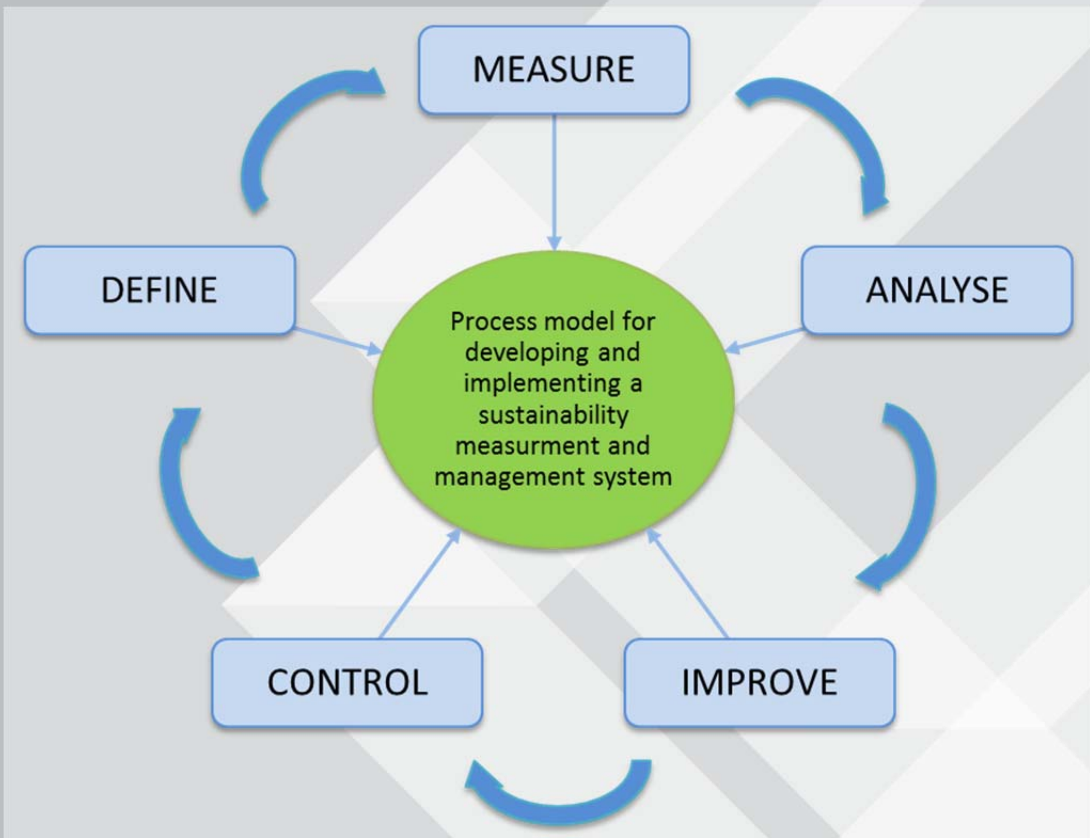
The concept for sustainability performance indicators, reporting and improvement

Final report from FIMECC MANU program project P6 NEXT GENERATION MANUFACTURING Subproject: Visualization of Sustainability Key Performance Indicators 2013–2015

VTT / Juhani Heilala, Marja Myllysilta, Saija Vatanen, TTY / Eeva Järvenpää, FIMECC / Kai Syrjälä



Juhani Heilala, Marja Myllysilta, Saija Vatanen, VTT,
Eeva Järvenpää, TTY, Kai Syrjälä, FIMECC

FIMECC Future Digital Manufacturing Technologies and Systems (MANU) Program

FIMECC Ltd.
Åkerlundinkatu 11 A
33100 Tampere

FOREWORD

This is final report from the VS-KPI subproject ("Visualization of Sustainability Key Performance Indicators"). VS-KPI was part of FIMECC's MANU program during 2013–2015. The aim of the subproject was to develop a process model for identifying and implementing relevant sustainability KPIs, and linking the measurement results to performance improvement and management. The special focus was on manufacturing and product design.

Research and development work was carried out at VTT Technical Research Centre of Finland Ltd (VTT) and Tampere University of Technology (TUT) in collaboration with MANU program partners.

Following persons have contributed to this work.

In funding period 1.10.2012-30.6.2014:

- VTT: Juhani Heilala, (VS-KPI-project manager), Mikko Koho, Hanna Pihkola, Hannele Tonteri
- TTY: Mikko Tapaninaho
- FIMECC: Kai Syrjälä,

In funding period 1.7.2014-30.6.2015:

- VTT: Mikko Koho, (VS-KPI-project manager 1.7.2014–15.1.2015), Juhani Heilala, (VS-KPI-project manager after 15.1.2015), Hannele Tonteri, Saija Vatanen, Marja Myllysilta
- TTY: Mikko Tapaninaho, Eeva Järvenpää
- FIMECC: Kai Syrjälä,

Test case was carried together with MANU LeanMES project, special thanks to; Eeva Järvenpää, Mikko Tapaninaho, Hasse Nylund, Ville Toivonen, Kimmo Ikkala (TTY) and Mikko Koho (VTT).

This report is targeted to MANU program partners and stakeholders.

The authors, Espoo/Tampere 30.6.2015

Juhani Heilala, Marja Myllysilta, Saija Vatanen, VTT,
Eeva Järvenpää, TTY, Kai Syrjälä, FIMECC

TABLE OF CONTENT

Juhani Heilala, Marja Myllysilta, Saija Vatanen, VTT,
Eeva Järvenpää, TTY, Kai Syrjälä, FIMECC

Juhani Heilala, Marja Myllysilta, Saija Vatanen, VTT,
Eeva Järvenpää, TTY, Kai Syrjälä, FIMECC

SUMMARY

Purpose – The purpose of this report is to introduce Sustainability Measurement Framework for Finnish manufacturing companies, specifically to FIMECC MANU program partners. This is also final report of VS-KPI subproject, showing aims of the project, background data, developed model and a detailed case study.

Design/methodology/approach – The research work in the subproject was carried out through the following steps: 1.) Clarifying the situation and challenges related to sustainable development and production in Finnish manufacturing industry. 2.) Developing a concept or model that assists Finnish manufacturing companies in improving sustainability performance and in realising and managing sustainable manufacturing. 3.) Testing, evaluating and further improving the developed concept or model.

Findings – Sustainability is more than just being green or nature friendly. Sustainability has three pillars, economics, social and environmental aspects. The results were summarised in project publications as well in this report. The developed Sustainability Measurement Framework is based on Six Sigma and can be adapted to all product life-cycle phases.

Research limitations/implications – The focus in this report is on sustainable manufacturing and product development. This work should be extended also to manufacturing and supply network level. For business benefits, sustainability-driven business models are required to specify sustainability changes concretely.

Practical implications – Sustainability Measurement Framework conceptual model was tested with one industrial case. This report also specifies sources for further information on sustainability. Many organisations are providing handbooks and training material for companies how sustainability can be taken into consideration and in business.

Social implications – Even there exist general definitions and concepts for sustainability, typically only the environmental pillar of sustainability is highlighted. More practical examples also on the two other dimensions of sustainability as well success stories are needed in the manufacturing industry. General overview as well as research needs on sustainability in the manufacturing companies in Finland were created with Internet questionnaires, company interviews and workshops. The subproject included extensive international dissemination with 5 research publications and 3 research reports targeted for MANU program stakeholders.

Originality/value – Report shows concept for Sustainability Measurement Framework. The aim is to use sustainability performance indicators, and data to create competitive advantage. Some examples are shown also on how to integrate sustainability aspects to digital manufacturing tools. More information can be found from the background material in this report.

Keywords Sustainability measurement in manufacturing industry, sustainable development, sustainable manufacturing, sustainability key performance indicators.
Paper type Research project final report

Juhani Heilala, Marja Myllysilta, Saija Vatanen, VTT, Eeva Järvenpää, TTY, Kai Syrjälä, FIMECC

1 INTRODUCTION

"To measure is to know“ and "If you can not measure it, you can not improve it.“ (Kelvin). Those statements apply also to sustainability, the improvements starts with measurements, and knowledge on processes you are studying. Most metrics can be classified into three functional categories:

- Control: Metrics to enable managers and workers to evaluate and control performance
- Communications: Metrics to communicate performance to internal finance and operations teams, executive management as well as external stakeholders
- Improvement: Metrics to identify gaps (between performance and expectation) that provides guidance on necessary steps for improvement

In industry today different 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 indices (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 (OECD 2010a).

The authors have studied the sustainability practices in Finnish manufacturing industry and observed that regardless of the wide variety of available tools and assistance, the path towards sustainability is proving a struggle for Finnish manufacturing companies (Koho et al. 2015a, Heilala et al. 2011). To provide these companies with support for realising sustainable development, the authors have focused on the development of sustainability performance measurement.

1.2 Objectives and structure of this report

VS-KPI was a part of FIMECC’s MANU program (FIMECC 2012) during 2012–2015. The aim of the subproject was to develop a process model for identifying and implementing relevant sustainability KPIs, and linking the measurement results to performance improvement and management. The developed process model is introduced in this report. The objective is to provide an overview of the process model and tools included in it, and to demonstrate the use of the model with a case study. The report is structured as follows.

Section 1 Abstract and introduction to this report

Section 2 briefly describes the MANU program and the objectives and approach of the here reported research project and VS-KPI.

Section 3 presents the background on sustainable development, sustainability performance measurement and eco-efficiency

Section 4 presents few examples on integration of sustainability aspects into digital manufacturing.

Section 5 presents the initial version of the process model.

Section 6 presents the proposed model applied in a case study. This carried out with LeanMES project.

Section 7 concludes the report.

2 MANU FIMECC PROGRAM

2.1 General overview of the program

MANU is FIMECC program is scheduled to years 2012–2017 with estimated total volume 35 M€ (FIMECC 2012). The program is industrial driven and partially funded by TEKES. The public co-funding is depending on company size. There are more than 30 participating companies and 6 research institutes. There is co-operation with several countries. The focus area is manufacturing technology and creating digital solutions for product creation from concepts to managing mass production. The MANU Program is providing digital solutions for manufacturing industry based on research results. The aim is to increase the competence by new simulation, optimisation and configuration of products and digital lean production and supply chain networks.

