process. The volatile organic compounds emitted by the curing process contribute up to 25% of the total amount of EP. From the sensitivity analysis it was also found that energy used in the production phase has small environmental impact compared to raw materials production. With regards to the Ozone Depletion, for instance, the variation is mainly caused by the use of stabilisers, whose characterization is not well defined in literature or in practice.

The combination of the two tests (sensitivity and gravity) showed that the materials that require more attention are the plasticisers as changes in these affect all the impact categories. Local considerable improvements can be reached in the ODP category respectively by changing the amount of flame retardant.

The comparison was also discussed with an expert from the organisation who recognised that the differences observed between some categories are due to the lack of standardisation of material grades and lack of data available from the suppliers.

3.4. Energy analysis and energy model validation

In parallel to the LCA, practitioners may also develop their understanding around energy usage on the shop floor. In lack of a dedicated monitoring system, the only available option for UK manufacturers is the central energy meters for electricity and gas that produce half-hourly energy measurements. Every 30 minutes, the energy provider records the energy being used (in kilowatt-hours). This can then easily be converted into hourly energy cost by multiplying the measurement with the cost of the kilowatt-hour for electricity and gas. It can be noted that equal amounts of electric energy and gas energy will have different carbon footprints, making gas a more sustainable source of energy compared to electricity.

The challenge of understanding energy usage better required a careful monitoring of the half-hourly changes against the production and facilities operations. For during the night shift, electric consumption for facilities (offices, lights etc) is very low if not negligible (estimated less than 10% of total power and decoupled from production pattern).

The energy consumption of the shop floor and offices has been first calculated theoretically. It is then compared to the half-hourly data extracted from the electricity and gas meters. Proceeding from the framework of Rahimifard, Seow and Childs [23], the energy consumption was sorted in:

- Process: i.e. the value added energy used to manufacture the product.
- Transportation: i.e. the energy used to handle raw materials, work in progress and finished products and enables production (e.g. compressed air).
- Indirect: i.e. energy used for shop floor lighting.
- Offices: i.e. energy to light the offices.

The electricity consumption has been estimated using the nominal power estimated conducting an energy audit on the shop floor and by listing machine labels. Together with the labels, measurements were used when applicable. Once obtained the nominal power, the energy required for the production of one standard roll has been calculated using:

$$Energy = \frac{Power(KWh) * CycleTime(s) * StdRollSurface(m^2)}{StdQuantity\ of\ Rolls\ *\ 3600(s)} \quad (1)$$

Power is the sum of the nominal power from the machine plates and cycle time is the time required to make a standard (40 meters long by 2 meters wide) roll of flooring.

It falls outside of the authors' intention to describe in detail the calculations made for every process area. Every company would have different requirements and running conditions. Nevertheless, it is important to acknowledge energy usage in the LCA model and understand what the process environmental impacts are. In this particular case, environmental impacts in manufacturing were found to be small compared to the materials environmental impacts (as shown in section 3.3). Collecting energy information from the shop floor can be a very laborious task without appropriate monitoring equipment. The authors see this as necessary step however, to understand what the key process areas are for energy monitoring (understand frequency of measurements and impact to baseline cost).

3.5. Use of sub-routines for decision support

Generating an EVSM is possible at this stage of the analysis as it can be seen in figure 3. Time, energy and materials are projected against all main processes (see figure 2). By observing the map, a practitioner may identify a number of losses in time, energy and materials and propose ways of reducing these losses. Combined with the LCA results, one can re-run the LCA and test the way that environmental impacts may change.

From the EVSM has been identified that:

- The main source of energy consumption is the oven which, during the changeover, consumes almost as much as during process phase.
- The main source of electric consumptions is due to internal transportation. Mainly from and to the mixing process.

- The most polluting process is the paste production and curing since it uses the highest amount of energy. Moreover, the curing process emits volatile compounds.
- The oven is also causing the highest amount of materials wastes.

Following these observations and given that the composition of the product could not be changed, the improvements actions have to focus on the optimisation of the oven, paste production and transportation system.

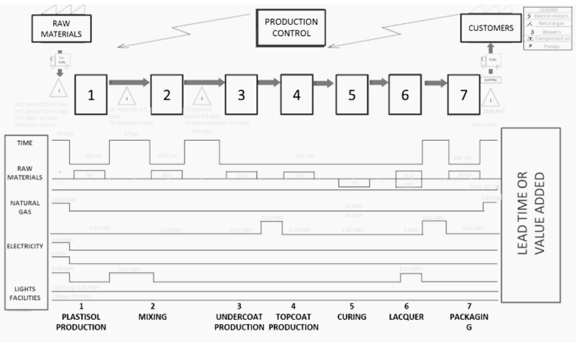

Figure 3. The complete picture of an EVSM, showing time bottlenecks, energy and materials inputs and losses. Processes (1-7) are numbered and explained at the bottom of the figure.

In this paper the authors propose the use of two variants of the waste hierarchy [24], [25] that can offer additional support for environmental performance improvements. In figure 4, the modules are represented as pyramides with most beneficial types of improvements on the top of the pyramid.

