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Abstract. Energy efficiency has become a key concern in industry due to increased energy cost and associated environmental impacts. It is as well factor on marketing and reputation. Customers require information on the ecological performance of products and the process to build that product. Therefore eco-efficient manufacturing is in our days a matter of competitiveness and economic success. This paper presents industrial driven research and the key findings from production eco and energy efficiency analysis and development projects. Both static and dynamic multi-level modelling and simulation is covered with examples. The use of Value Stream Mapping and Discrete Event Simulation with life cycle inventory data for production eco efficiency analysis is explained. Generic developement steps for process, machine and production system model with environmantal aspects is shown. Development continues in EPES "Eco Process Engineering System for Composition of Services to Optimise Product Life-Cycle"- project.

Keywords: Energy efficiency, modeling and simulation, manufacturing

1 Introduction

In order to win future markets, industrial firms are under pressure to achieve sustainability targets related to their products and services. The reduction on materials and energy on products and production systems is acknowledged as a key strategy in this journey [1]. Also the directives and legislation [2] are drivers for environmantal end energy efficincy improvements in manufacturing.

Satisfactory results on manufacturing systems often require detailed studies to understand where and how the energy has been used. This transparency to energy utilization is the basis for optimizing the energy use performance on production systems. Once visibility is achieved, a question remains on the choice on improved decision support methods and tools guiding practitioners on energy efficient investments in

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manufacturing systems. A current gap is the availability of software supporting production engineers in this type of decision making. This is not a simple task since it involves balancing conflicting criteria such as financial costs, energy consumption, equipment reutilization, and manufacturing system availability.

The sustainability assessments of a product, and its corresponding processes, have different emphases. The manufacturing processes, serve to implement a product design, and their constraints are decided by the current product design. To evaluate a manufacturing process, its fulfilment of product design features and requirements need to be considered. For sustainability assessment of a product design, the overall product sustainability performance is the ultimate criteria and the process assessment is only one of the sub-elements. To be specific, the sustainability assessment of a process would not cover the other phases of the manufactured product's life-cycle [3].

An optimized manufacturing process routine does not necessarily mean that the product is optimal concerning its sustainability performance. On the other hand, to achieve optimal overall sustainability performance when designing a product, the corresponding manufacturing processes need to be optimized based on some sustainability criteria and this is one of the aims in the EPES project [16].

Typical tools for eco efficiency analysis of discrete part manufacturing system and processes are Life Cycle Assestment (LCA), Value Stream Map (VSM) and Discrete Event Simulation (DES). This paper reviews those tools for assesstment of energy efficiency in manufacturing, shows challenges and development need as well research results.

2 Manufacturing Sustainability with Modelling and Simulation

In addition to the problems for traditional manufacturing modelling and simulation, there are some new challenges for simulation of sustainable manufacturing, such as the lack of [4]:

- Source of the sustainability information, sustainability metrics and indicators
- A reference model to identify appropriate information
- Information models that support simulation for sustainable manufacturing
- Modeling methods for simulation of sustainable manufacturing
- Measures to evaluate sustainability.

2.1 Sustainability indicators

In industry today sustainability measures are common. Ideally measures can be a guide to where you are, where you are heading and how far you are from the ultimate vision. There are parameters (figures you measure), indicators (figures that indicate something) or index (several indicators combined into one). They can be used for benchmarking, decision making, measuring or guiding to improvement on the operational level or enabling companies to identify more innovative solutions to sustainability challenges [5].

Feng & Joung, 2009 [6] describes a multitude of various measurement initiatives for measuring sustainability metrics. It has been recommended to pursue a multi-level approach for metrics, with simple metrics at the highest level. Methodology for sustainable production indicator development has been presented by Velava & Ellenbecker [7]. Examples of indicators have also been presented by Krajnc and Glavic [1]. It should be noted and identifyi the interdependencies between the different indicators. For instance, carbon dioxide emissions are dependent e.g. on the energy consumption and sulfur dioxide air emissions from transportation are dependent e.g. on the sulfur contents of the fuel.

2.2 Research on Manufacturing System Modelling and Simulation With Energy Use Parameters

The methods, specifically decicated to production system development are production and material flow simulation, e.g. Discrere Event Simulation and process mapping methods, e.g. Value Stream Mapping.

In Discrete Event Simulation (DES), the operation of a system is represented as a chronological sequence of events. Each event occurs at an instant in time and marks a change of state in the system. DES is well suited for modelling a specific well-defined system, such as a production system. It can provide statistically valid quantitative estimates of performance metrics as-sociated with the system. Integration of sustainability and environmental aspects to simulations is development topic in many research institutes. Currently most of the research efforts have been focused on energy efficiency, examples shown in [8, 9, 10]. Wider scope, sustainability and environmental aspect analysis are shown in [11, 12].

Value Stream Mapping (VSM) relies on Lean principles and identifying and eliminating wasteful activities. It is a process mapping method, and it can be also employed to environmental assessment. The potential of VSM has also been noted by the US Environmental protection agency EPA [13]. EPA has gathered case studies, fact sheets and tools containing techniques for integrating environmental considerations into Lean initiatives and methods [13]. A lot of research has been carried out in various research institutes to use VSM for sustainable production system development.