MANU is divided in six projects:

P1. *Digital manufacture and fatigue optimisation for superior reliability (DIGFOSURE*) – Project is focusing on demanding welded structures and their simulation

P2. *Digital Management of Manufacturing Process (DigiMAP)* – Project is focusing on machining of high strength materials and its control through digitalization

P3. *Product Knowledge Management in Global Networks (ProMagnet*) – Project is focusing on change and information management in global manufacturing network

P4. *Accelerating and developing operations in supply network by means of digitalization (ACCELERATE) – Project is focusing on network development*

P5. *Lean Manufacturing Execution System (LeanMES)* – Project is focusing on Manufacturing Execution System for SMEs

P6. *Next generation manufacturing (Next)* – Project is focusing on future manufacturing.

The MANU program has 5 industrial oriented projects (as listed above) which are focusing on most important manufacturing methods, welding, machining, and factory level operations and manufacturing network information flow challenges.

There is also the sixth project “Next Generation Manufacturing”, focusing on future manufacturing. It is more research oriented and the aim is that this project feeds fresh ideas to the other projects thus supporting high scientific level of the program and flexibility. During the two first funding periods, project had two subprojects, one focusing on additive manufacturing and the second focusing on sustainability as show here.

2.2 VS-KPI subproject objectives and approach

2.2.1 Research gap, needs and current status

The following research gap was identified in an international workshop (The Second IMS Workshop on Sustainable Manufacturing, April 2012, Gothenburg, Sweden).

- Despite large amounts of data being gathered and there is very little impact on improving sustainability in manufacturing.
- The problem is that the data has to be: packaged, distributed, understood, and used at the level of operations where a difference can be made.
- There is a disconnect between collectors of data and those capable of influencing sustainability in manufacturing.

- Data needs to be properly disaggregated in order that it be understood and be acted upon.
- Using single value metrics tends to sub optimize the total picture.

International roadmaps e.g. IMS2020 Roadmap on Sustainable Manufacturing, Energy Efficient Manufacturing and Key Technologies (2010) (www.ims2020.net), list research need for sustainable manufacturing. Also The European Factories of the Future Research Association (EFFRA), an industry-driven association, is promoting the development of new and innovative production technologies and shows priorities and research needs in the roadmap; “Factories of the Future 2020': Roadmap 2014-2020” (EFFRA 2013). The roadmap lists in the challenges and opportunities all sustainability aspects; economic, social and environmental sustainability in manufacturing.

Road-mapping the business potential of sustainability within the European manufacturing industry was studied by Valkokari et al. (2014). One of the findings is that studies of sustainability within the manufacturing industry have focused mainly on green issues in supply-chain management or corporation-level governance models and reporting practices.

2.2.2 Status in Finnish manufacturing companies

Finnish manufacturing companies’ views on sustainable development and sustainable production have been studied earlier in national research projects as shown in next chapter. The findings of those projects include the following:

- Sustainable development is an important issue and objective, its importance is expected to increase in the future.
    - Customers, personnel, legislation, competitiveness
- Currently the role of sustainable development in functions and operations of companies is relatively small
- Sustainable development and related practices are realized and implemented only to a moderate level
- Sustainable practices are considered in general to be too expensive to realize
- Realizing sustainable development requires
    - Putting it to a central role in vision and strategy
    - Deriving it to the daily operations and decision making
    - Identifying and developing practical means and metrics
    - International consensus for legislation

2.2.3 Objectives of VS-KPI

The objective of the VS-KPI subproject was to support Finnish manufacturing companies in realising sustainable production and achieving sustainable development. A more concrete aim was to develop a process model that assists the companies in measuring and improving sustainability performance, and developing a system for managing and controlling sustainable production. With regard to research approach and methodology, the project aims at developing a concept for improving the current situation, and can be categorised as an innovation-building design science study (Järvinen 2008). The research project consists of the following phases (see Figure 1), which are typical for a design science study (e.g. Takeda et al. 1990):

1. Clarifying the situation and challenges related to sustainable development and production in Finnish manufacturing industry;
2. Developing a concept or model that assists Finnish manufacturing companies in improving sustainability performance and in realising and managing sustainable manufacturing;

3. Testing, evaluating and further improving the developed concept or model;
4. Finalising the concept or model and concluding the research work.

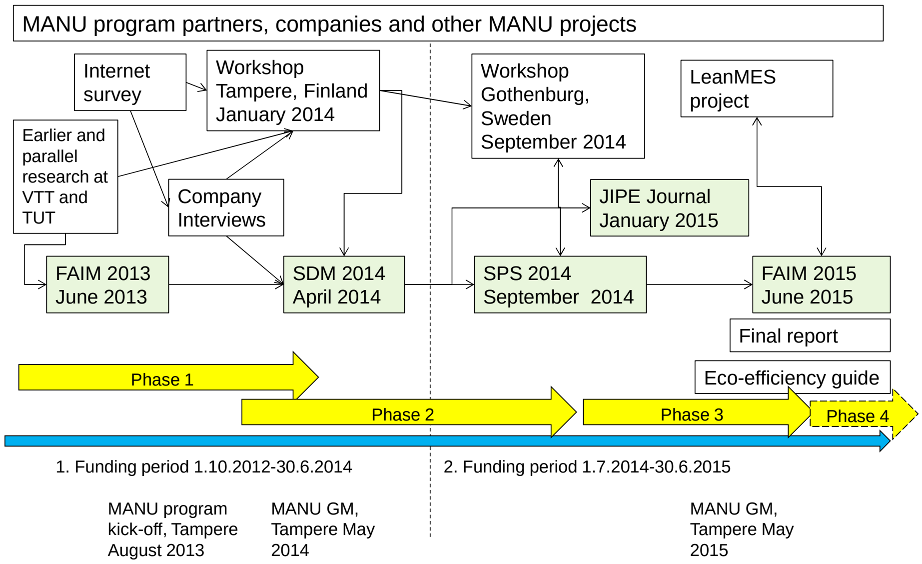


Figure 1. VS-KPI subproject.

In the first phase, (in funding period 1) questionnaire surveys, workshops and interviews were used to clarify the current situation and challenges of sustainable development in Finnish manufacturing industry (see also Appendix 1 and Appendix 2). This was supported by earlier national research projects "KEstävän KEhityksen kilpailukykyinen ekotuotanto" (KEKE) and "Research Agenda for Re-newing Finnish Manufacturing Technology Industry (FOFFI) projects, both project did collect industrial status, challenges and research needs. Also parallel running international projects with Finnish partners were followed at VTT and TUT, (e.g. ENEPLAN – "Energy Efficient Process pLAnning system" http://www.eneplan.eu/, SUSTAINVALUE – "Sustainable Value Creation in Manufacturing Networks" http://www.sustainvalue.eu/, EPES – "Eco Process Engineering System for composition of services to optimize product life cycle" http://www.epes-project.eu/, OEPI – Solution and Services Engineering for Measuring, Monitoring, and Management of Organizations' Environmental Performance Indicators www.oepi-project.eu, EUROENERGEST Increase Of Automotive Car Industry Competitiveness Through An Integral And Artificial Intelligence Driven Energy Management System, http://www.euroenergest.eu/, and SAMT – "Sustainability assessment methods and tools to support decision-making in the process industries" http://www.spire2030.eu/samt/). The current status was also observed from literature and international workshop in Sweden. The progress, content and results of the first phase are described in more detail in Koho et al. (2014, 2015a).

In the second phase (in funding period 1 and 2), which focused more on developing the process model and assisting tools for identifying and implementing relevant sustainability KPIs, and linking the measurement results to performance improvement and management. Results of the first phase provided the basis for the development work. The general structure of the process model, as well as the content, that consists of tools that assist in conducting the different phases of the process, have been developed with help of literature reviews and observation in companies. The initial version of the process model is presented in Section 5.

In the third phase (in funding period 2), case study was used to test, evaluate and validate the process model (Koho et al. 2015b). First case study is reported more detailed in this report (Section 6). Further case studies and finalization of the model

Juhani Heilala, Marja Myllysilta, Saija Vatanen, VTT, Eeva Järvenpää, TTY, Kai Syrjälä, FIMECC

are part of the planned future work, which could be carried on the other MANU program projects or with separate funding.

The fourth phase includes compiling this report which aims to summarize the development efforts on the whole project. Future development depends on industrial interest and funding.

2.2.4 Dissemination of VS-KPI

The conferences and publications were used to disseminate project results to international audience. The first funding period included two conference presentations, the FAIM 2013 (Tapaninaho et al. 2013) and SDM 2014 (Koho et al. 2014). The SDM 2014 conference paper was extended to journal publication JIPE 2015 (Koho et al. 2015a). The second funding period had two conference presentations, the SPS 2014 (Tapaninaho et al. 2014) and FAIM 2015 (Koho et al. 2015b). The conferences and the international workshop were also benchmarking events.

Publications for external dissemination activities:

1. Tapaninaho, Mikko, Koho, Mikko, Nylund, Hasse, Heilala, Juhani, Torvinen, Seppo (2013). Sustainability Performance Indicators for Supporting the Realization of Sustainable and Energy-Efficient Manufacturing. FAIM 2013, June 2013.
2. Koho, Mikko; Tapaninaho, Mikko; Heilala, Juhani; Torvinen, Seppo (2014). Measures and a Concept for Realizing Sustainability in the Manufacturing Industry. SDM 2014, April 2014
3. Tapaninaho, Mikko; Koho, Mikko; Pihkola, Hanna; Heilala, Juhani (2014). Developing A Concept For Sustainability Indicators And Reporting Systems For Finnish Manufacturing Industry. SPS 2014.September 2014. Available at http://conferences.chalmers.se/index.php/SPS/SPS14/paper/viewFile/1690/363
4. Mikko Koho, Mikko Tapaninaho, Juhani Heilala, Seppo Torvinen (2015a). Towards a Concept for Realizing Sustainability in the Manufacturing Industry (JIPE SDM14 Special Issue), Journal of Industrial and Production Engineering (earlier known as The Journal of the Chinese Institute of Industrial Engineers (JCIIE)). Published online: 12 Jan 2015. DOI:10.1080/21681015.2014.1000402
5. Mikko Koho, Mikko Tapaninaho, Eeva Järvenpää, Minna Lanz, Juhani Heilala (2015b). Sustainability Performance Measurement and Management: Process Model. FAIM2015, June 2015.

The other internal MANU program reports are on MANU-portal.

3 SUSTAINABILITY BACKGROUND

This section includes the background for sustainable development and sustainable manufacturing with special focus on sustainability performance measurement and indicators as well as assessment methods.

3.1 Definitions for Sustainable development, sustainable manufacturing and sustainable production

There are many definitions to sustainability, here are presented some of the most commonly used.