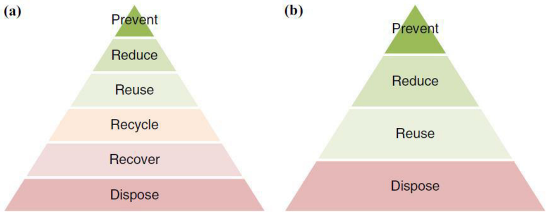

Figure 4. Two variants of the waste hierarchy: (a) for waste/materials and (b) for energy efficiency (found in [24].

In alignment to these modules examples of the how improvements were characterized are presented below for energy and materials waste:

a) Machine switch-off (Reduce)

By observing the power levels during shutdown periods it was found that the company may save approximately £4,000 by switching off certain control panels on weekends (48hr shutdown period). This observation also led to additional improvements on condition maintenance that was necessary to support the switch-off and make the system more reliable. Typically, this type of recommendation would not have been identified by practitioners in this case and a solution at the lower ends of the pyramid would have been implemented (i.e. dispose of existing equipment and replacement with more efficient type).

b) Pull Mixing System (Preventive system)

As observed from the EVSM, the paste production consumes a significant amount of energy both for transportation and production. This is due to the fact that the mixing is continuously prepared according to the production schedule and stored in the six holding tanks. Implementing a pull system, in which the paste is prepared just-in-time, would decrease the electricity consumption in mixing by 36%. This improvement was also supported by timings in the classic VSM tool as well as from the wastage observed during changeovers.

4. Discussion

The paper illustrated the process of developing and applying a type of EVSM tool in the flooring industry (see figure 5 for a complete picture). The focus audience for this illustration is industrial practitioners as well as academics. By describing the application process through a case study, the readers may view this work from a tool design perspective. The tool design guidelines by Ilevbare et al., (2016) were found to be helpful as the tool development remained consistent with the business aims (lean and green strategy) and further attention was paid in the internal functionality of the tool. More specifically, the EVSM tool expresses the business desire to improve environmental and economic performance by creating a common platform for improvements. The development of the case study showed a path to combining existing data available to the business, such as energy readings, software (i.e. GABI®) with sustainability frameworks such as the waste hierarchy. This approach is consistent with condition 1 (see section 2).

The application process further highlights the importance of gaining validation of results in each module output. In the case of the environmental impacts, the results were compared to industry performance levels. In the case of energy efficiency, an energy model was developed and tested by collecting nominal values from machines on the shop floor and energy central metering. One of the challenges in this work has been to allocate energy usage in different processes. Estimations of energy usage in different stages were achieved by comparing energy usage patterns between shifts and day-night production. The predicted energy usage was compared to the energy usage from a factory-central metering point (widely available to manufacturers in the UK). The second condition set by Ilevbare et al., (see section 2, [19]) is partially fulfilled as more work is necessary to refine the integration of all modules into a robust framework for eco-efficiency.

EVSM requires an alignment of process phases between the modules. This was found to be challenging in this case of process industry compared perhaps to discrete manufacturing, where VSM is primarily being utilized as a tool. As the production line is designed for continuous flow, it is difficult to estimate with accuracy the performance of key sub-processes when it comes to improving eco-efficiency.

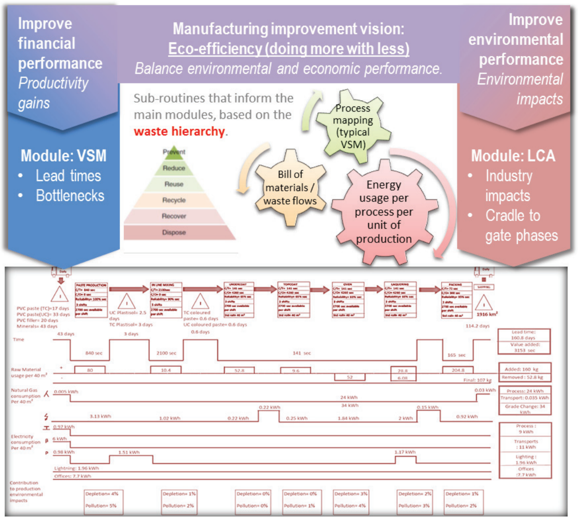

Figure 5. The EVSM tool

5. Conclusions

The paper demonstrated the step-by-step development of a type of an environmental value stream mapping tool. The tool offers a visual representation of time, energy, and material losses. As a management tool, attention has been paid to the integration of frameworks and methods that support decision making on eco-efficiency improvements. This extends the literature on sustainability and environmental VSM-based tools. The authors propose that the use of the sub-routines that are based on the waste hierarchy are a necessary element of these tools. It is also proposed that the tool structure needs to reflect the business requirements and be transparent to the users that practice the improvements required for eco-efficiency.

A management tool design approach has been adopted in this work and aimed to highlight, through a case study, how similar tools can be developed by practitioners. The authors also addressed the development challenges when merging tools that are fundamentally different in scope and aim to improve manufacturing performance in different ways. In this case the authors explored how eco-efficiency improvements can be identified on a value map that merges environmental and economic dimensions.

Future work may include an additional module that balances the trade-offs between saving time, energy efficiency and reducing waste.

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