Typically LCA is conducted for a pre-specified use purpose. It can be decision making, e.g. when comparing two alternative materials, communication purpose, in a form of an environmental product declarations (EPD), or something else. Typically LCA is done for a product system. Use of LCA methods for assessmrent of production system footprint requires specific development in life cycle modeling. In practice light, streamlined or screening LCAs are common since full LCA may be too extensive.

Each analysis method has their limitations and assets which shall be taken into consideration. The essential difference between the three methods is that DES and VSM have generally been used for manufacturing processes and supply chains whereas LCA covers the whole product life cycle including manufacturing, transportation, use, maintenance and end-of-life. LCA method with ISO standardisation (ISO 14040/14044), is solely meant for environmental impact analysis. However DES and

VSM have more flexibility in applications and can be used in light environmental analysis. DES is a tool more specifically aimed at production system life-cycle studies. Economic indicators, investment cost and total cost of ownership (TCO) or Activity Based Costing (ABC) analysis can be integrated to DES.

Both LCA and DES require high expertise from the user and computerised tools, while VSM in its simplest form can be done with paper and pencil.

Use of DES. In the SIMTER project [11] environmental analysis simulation tool was created (Fig. 1). Data management is in the simulation software interface. The user can control following simulation variables and their relationships: resource – energy; part – material; and system input, system output and layout properties.

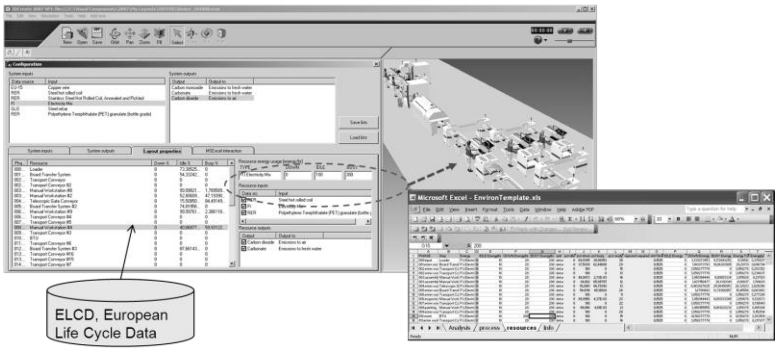

Fig. 1. VTT SIMTER Environmental analysis tool interface.

Simulation run provides book keeping of events, resource utilisation as well state of the resource (down, idle, busy), material flow statistics, and number of products/parts manufactured (ready, rejected, repair) etc. data. Simulation model and run results can pin point in a detailed way, bottlecks of the system, where and how energy and materials are used, whether material is disposed / recycled, and what emissions and waste are produced. Life cycle inventory (LCI), e.g. energy type and material related data, were either selected from EU-LCA database (http://lca.jrc.ec.europa.eu/lcainfohub/datasetArea.vm) or user editable. Manufacturing process specific data is typically a challenge in the LCI databases.

MS-Excel is used for detailed analytical calculation and summary results can be shown in the simulation software interface. Product, resource or process based and piece count or time frame analysis can be reported using MS-Excel. Similar approach as SIMTER, can be used with other commercial factory simulation tools.

Use of VSM. In a recent discrete manufacturing research project Ekoteho [14], methods and tools for environmental assessment were studied. The methods and tools vere divided into those that are used primarily for the assessment of environmental aspects, such as LCA, and those that use environmental assessment as an add-on element. Add-on tools, such as VSM, require less effort to adapt to existing manufacturing modelling tools, but they compromise on comprehensiveness in the environmental assessment part.

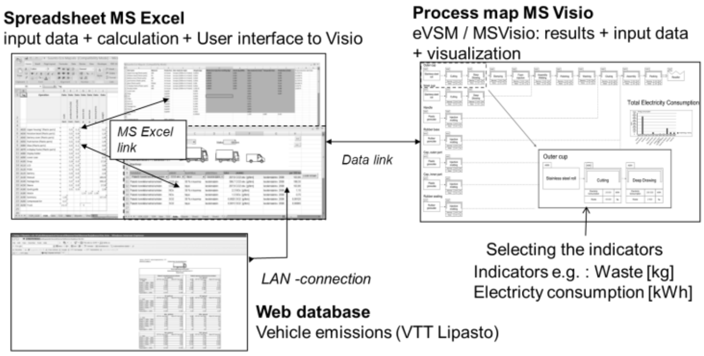

Fig. 2. Use of VSM for production system energy efficiency analysis

In the project new methodology was created based on VSM (Fig. 2). Choosing the right indicators according to the goal, and setting the system boundaries are essential steps for the new methodology as shown in in Paju et al. (2010) [14]. To test the methodology some simplified and connective process flow chart models were created with eVSM tool (http://www.evsm.com/). eVSM is a commercial tool that creates link between MS Excel and MS Visio. The modelling test platform utilizes pre-selected indicators and limited amount of visible parameters. The test platform had connections to web databases Lipasto (http://www.lipasto.vtt.fi/yksikkopaastot/indexe.htm) to import logistic emission data.