“*Meeting the needs of the present without compromising the ability of future generations to meet their own needs*” (WCED 1987) is the often presented definition of sustainable development. This requires a balancing of humanity’s demand for natural resources and the planet Earth’s supply of such resources. The current situation, however, is far from this objective. In 2014, the Earth Overshoot Day, which marks when humanity has exhausted the Earth's annual resource budget, was the 19th of August. This means we already demand the resources of more than 1.5 planets, and the "business as usual" projection indicates that the resources of more than two planets will be needed by 2030. (Global Footprint Network 2014), (WWF 2012).

To concretise the concept and the general-level definition, sustainable development is typically further divided into three pillars: environmental, social and economic sustainability. These are often referred to as "the triple bottom line" or "the 3 Ps": planet, people and profit (e.g. (Elkington 2007), (Martins et al. 2001). The economic aspect focuses on securing both short- and long-range profitability and economic viability. Social sustainability entails that people feel they can have a fair share of wealth, safety and influence (Jovanne et al. 2008a, 2008b). Issues such as safety and well-being, employment and human rights are central to this aspect. Environmental sustainability "seeks to improve human welfare by protecting the sources of raw material used for human needs and ensuring that the sink for human wastes are not exceeded, in order to prevent any harm caused to human beings"(Goodland 1995).

Concentrating more closely on the aspects of business sustainability rather than a more generic definition of sustainability as shown above, business sustainability is defined as ***"an increase in productivity and/or reduction of consumed resources without compromising product or service quality, competitiveness, or profitability while helping to save the environment*"**. The duality of function outlined by the definition of sustainability above requires companies to achieve both business growth whilst also simultaneously reducing the consumption of resources which goes into producing the product. (Institute for Sustainability 2011).

The US Department of Commerce defines sustainable manufacturing as the "*creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound*" (U.S. Department of Commerce 2008)

Sustainable manufacturing definition as shown above means doing more with less, i.e. maintaining or increasing productivity levels while using fewer resources (materials, energy, water, transport, etc.) and creating less waste and pollution. Sustainable manufacturing also encompasses aspects of product design such as ease of disassembly for refurbishment, re-use or recycling and minimising or eliminating the use of hazardous or scarce materials. In addition to the need to comply with a growing raft of environmental and allied legislation, manufacturing companies are under mounting consumer pressure to adhere to "green", ethical and sustainable practices. (Bogue 2014).

Sustainability can also be divided to the perspectives of consumption and production. Sustainable consumption is "the use of goods and services that respond to basic needs and bring a better quality of life, while minimising the use of natural resources, toxic materials and emissions of waste and pollutants over the life cycle, so as not jeopardise the needs of future generations" (IISD). Sustainable production has been defined by the Lowell Centre for Sustainable Production as "the creation of goods and services using processes and systems which are non-polluting, conserving of energy and natural resources, economically viable, safe and healthful for employees, communities and consumers and socially and creatively rewarding for all working people" (Veleva and Ellenbecker 2001).

Jovanne et al. (2008b) link sustainability of production with the three pillars of sustainability and state that sustainable production must respond to:

Juhani Heilala, Marja Myllysilta, Saija Vatanen, VTT,
Eeva Järvenpää, TTY, Kai Syrjälä, FIMECC

- economic challenges, by producing wealth and new services ensuring development and competitiveness through time;
- environmental challenges, by promoting minimal use of natural resources (in particular non-renewable) and managing them in the best possible way while reducing environmental impact;
- social challenges, by promoting social development and improved quality of life through renewed quality of wealth and jobs.

The same topics are listed in Factories of the Future 2020': Roadmap 2014–2020, by EFFRA (2013). The roadmap is used for planning of Horizon 2020 research program. Figure 2 shows some key aspects on competitive sustainable manufacturing.

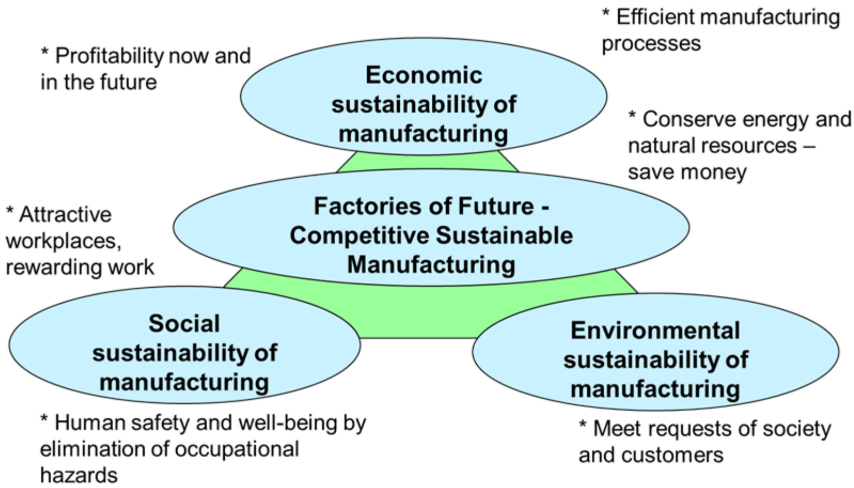


Figure 2. Triple bottom of competitive and sustainable manufacturing, economic, social and environmental aspects.

3.2 Drivers and tools towards more sustainable development in manufacturing

Today, sustainability is driven by the need for regulatory compliance, environmental and allied legislation, directives, corporate social initiatives as well cost savings through eco-efficiency and satisfaction of customer demand. In addition the manufacturing companies are under mounting consumer pressure to adhere to “green”, ethical and sustainable practices.

Sustainable concepts now play a critical role in today’s manufacturing, assembly and processing industries and seek to minimise the impact of these on the environment and human health. Their use reflects both legislative and ever-growing consumer pressures to create a more sustainable world economy and numerous standards, government programmes and information sources exist to assist in their adoption, particularly by SMEs with limited resources.

Labuschagne and Brent (2005) presented drivers for incorporation of sustainable development in business practices. They categorised drivers in to Pressure, Push, Pull and Support as seen in Figure 3.

Juhani Heilala, Marja Myllysilta, Saija Vatanen, VTT, Eeva Järvenpää, TTY, Kai Syrjälä, FIMECC

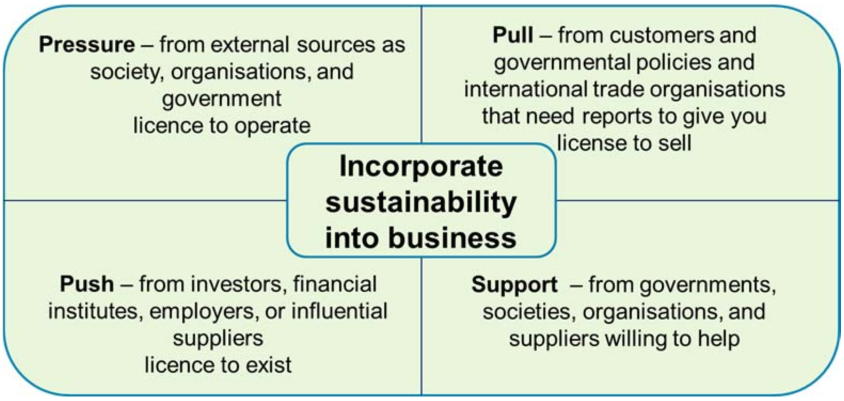


Figure 3. Drivers for sustainable development, inspired by Labuschagne and Brent (2005).

To realise sustainable development, a radical change is needed both on a global level and in the manufacturing industry, which has an important role in reducing resource use, waste and emissions (see e.g. Wiktorsson et al. 2008). For example, the European Commission (European Commission 2008) states that although progress has been made in addressing environmental issues of production and consumption, fundamental changes and significant improvements are needed in the ways and practices of extracting natural resources, and producing, distributing, using and disposing of products. The trend of increasing demand and increasing manufacturing activities adds to the need for reducing the environmental impact of manufacturing and the need for "doing more with less" (Wiktorsson et al. 2008).

Many organizations, European Commission, universities and research institutes, provide tools, such as training material, methodological standards and communication guidelines, to support companies moving towards more sustainable business. For example, the World Business Council for Sustainable Development (WBCSD 1997), the Global Reporting Initiative (GRI 2013) and the Organisation for Economic Cooperation and Development (OECD 2001, 2010a, 2010b, 2011) have developed standards and guidelines for sustainability reporting and development.

Several research organisation and researchers, e.g. Jovane et al. (2008a), Jawahir et al. (2006), Shuaib et al. (2014), have provided reference models and frameworks to assist in achieving sustainability in manufacturing. Sustainable manufacturing involves the manufacturing of sustainable products and the sustainable manufacturing of all products (NACFAM 2012). The focus in sustainable manufacturing practices should incorporate both product and process sustainability. It should be noted that achieving sustainability at product and process levels also requires sustainability at the manufacturing systems level, because the sustainability performance of three elements of manufacturing (products, processes, and systems) are closely interrelated (Jayal et al. 2010).

Many US organisations are assisting with the development and deployment of sustainable manufacturing. The US Environmental Protection Agency (EPA) provides a great deal of information, accessible through its "Sustainable Manufacturing" web pages (http://www.epa.gov/sustainablemanufacturing/), covering issues such as life cycle assessment (LCA), energy tracking tools, lean manufacturing and environment toolkits and a link to the U.S. Department of Commerce's "Sustainable Manufacturing 101 Module" (http://www.trade.gov/green/sm-101-module.asp). This is a collection of training presentations designed to familiarise companies, in particular SMEs, with key concepts, approaches, strategies, terminology and regulations relating to sustainable manufacturing.

Juhani Heilala, Marja Myllysilta, Saija Vatanen, VTT,
Eeva Järvenpää, TTY, Kai Syrjälä, FIMECC

The US National Institute of Standards and Technology (NIST), has launched the "Sustainable Manufacturing Programme" which seeks to develop and apply advances in measurement science to enable improvements in resource efficiency and waste reduction to manufacturing processes and product assembly. NIST has also created web-based resources, the "Sustainable Manufacturing Portal" (http://www.nist.gov/sustainable-manufacturing-portal.cfm) and a "Sustainability Standards Portal" (http://www.nist.gov/el/msid/ssp_portal.cfm) (NIST 2010). There are many other web pages available e.g United Nations Environment Programme (UNEP) and European Commission (EC) proving support.

3.3 Eco-Efficiency assessment

The main idea of eco-efficiency is, in brief, to produce more with less. World Business Council for Sustainable Development (WBCSD), pointed out that high eco-efficiency products or services can be achieved through improving seven key eco-efficient elements as shown here (REDUCES, in short).

1. **R**educe material intensity;
2. **E**nergy intensity minimized;
3. **D**ispersion of toxic substances is reduced;
4. **U**ndertake recycling;
5. **C**apitalize on use of renewable resources;
6. **E**xtend product durability, and
7. **S**ervice intensity is increased.

Improved quality or increased value and reduced environmental impact lead to better eco-efficiency of a product or production system. Eco-efficiency can be quantified as shown in the following figure.

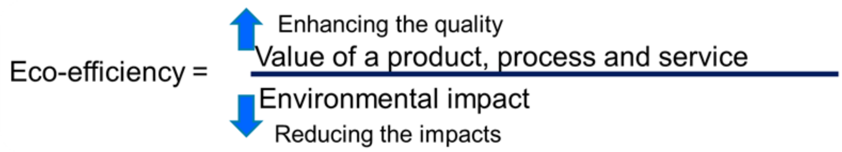


Figure 4. Quantification of eco-efficiency, do more with less.

It should be pointed here that product system value can include also the social dimension, for example value created for the customer with the product.

The ISO published in 2012 an International Standard (ISO 14045:2012) on eco-efficiency assessment. The objective of eco-efficiency assessment is to provide environmental management tool to evaluate the environmental impacts alongside with the product value. The assessment framework is presented in Figure 5. The assessment can be employed for products, services or production systems. Eco-efficiency assessment can produce a single index, considering both environmental and environmental aspects. The index can be employed for comparing different products or production systems.

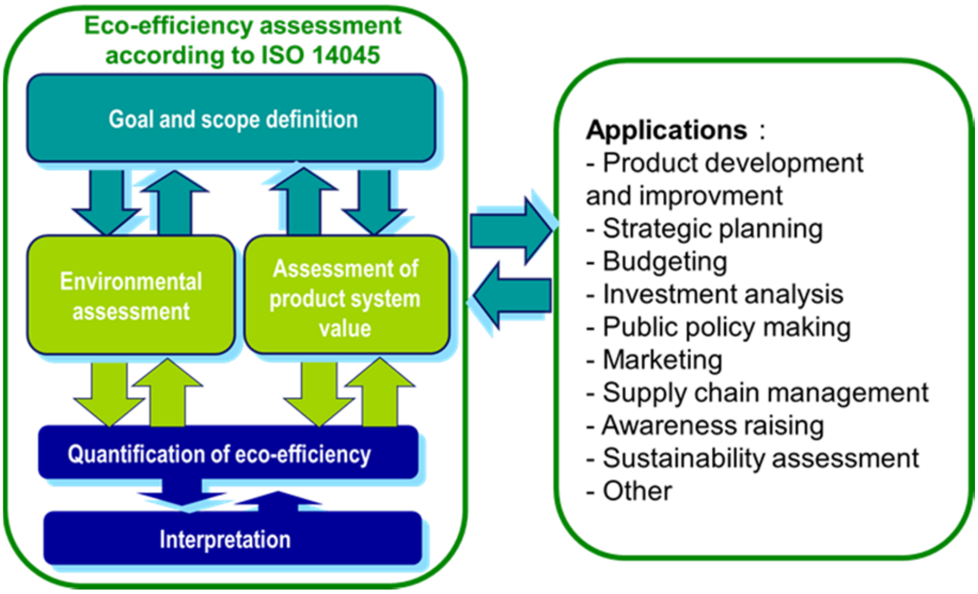


Figure 5. Eco-efficiency assessment framework (ISO 14045:2012).

Eco-efficiency assessment is a quantitative management tool which enables the study of life-cycle environmental impacts of a product system along with its system value for a stakeholder. The product value can be different from different stakeholders' viewpoint. Eco-efficiency assessment is a tool to develop more economic and environmental aware product systems. The evaluation of eco-efficiency measures of the performance of the product systems to improve their ability to do more with less. The environmental assessment in eco-efficiency shall be conducted based on life cycle assessment standards ISO 14040/14044. The eco-efficiency assessment also shares with life cycle assessment many principles such as life cycle perspective, comprehensiveness, functional unit approach, iterative nature, transparency and priority of scientific approach.

Myllysilta et al. (2015) provide eco-efficiency assessment guidelines and calculation examples based on ISO 14045 for MANU industrial partners.

3.4 Standards overview

Standards are tools which may help companies in sustainability assessment. Using ecolabeling companies could gain business advantage. The following list includes some commonly used standards or standardization portals, divided under three thematic topics. The standards mentioned below are mainly standardized by International Organization for Standardization (ISO).

Environmental management

- ISO 14040:2006 Environmental management – Life cycle assessment – Principles and framework.
- ISO 14044:2006 Environmental management – Life cycle assessment – Requirements and guidelines.
- ISO 14045:2012 Environmental management – Eco-efficiency assessment of product systems – Principles, requirements and guidelines.
- ISO 14046: 2014. Environmental management – Water footprint – Principles, requirements and guidelines.
- ISO/TS 14067:2013 Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification and communication.

- ISO/TR 14069:2013 Greenhouse gases – Quantification and reporting of greenhouse gas emissions for organizations – Guidance for the application of ISO 14064-1.
- ISO 14064-1:2006 Greenhouse gases – Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals.
- ISO 26000:2010 Guidance on social responsibility
- ISO 50001:2011 Energy management systems - Requirements with guidance for use
- Greenhouse Gas Protocol (GHG Protocol) http://www.ghgprotocol.org/

Environmental labels and declarations

- ISO 14020. 2000. Environmental labels and declarations. General principles.
- ISO/TR 14025. 2006. Environmental labels and declarations. Type III environmental declarations. Principles and procedures
- EPD International (2015) General Programme Instructions of the International EPD® System. Version 2.5. The General Programme Instructions are the rules guiding the overall administration and operation of the International EPD® System in accordance with ISO 14025 (Environdec 2015)
- Ecolabelling Network (GEN) http://www.globalecolabelling.net/

Environmental assessment and energy efficiency of machine tools, automation and manufacturing systems (only latest):

- ISO 14955-1:2014 Machine tools - Environmental evaluation of machine tools - Part 1: Design methodology for energy-efficient machine tools.
- ISO 20140-1:2013 Automation systems and integration - Evaluating energy efficiency and other factors of manufacturing systems that influence the environment - Part 1: Overview and general principles.

Some existing regulatory initiatives:

- Restriction of Hazardous Substances Directive (RoHS)
- Registration, Evaluation, Authorisation and Restriction of Chemical substances (REACH)
- Waste Electrical and Electronic Equipment Directive (WEEE)
- End of Life Vehicles (ELV)

3.5 Sustainability in product development

Perhaps the most critical aspects of sustainable manufacturing is the product design stage and the EU estimates that 80 per cent of the environmental impact of products and services are determined at the early design stages (Bogue 2014). However, a major problem facing the “green” designer is that a diversity of sustainability factors influence design in addition to environmental considerations.

Design for Sustainability (DFS) has multiple dimensions, thus it is multi-objective optimisation task. Jawahir et al. (2007) developed a model with six DFX elements: disassembly, environment, recycling, societal impact, functionality, and resource utilization and economy. See Table 1.

Juhani Heilala, Marja Myllysilta, Saija Vatanen, VTT,
Eeva Järvenpää, TTY, Kai Syrjälä, FIMECC

Table 1. Design for Sustainability (DFS) (Lu et. al. 2010) (Jawahir et al. 2007).

Design for Functionality	Service life/Durability Modularity Maintenance/Serviceability Upgradeability Ergonomics Reliability Functional Effectiveness
Design for Manufacturability	Transportation Storage Assembly Packaging Manufacturing Methods
Design for Resource Utilisation and Economy	Energy Efficiency/Power consumption Material utilisation Use of Renewable Sources of Energy Purchase/Market Value Installation and Training Cost Operational Cost
Design for Environmental Impact	Life-Cycle Factor Environmental Effect Economical Balance and Efficiency Regional and Global Impact
Design for Recyclability and Remanufacturability	Disassembly Recyclability Disposability Remanufacturability/Reusability
Design for Societal Impact	Operational Safety Health and Wellness Effect Ethical Responsibility Social Impact

Arnetta et al. (2014) shows taxonomy of DFS techniques and also primary design considerations and potential performance outcomes, focusing on supply chain issues.

To summarise some key sustainable product design considerations (Bogue 2014)

For product concept:

- Conduct LCA
- Consult sustainable design standards and guides
- Aim for a design which maximises the product's lifespan
- Benchmark the design against competitive, sustainable products
- Design with disassembly and recycling in mind, ideally via automated or simple processes

For material selection

- Minimise or eliminate the use of hazardous materials
- Minimise or eliminate the use of scarce materials
- Use materials that can be reclaimed or recycled
- Consider the use of recycled materials
- Use biodegradable materials where recycling is impossible
- Use lightweight materials (minimises energy in handling and transport)
- Minimise different materials. If possible, use a single material
- Attempt to use locally produced/sourced materials

For product development purposes LCA can be applied at screening level to save time and. This means LCA is more simplified than the full or extensive LCA. More information on LCA can be found in FIMECC reports (FIMECC 2014a, 2014b). A roadmap towards sustainability can be found on (http://hightech.fimecc.com/results/a-roadmap-towards-sustainability). Other suitable sources of information are European Commission. Life cycle thinking. Available at: http://lct.jrc.ec.europa.eu/ and United Nations Environment Programme (UNEP 2007, 2011). In Finland companies can get support from MANU program research partners, TTY, other Universities and VTT. More information on VTT support is available at (VTT Sustainability Assessment).

3.6 Sustainability in manufacturing

As stated earlier, achieving sustainability at product and process levels also requires sustainability at the manufacturing systems level. 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. The product assessment usually covers broader aspects than the process assessment, such as the entire life-cycle and 6R aspects (reduce, reuse, recycle, recover, redesign, remanufacture) (Lu et al. 2010).

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.

The other stages of life cycle such as use of the product, maintenance, services, re-use and finally end-of life treatment issues have also effect on sustainability.

In the model by Bi (2011) the life cycle of product is divided into four phases: 'pre-manufacture', 'manufacture', 'use', and 'post-use'. The impact on sustainability from the four phases has been shown individually in Figure 6.