3 Genaral Model Development Steps

The general methodology for developing the process-oriented, environmental modules of the sustainability simulation toolkit involves the following steps according to Zhou and Kuhl [15]:

1. Identify sustainability factors and environmental performance measures for systems of interest.
2. Establish simulation state variables to represent the sustainability factors and performance measures.
3. Identify the events in the system that cause changes to the state variables, and translate these system events to simulation events and the associated event triggers.
4. Establish the mathematical, statistical, and logical relationships among the state variables to update and change the values of the state variables as events occur in the system over time.
5. Implement state variables, relationships, and events into a robust, flexible simulation toolkit modules.
6. Perform verification, validation, and testing of the simulation toolkit modules.

The authors have used similar approach in the past and the presented case studies [11, 14] can be implemeted using also other commercial tools. Methodology and tool development for sustainability simulation toolkit continues in the EPES project [16]. The aim of the EPES project is to bring sustainability intelligence to the decision making process for optimisation of the product service system (PSS) life cycle.

In sustainability aspect simulation or any simulation study, one of the first steps is to define the scope of study and select suitable indicators for assesstment. Both VSM and DES, are process oriented and study is focused on manufacturing material flow, process cycle times, resources utilisation, equipment and even human operators activities.

Workstation and manufacturing process level data can be quite similar in LCA, VSM or DES. Here deep understanding of processes and equipment is needed. For sustainability issues we are adding energy flow study, (energy consumption), more detailed consumables study; e.g. materials, (dimensions, type), components, semi products, lubricants, chemicals, waste generation, and also emission study (air emission, aerosol particle, water emission), depending on the scope of the study (see Fig. 3). Equipment simpliest model, include only three states; down (off), idle (stand-by) and busy (working). In more detailed model the busy state energy consumptioncan depend of equipment speed or process load.

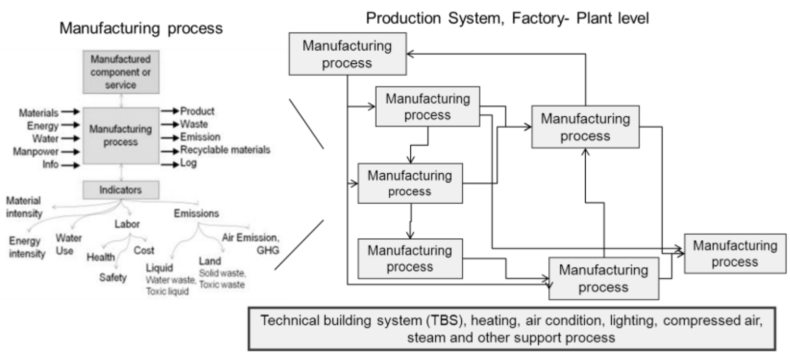

Fig. 3. From machine level to plant level analysis of complex process chains.

The system level combines the workstations and manufacturing processes together, (Fig. 3, see also case study Fig. 1 and 2). The production system model can aggregate workstation and process level results to the system level. The analysis of material flow can be complex and here DES has advanges over LCA or VSM. DES studies support multi-product environment, detailed bottleneck and production efficiency analysis.

LCI factors, environmental sustainability aspects, do not always have to be incorporated in the simulation itself. Sometimes it is sufficient to combine the results of a simulation with an LCA knowledge base as a post processing phase. For example, a simulation can provide the distributions of different states that a set of production machinery are in during the production process. This can be later combined with the knowledge of the impacts that each state has on the overall LCA indicators.

4 Discussion and conclusion

LCA and its integration with modelling and simulation for the sustainability evaluation of manufacturing systems and processes have been discussed. There is need for comprehensive and structured approach that provides the necessary coherent process design with a strong emphasis on energy- and resource-efficiency. Industrial companies need integrated product-process-production system modelling and simulation approaches for enabling them to select the manufacturing processes and associated manufacturing systems that fulfil production requirements with minimal economic and environmental costs, especially in the field of energy consumption and related emissions. The methods described in chapter 2.2.can be utilised to integrate sustainability assessment. European research project EPES [16] continues the development. In one of the demonstrators the early product concept will be analysed from both productivity and sustainability aspects using simulation as a service by non-simulation expert. The essential questions answered through this assessment step are:

- Productivity KPIs: What production rate can be achieved for a design using a given set of processes and resources?
- Sustainability KPIs: What are the energy consumption, the emissions and the hazardous material waste resulting from the manufacturing for a design using a given set of processes and resources?

Environmental data management is essential in assessing the environmental aspects and the real bottleneck is in getting data for analysis. Site specific data (energy, emissions, waste) must be collected from the existing manufacturing processes or from design documents, engineering and other legacy systems. Life cycle inventory data can be connected to complement the site specific data and to enable sustainability assessment throughout the whole life cycle. Alternative approach could be to transfer the results from life cycle assessment software to the simulation models. The manufacturing system simulation gives opportunity to analyse also multiproduct manufacturing with view to resource, product or time based analysis.

With methdos presented in this paper industry can gain the knowledge to compare different production system alternatives with regards to their life-cycle performance already during the early design phase.

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