Juhani Heilala, Marja Myllysilta, Saija Vatanen, VTT,
Eeva Järvenpää, TTY, Kai Syrjälä, FIMECC

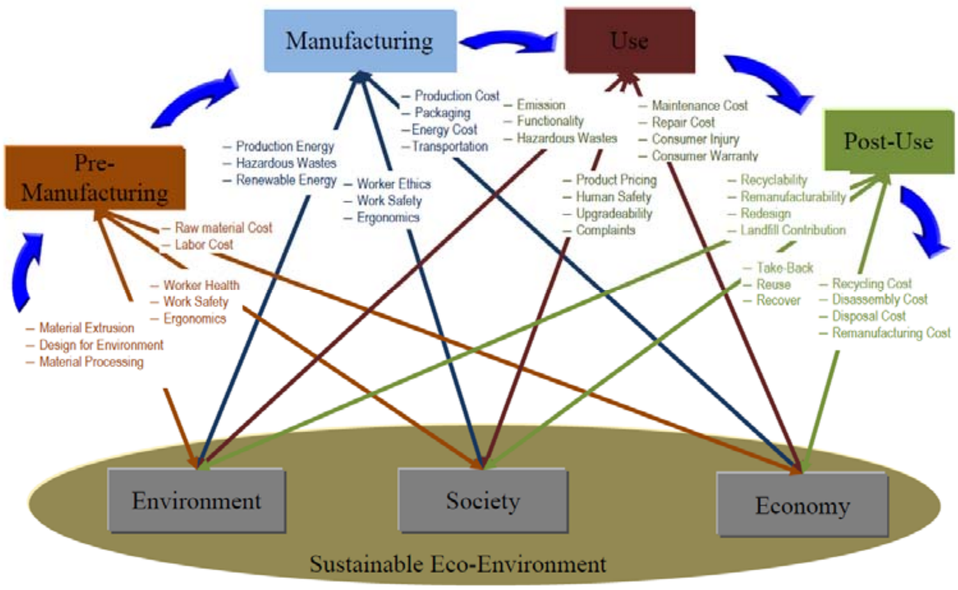


Figure 6. Manufacturing Contributions to Sustainable Environment (Bi 2011).

The OECD (2011) Sustainable Manufacturing Toolkit provides a set of internationally applicable, common and comparable indicators to measure the environmental performance of manufacturing facilities in any business size, sector or country. To make things simple to start the Toolkit offers two components – step-by-step Start-up Guide and a Web Portal where there is technical guidance on measurement (http://www.oecd.org/innovation/green/toolkit/) The Toolkit has been developed with small and medium-sized manufacturing enterprises in mind. The 7 action steps to sustainable manufacturing (OECD Sustainable Manufacturing Toolkit) are:

Prepare:

1. Map your impact and set priorities: Bring together an internal “sustainability team” to set objectives, review your environmental impact and decide on priorities.
2. Select useful performance indicators: Identify indicators that are important for your business and what data should be collected to help drive continuous improvement.

Measure:

3. Measure the inputs used in production: Identify how materials and components used into your production processes influence environmental performance.
4. Assess operations of your facility: Consider the impact and efficiency of the operations in your facility (e.g. energy intensity, greenhouse gas generation, emissions to air and water).
5. Evaluate your products: Identify factors such as energy consumption in use, recyclability and use of hazardous substances that help determine how sustainable your end product is.

Improve:

6. Understand measured results: Read and interpret your indicators and understand trends in your performance.
7. Take action to improve performance: Choose opportunities to improve your performance and create action plans to implement them.

3.7 Enterprise, supply chain, manufacturing network

Typically enterprise level reporting is covered with corporate sustainability reports. GRI is widely used. Typical sustainability targets, or eco-efficiency objectives, often self-reported by manufacturing enterprises are:

- Energy-savings, (electricity and fossil fuels), including increased use of renewable energy sources
- Reduced carbon dioxide emissions (CO2); other emissions, like volatile organic compounds (VOC)
- Reduced the fresh water usage
- Reduced raw material consumption
- Reduced amount of waste
- Workplace safety, zero work-related accidents

The Supply Chain Operations Reference (SCOR) Model, a global standard for supply chain projects developed by the Supply Chain Council, has been updated to address environmental sustainability efforts already 2008. The GreenSCOR capabilities include:

- Industry best practices for making the supply chain more environmentally friendly, such as collaborating with partners on environmental issues, reducing fuel and energy consumption, and minimizing and reusing packaging materials.
- Metrics to measure the effects of greening, including carbon and environmental footprint, emissions costs per unit, energy costs as a percent of production costs, waste produced as a percent of product produced, and returned products disposed of versus remanufactured.
- Processes to address waste management, such as how to collect and manage waste produced during production and testing (including scrap metal and nonconforming product).

Sustainability has impact on supply chain and production network. In a recent study by Valkokari et at 2014 was stated a more system-oriented approach, new models for collaboration between network actors and transparently shared network-level KPIs are required before further steps towards a sustainable manufacturing industry can be taken. In addition, sustainability-driven business models are required to specify these changes concretely.

3.8 Metrics and monitoring in manufacturing

The revolution in industry has come along from pure cost to quality and productivity efficiencies and is in the transition toward including also environmental performance efficiency. Manufacturing performance related metrics are typically time-based; e.g. production rate, equipment utilisation rate. From environmental side typically the focus has been on energy efficiency.

Energy efficiency in manufacturing

Current efficiency or effectiveness indicators of equipment are time-based (e.g. OEE). However, to fully assess the energy-related efficiency or effectiveness of an equipment, the time-based view alone is not sufficient. It is necessary to create energy-related key performance indicators (e-KPI) (May et al. 2015).

The e-KPI method comprises the following steps

- Definition of the reference production system.
- Identification of different power requirements of the productive resource.

- Analysis of manufacturing states as causes of energy inefficiencies of the productive resource.
- Linking drivers (time view) with the appropriate power requirements (energy view).
- Building a hierarchical framework of machines' energy consumption.
- Development of e-KPIs.
- e-KPI design and management.

Measurement data collection and data manipulation

Standardisation on communication and system integration are a must while developing data collection system, it is a question about interoperability. Enabling energy and other sustainability monitoring via standardised protocols, such as MTConnect (http://www.mtconnect.org/), OPC-UA, and other similar provides means to get data from production machines. Use of MTConnect is shown in Lanz et al (2010). Also the following standardisation ISA-95, Enterprise-Control System Integration (IEC 62264:2013) and condition monitoring and diagnosis of machines (ISO 13374-1:2003, ISO 13374-2:2007) and other similar (e.g. MIMOSA, http://www.mimosa.org/) could be useful while developing data collection and data processing system.

Use of industrial internet, provides new means for data collection. This VS-KPI project did not study data collection.

3.9 Sustainability performance measurement and indicators

Several authors and organizations regard sustainability performance measurement and indicators as important enablers of realizing sustainable development and sustainable production in industry (e.g. (Feng et al. 2010), (Shuaib et al. 2014), (Singh et al. 2012), (Singh et al. 2009), (Lu et al. 2010), (Paju et al. 2010), (Lanz et al. 2014). As a result of research and development work in this field, a variety of sustainability performance indicators, as well as guidelines for measuring and reporting sustainability, are available. The Global Reporting Initiative (GRI) provides guidelines for sustainability measurement and reporting, and presents 91 sustainability indicators (GRI 2013), OECD presents 18 Sustainable Manufacturing Indicators (OECD 2011), and EUROSTAT has identified and proposed 15 Sustainable Consumption and Production Indicators (Eurostat).

Although a variety of indicators, tools and guidelines are available, the authors argue that further research and development related to sustainability performance measurement and improvement is needed. A review of available indicators, guidelines and companies' practices indicates that sustainability performance measurement and reporting are mainly carried out at company level, with only limited influence on decisions related to production and product design. Examples of this are annual sustainability or corporate social responsibility (CSR) reports, which provide high-level, aggregated data, but insufficient assistance for decision-making in production and product design. Hence, performance indicators that better support sustainability-related decision-making and improvement need to be developed. This argument is supported e.g. by Winroth et al. (2014), Feng et al. (2010) and Lu et al. (2010).

An indicator has three main purposes in companies: to raise awareness and understanding of the issues it indicates, to help in decision-making, and to measure the achievement of established goals. Adapted or developed indicators, in general, should has some characteristics like below (partially based on http://www.sustainablemeasures.com)

Juhani Heilala, Marja Myllysilta, Saija Vatanen, VTT,
Eeva Järvenpää, TTY, Kai Syrjälä, FIMECC

- **Measurable**: Indicator must be capable of being measured quantitatively or qualitatively in multi-dimensional perspectives, e.g., economic benefit, social well-being, environmental friendliness, technical advancement, etc.
- **Relevant**: Indicator must show useful information, meaning on the manufacturing processes, or other product life-cycle phase, e.g. operations, maintenance under evaluation. It must fit the purpose of measuring performance and address organization's major aspects and objectives.
- **Understandable**: Indicator should be easy to understand by the community, especially, for those who are not experts.
- **Manageable**: Indicators are limited to the minimal number required to meet the measurement purpose. At the same time, the organization should be allowed to make the decision on the number and type of indicators to apply.
- **Reliable/Usable**: Information provided by indicator should be trusted and useful. Reliable measurement is necessary.
- **Cost-Effective Data access**: Indicator has to be based on accessible data. The information needs to be available or can be gathered when it is necessary from existing sources or otherwise easily collected.
- **Timely manner**: Measurement takes place with the frequency to enable timely, informative decision-making.
- **Flexible**: An indicator must be compatible with open standard expressions, such as ontology base and XML documents, to support long-term archival and flexibility for future generations.

A majority of the indicators are "normalized" according to The OECD Sustainable Manufacturing Toolkit Portal http://www.oecd.org/innovation/green/toolkit/aboutsustainablemanufacturingandtheto olkit.htm). Instead of using the total amount, the indicators are presented in relative terms as a ratio of performance per specific unit of output ("intensity"). What this means is that, instead of simply reporting a total amount, the indicator for water intensity, for example, is defined as water consumption per unit of output from the facility. Normalization helps users understand performance in a particular context. If, on the other hand, water were only measured as a total consumption figure, it would change according to levels of production and would not provide any real insight to water efficiency or allow a comparison with other facilities.

A variety of factors may be used to normalize performance, including:

- Number, weight or units of products produced in the facility
- Sales or value added in the facility
- Person-hours worked in the facility
- Units of function or level of services to be provided by the products produced in the facility
- Lifetime of the products produced in the facility

In order to get the best use out of the indicators and improve the performance, it is important to use the defined normalization factor consistently over time. One should also use the normalization factor used by any peers against whom one would like to benchmark one's own performance, e.g. other facilities in your business or competitors. The industry or trade associations may provide standard factors to be applied in the specific sector. It is also essential to report transparently if normalization has been applied and document the value the normalization factor applied.

3.9.1 Selecting the indicators

The Figure 7 displays basic dependencies on objectives, KPIs and variables for analysis and decision making. The process of definition of KPI is shown in Figure 8.

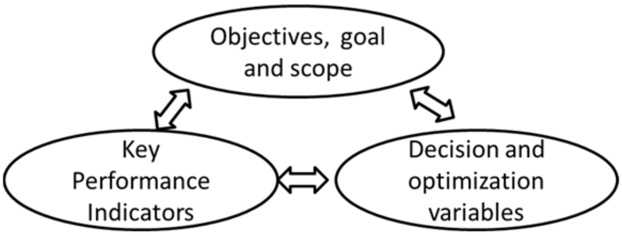


Figure 7. Objective, KPI and variable dependencies.

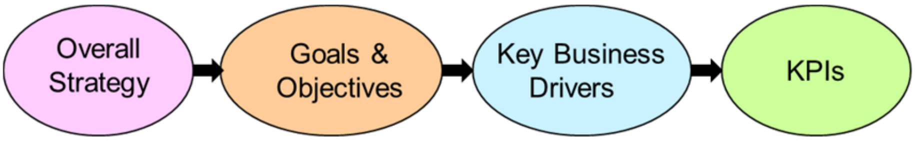


Figure 8. The KPI extraction process.

Figure 8 above presents the KPI extraction process. The starting point of the extraction process is a formulation of the overall strategic goals of the business. From this formulation, a set of objectives and constraints are derived. Key business drivers are specified on the basis of the objectives and constraints. These key business drivers are identifiable specific items that already have operative context, such as save energy, minimise quantity of waste etc. From the key business drivers, actual measurable indicators are formulated. ECOGRAI method (FITMAN 2013) and other methods for business performance indicator could be useful here.

4 EXAMPLES ON INTEGRATION OF DIGITAL MANUFACTURING AND SUSTAINABILITY ASPECTS

This chapter shows a few examples on MANU program domain. It describes on how to integrate sustainability analysis to digital design tools and digital manufacturing.

4.1 Conceptual design phase

The sustainability aspects to decision making should be introduce as early as possible. The challenge in conceptual phase is poor fidelity of data available. The product bill of material (BOM) is still evolving as well the manufacturing methods to be used.

In the EPES project one of the demonstrations was focusing conceptual wing design analysis from both productivity and sustainability aspects. SDFM (Sustainability Design For Manufacturing) method and tool was developed and tested in a industrially relevant environment. The solution is based on engineering and manufacturing knowledge database having also sustainability aspects, and cloud based discrete event simulation on a collaborative space. The EPES system supports the creation of re-usable and configurable services for non-simulation experts. The wing design concepts manufacturability was studied and concepts were compared. In the second step the selected concepts future production system was optimised. The wind design in this early stage was an excel file having right data. More detailed information from project webpages (http://www.epes-project.eu/)

4.2 Product development phase

Here are a few examples to show how sustainability aspects can be integrated to design processes and decision making.

Juhani Heilala, Marja Myllysilta, Saija Vatanen, VTT, Eeva Järvenpää, TTY, Kai Syrjälä, FIMECC

CAD Tools with LCA or sustainability analysis, examples:

SolidWorks Sustainability, is a screening level life cycle assessment (LCA) tool for SolidWorks that offers cradle-to-grave analysis of products, was introduced 2010 [http://www.solidworks.com/sustainability/]. Database and GaBi software form PE International of Stuttgart, Germany [http://www.pe-international.com/nw-eu-english/index/], http://www.solidworks.com/sw/products/simulation/solidworks-sustainability.htm are used within SolidWorks Sustainability. The Solidworks CAD user interface is showing the environmental impact of the product, broken down into four areas including carbon footprint, energy consumption, air pollution (which refers to contribution to acid rain) and water eutrophication (which is the overabundance of nutrients in water that kills local life). In each chart the user can drill down further to look at the impact of material choice, manufacturing, transportation and use, plus end of life.

Sustainable Minds [http://www.sustainableminds.com/product] company provides web-based, on-demand ecodesign and LCA software that can be used to investigate the environmental impact of both current products and future concepts. Sustainable Minds steps designers and engineers through each stage of a product's life cycle to model new product concepts and understand what is causing potential environmental impacts and where in the lifecycle they are occurring. Autodesk Inventor provides a streamlined workflow with Sustainable Minds LCA.

PLM, Product Lifecycle Management: Responding to rising demands for sustainable design development tools, also PLM vendors offers LCA module for manufacturers who are interested in lifecycle assessment, sustainability, and compliance. E.g. PTC Windchill LCA utilizes material content and environmental impact data to give users visibility into LCA data during the innovation and design process. http://www.ptc.com/product/windchill/lca

CAD and LCA integration could be realized so that any CAD system will output a BOM as a spread sheet, and this list can be downloaded to most of the existing LCA tools e.g. SULCA, GaBi. The user needs to ensure that the correct fields are output. Typically this includes part name, number, quantity, volume, material and a description. The key values are the volume and the material and it is from these that the system calculates the material usage.

Digital product model and integration to LCA

VTT has developed life cycle assessment software tool SULCA (https://www.simulationstore.com/SULCA) former known as KCL-ECO. The latest update, SULCA 5, was released for public audience in April 2015. Integration of electric motor design tool (Matlab) to LCA tool (SULCA), was studied in VTT Multidesign research program. It was tested how the SULCA tool can be employed in economic and environmental assessment utilizing product design parameters. Simplified life cycle model (Figure 9) of electric motor was created.

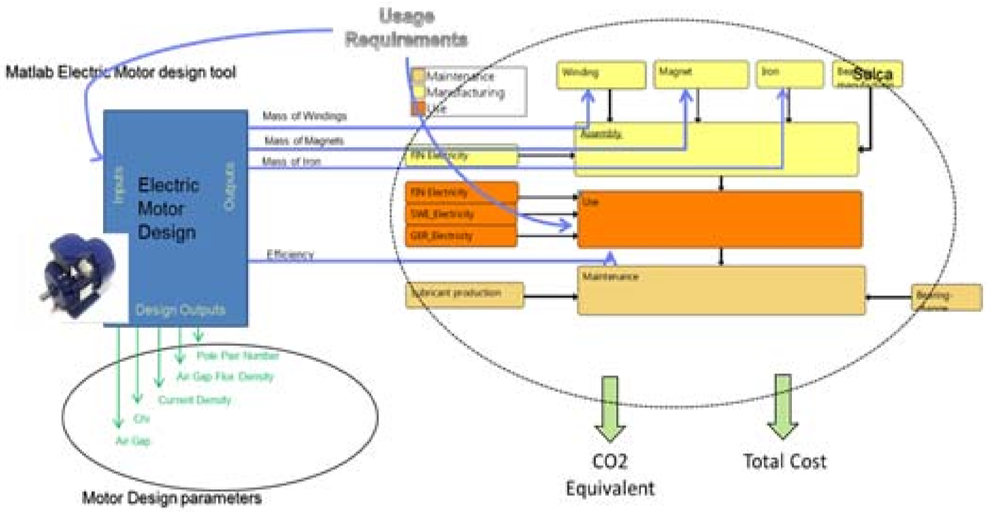


Figure 9. Integration of electric motor design tool (Matlab) to LCA tool (SULCA), case study in VTT Multidesign research program. Created by VTT researchers in 2014.

This example shows how the user requirements from product's functional design model can be connected with life cycle analysis software. Manufacturing, use and maintenance phases are included. The integrated model can be used in multi-objective optimisation during the design phase and it allows finding best compromise between total cost and eco-efficiency indicators, while achieving technical requirements.

4.3 Production system development

Modelling and simulation for has a positive impact on design and optimization of a manufacturing system. To maximize both product and related manufacturing system sustainability, it is desirable to integrate environmentally conscious efforts with the design of manufacturing systems.

Typical task for production engineering is to design a new production system, or improve existing one. Production system simulation and other modelling methods are typically used in the development. Here are show some examples from research projects: ENEPLAN, Ekoteho and SIMTER projects

Manufacturing, machining process

Input data collection may be considered the most critical phase of an LCA. It may require a lot of resources and it is also crucial part for data quality and credibility of the study. In machine tools, data collection is especially complex due to their operational behaviour alternatives. Zendoia et al. (2014) describe an inventory data collection method for machine tools based on work done in ENEPLAN EU-project. They provide a new method based on draft standard ISO/DIS 14955-to improve the transparency and consistency of LCA data. The new method is presented along with the demonstration in two different manufacturing cases, manufacturing of an aeronautic part and part manufactured for the household sector. These two parts are produced by a traditional process and by an alternative process. In the paper the environmental impacts are calculated utilizing the novel LCI method as part of a LCA. It was shown that the new tool can be used as a decision support to assess the environmental impact of the manufacturing of a product using machine tools. The novel LCA method for machine tool was divided into three main phases: Life Cycle

Inventory (LCI), Life Cycle Impact Assessment (LCIA) and interpretation of results. LCI is described in more detailed in the following Figure as four main steps.

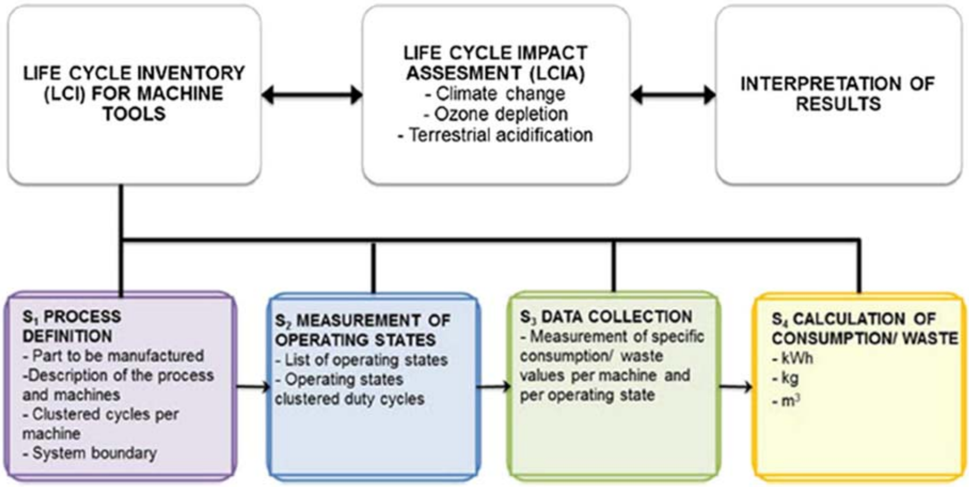


Figure 10. Overview of the Life cycle inventory method for machine tools (Zendoia et al. 2014).

ENEPLAN method provides tool for evaluation of, e.g., alternative manufacturing processes.

Energy data to design systems

Energy related metadata can be integrated to product data as shown by Peng et al. (2012). Energy analysis relates to information distributed among a number of processes, which requires full energy data integration. Existing international standards, such as STEP and STEP-NC, encompass all aspects of a product life cycle, laying the fundamentals for establishing the energy data models. This keeps energy data informed of a wider range of activities in a standardised format that is considered an implacable step towards overall energy efficiency. Peng (2014) presents how to integrate energy consumption modelling approach to STEP and STEP-NC.

Production system analysis and development

In Eco-efficient production research project (Ekoteho coordinated by VTT, Paju (2012)) methods and tools for environmental assessment were studied in the discrete manufacturing industry. The methods/tools can be 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. Data collection could be a bottleneck to assessment methods that take a life cycle approach. In the project a new methodology was created based on VSM and on the selection of environmental indicators. Choosing the right indicators according to the goal, and setting the system boundaries are essential steps for the new methodology. Some background work has been documented in Paju et al. (2010). To test the methodology some simplified and connective process flow chart models were created with eVSM tool (http://www.evsm.com/). eVSM is a tool that creates link between MS Excel and MS Visio (Figure 11). The modelling platform utilizes pre-selected indicators and limited amount of visible parameters. The platform has connections to web databases [e.g. Lipasto 2009] to import data.

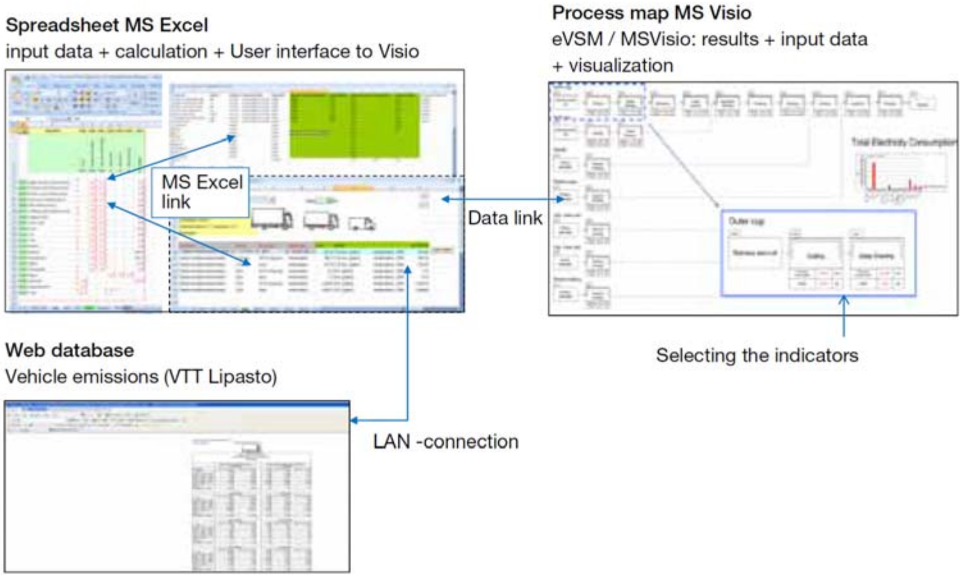


Figure 11. Model for data integration in EKOTEHO project.

In SIMTER project Environmental analysis simulation tool was created, snapshot shown in Figure 12. SIMTER had three sub tools; Ergonomics, Level of Automation and Environmental analysis. Due to operator ergonomic analysis sub tool, the detailed 3D layout was needed (Lind et al. 2009). For the environmental impact analysis 3D features are not necessary.

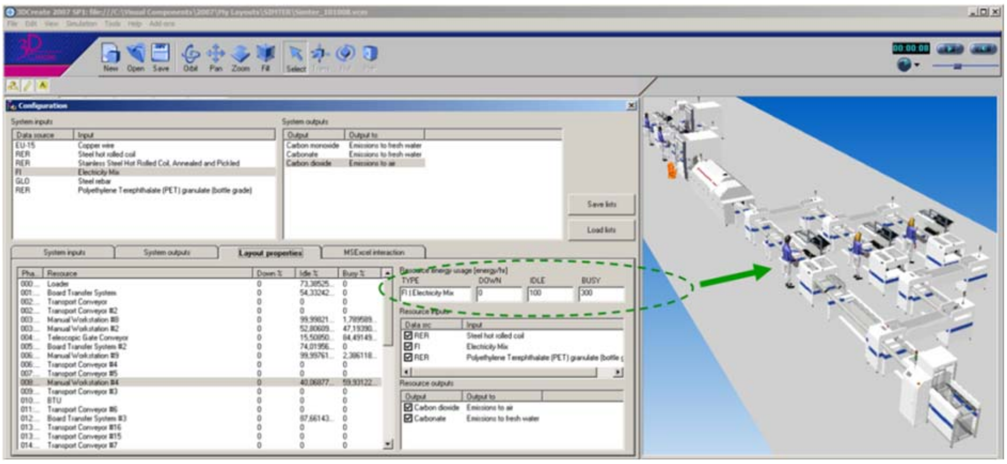


Figure 12. VTT SIMTER Environmental analysis tool interface in Visual Components software.

Data management is in the simulation software interface. The variables were relationships resource – energy; part – material; system Input; system output and layout properties.

Simulation run provides statistical, resource utilisation and material flow etc. data. Simulation model run results tell in a detailed way, 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 from ELCD (European reference Life Cycle Database) database. Process specific data is typically a challenge (Heilala et al. 2008).

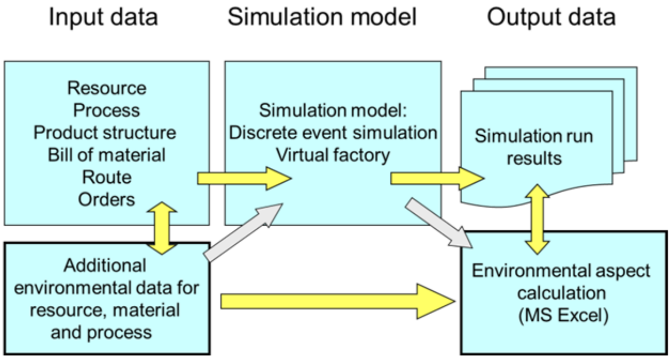


Figure 13. SIMTER Simplified analysis flow.

MS-Excel is used for detailed analytical calculation and summary results can be shown in the simulation software interface. Simulation writes input data and output data to Excel: Product, resource or process based and Piece count or time frame analysis.

Energy consumption values can be classified by phase and by state of the phase (Down, Idle, Busy). Simulation run indicates book keeping of events and data: machine utilization (%) by phase and by state of the phase, products/parts manufactured (ready, rejected, repair) and simulation run length.

Output, using simulation results and machine specifications calculation, were material and energy usage per product in phase, total energy and CO2 (direct and indirect).

Similar approach as SIMTER can be used with other factory simulation tools as well. Typically this kind of simulation system has following elements:

1. Modelling
2. Data handling
3. Run scenario management
4. Result visualisation and analysis.

SIMTER tool prototype is a sustainable production development tool, it has elements for economics (level of automation, costs, productivity), social (production ergonomics, worker safety), and environmental (energy, emission, waste) analysis.

Later examples and state-of-the art on energy oriented simulation is shown by Herman et al. (2011), environmental aspects in manufacturing system modelling and simulation is shown by Thiede et al. (2013). Sustainability aspects are studied by Chen et al. (2013) and Lee et al. (2014).

There are other type of simulators as well, including various process simulators. Use of system dynamics models was shown by Kibira et al. (2009).

5 PROCESS MODEL FOR DEVELOPING AND IMPLEMENTING A SUSTAINABILITY PERFORMANCE MEASUREMENT AND MANAGEMENT SYSTEM

This section is adapted from Koho et al. 2015b.

The process model for developing and implementing a sustainability performance measurement and management system follows the well-known DMAIC approach (e.g. Stamatis (2004)) that is widely used to structure performance improvement projects. The phases of the process are: Define, Measure, Analyse, Improve and Control. The DMAIC structure and approach were seen to be suitable as they emphasise measurement as a basis of improvement, and include the key elements of an improvement project and management. In the Figure 14, and in the following sections, the key objectives, content and the assisting tools of each phase are presented. This is an initial version of the model and it is analysed, in Section 6 case study.

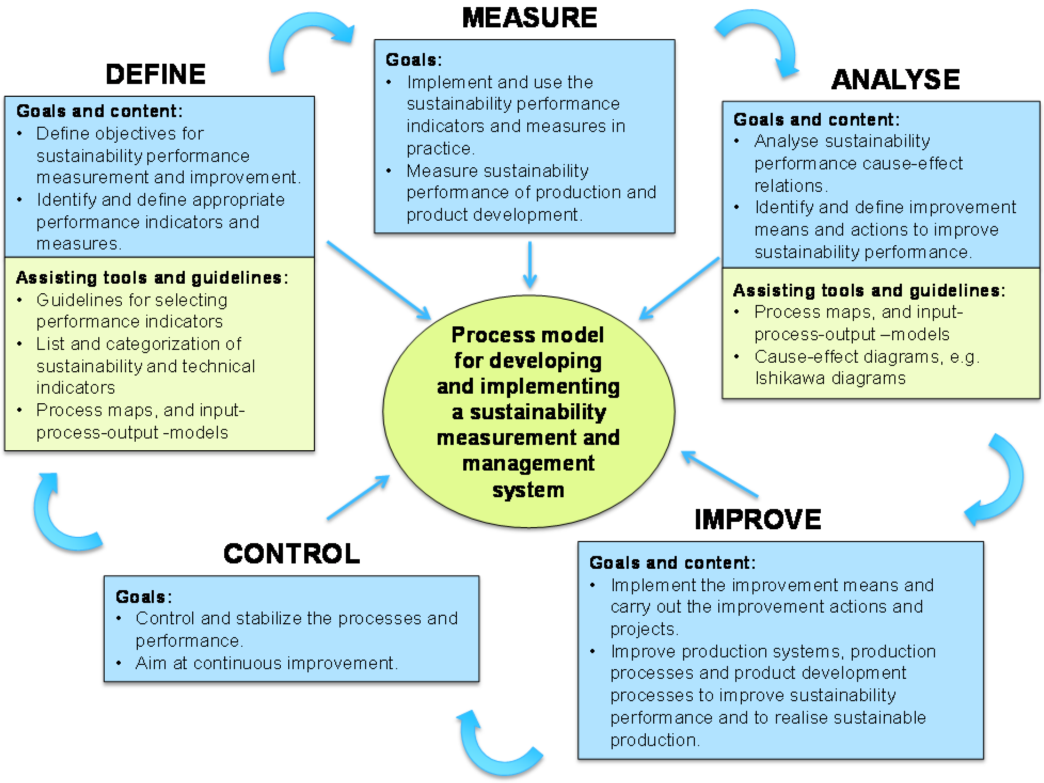


Figure 14. Process model for developing and implementing a sustainability measurement and management system (Koho et al. 2015 b).

5.1 DEFINE

The define phase focuses on defining and identifying appropriate and useful sustainability performance indicators for a company. This requires clarification within the company and among the stakeholders, e.g. customers, investors, and legislators, of the objectives of improvement and the measurement needs. Sustainability performance indicators relevant to the identified needs are subsequently selected and defined. Hence, this phase focuses on “What should be measured?” and “How should it be measured?”. The aim is to identify sustainability performance indicators that provide real-time data at factory, process and machine level, and support decision-making related to production and product design.

Guidelines and tools assisting in this phase have been identified from the literature and developed by the authors. Literature provides guidelines and requirements for selecting performance measures for a company. For example, Feng et al. (2010) state that the indicators should be measurable, relevant and comprehensive, understandable and meaningful, manageable, reliable, cost-effective, and timely. For more practical assistance, Lanz et al. (2014) have listed over 200 sustainability and technical indicators and categorised these based on three dimensions: level of measurement within a company, measurability and temporal focus. These are intended to assist companies in identifying indicators that are relevant to their objectives and measurement needs.

Furthermore, process mapping and models (Figure 15) are seen to be useful in considering what and how should be measured within production.

5.2 MEASURE

In the measure phase, the sustainability performance indicators selected in the previous phase are implemented and used in practice. This includes collecting the required data and carrying out the required calculations. Further research and development work is needed to define and describe an approach and process for implementing the sustainability performance measurement system efficiently and effectively within a company. Methods also need to be developed for collecting the required data at factory or machine level in real time.

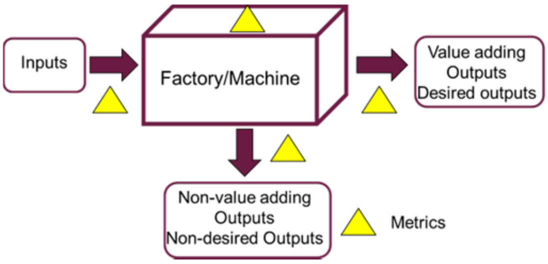


Figure 15. Generic model of the inputs and outputs relating to the metrics.

5.3 ANALYSE

The analyse phase aims to facilitate the reporting of relevant and useful information both within the company and to external stakeholders, and to enable performance improvement and management. With regard to reporting, the measurement data must be analyzed and summarized to provide useful information for stakeholders. To enable performance improvement, the cause–effect relationships between measurement results and decisions, related to production and product development, must then be identified and described. This should enable practical performance improvement actions and projects based on the measurement results and current sustainability performance to be determined. Hence, the phase aims at answering the question “How can sustainability performance be improved?” For this, the use of cause-effect tools and diagrams, such as Ishikawa or fishbone diagrams, is recommended. Also process maps and models (e.g. Figure 15) will be useful in identifying how the outputs and performance can be affected and improved.

5.4 IMPROVE

In the improve phase, the planned improvement actions and projects are executed. Changes and improvements are made to product development processes, products, production systems and production processes in order to achieve higher levels of sustainability performance.

5.5 CONTROL

In the control phase, the aim is to stabilize, standardize and control the new processes and improved sustainability performance. Processes and sustainability performance are monitored using the performance indicators and analysis systems developed in the previous phases. Aim is to identify deviations from the standardised processes and performance, and opportunities for further performance improvements. Hence, the control phase contributes to a sustainable production management system that aims to standardise the processes and sustainability performance, and to enable continuous improvement.

Next section illustrates in more details use of the process model in manufacturing company. The test case was carried out together with MANU LeanMES project.

6 LEANMES-CASE

6.1 Introduction to LeanMES case

The proposed process model for developing and implementing a sustainability performance measurement and management system, presented in the previous chapter, was partially tested for a virtual case environment, named as LeanMES Concept Factory. The LeanMES Concept Factory is being developed in the LeanMES project, which is another sub-project of MANU research program. LeanMES aims to develop a concept of a new type of MES (Manufacturing Execution System), which is lean, scalable and extendable, and supports human operator in a dynamically changing environment. The aim with the LeanMES Concept Factory is to act as a virtual environment, where different concepts developed during the LeanMES-project can be tested and visualized. Figure 16 represents the idea and viewpoints of the LeanMES Concept Factory.

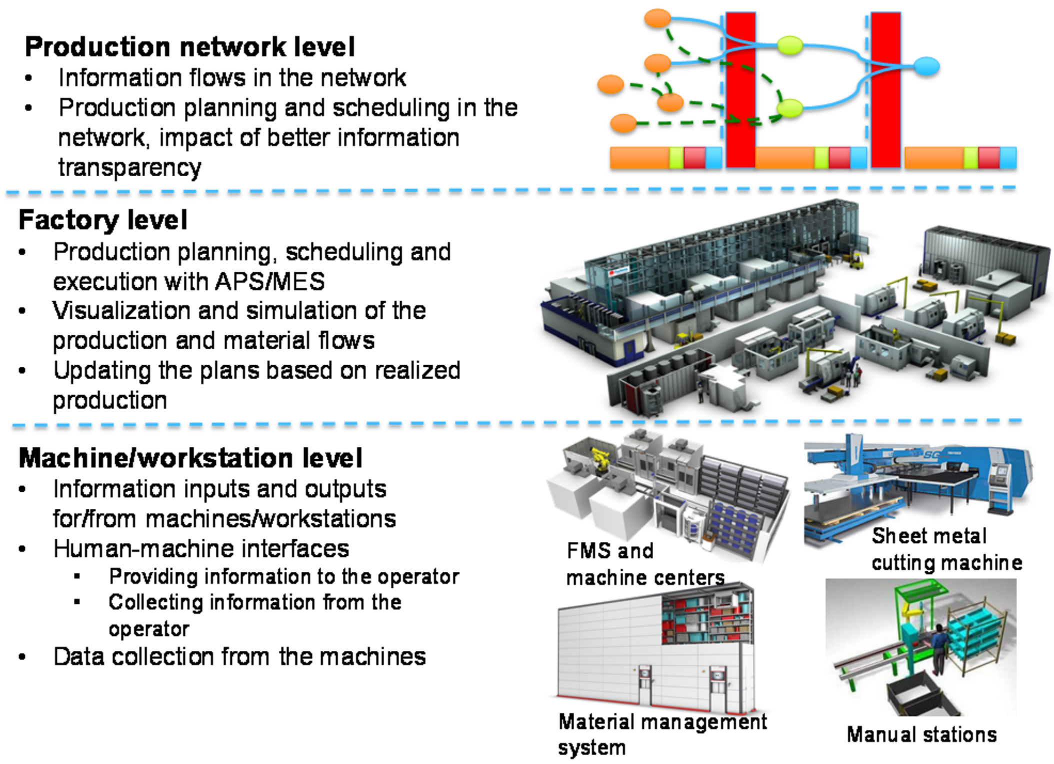


Figure 16. Viewpoints in the LeanMES Concept Factory (Järvenpää 2015).

As the measurement of production sustainability indicators is strongly related to collecting data from the factory floor, LeanMES-project is especially interested in what the sustainability reporting and optimization will require from the future MES and other manufacturing IT-systems. It is seen, that customers are becoming more and more interested in the ecological footprint of the products they buy. Therefore the product manufacturers need to be supported by proper IT-tools, which can assist in providing reliable information, relating to the product and production sustainability, to the customers. Furthermore, this information is needed to support sustainable production planning, scheduling and control.

The motivation of companies for measuring sustainability and controlling the production towards better sustainability performance is usually somehow related to the profitability and expected economic benefits, or the prerequisites for the operation. They may be derived for example from:

- Building better company or brand image
- Possibility to enter to new markets or grow the existing markets
- Possibility to more profitable pricing
- Reducing the costs of production (e.g. waste management costs, energy cost, or personnel costs relating to absence or injuries)
- Increasing the wellbeing of the workforce
- Complying with the regulatory requirements (relating e.g. to energy efficient products or labor aspects)

6.2 Applying the DMAIC model in LeanMES Concept Factory

The DMAIC model served as the basis and guideline for developing the sustainability measurement concept model for the LeanMES Concept Factory, targeting at the shop floor level. The focus and objective of the case study was to introduce sustainability performance indicators and measurement to the LeanMES Concept Factory, and analyse how those indicators can be controlled and improved by production planning and control decisions. In the following sections the phases of the DMAIC model in the context of LeanMES Concept Factory are described.

6.2.1 Define

The define phase, i.e. identifying and selecting relevant sustainability performance indicators, was carried out in workshops with the case study participants from the LeanMES-project, including both academic and industrial representatives. Initially, a plethora of sustainability metrics, relating to environmental, social, economic and technical aspects, documented in (Lanz et al. 2014), were introduced to the participants. The performance indicators that could and should be implemented to the LeanMES Concept Factory were then selected in two workshops. As the LeanMES project focuses on Manufacturing Execution Systems, the objective was to identify especially those aspects and indicators of sustainability performance that can be affected by production planning, scheduling and control decisions. Additionally, indicators of sustainability that are not directly linked to such decisions, but were considered important to be measured and reported, were also included. The economic and technical metrics were left out intentionally, because they are already commonly measured in the industry, and the manufacturing IT-systems provide support for them. The selected metrics were then categorized into metrics that could be optimized by operative production planning and control decisions in the concept factory, and general reportable metrics. The selected metrics are presented in Table 2.

Table 2. Metrics to be optimised and general reportable metrics for the LeanMES Concept Factory.

Metrics to be optimized	General reportable metrics
Energy consumption within the whole organization Energy consumption of individual resources Energy Cost Energy Efficiency Materials used by weight or volume Material Efficiency (used material/waste material) Waste (total weight of waste by type and disposal method)	Percentage of materials used that are recycled input materials Direct greenhouse gas emissions Emissions of ozone-depleting substances (ODS) NOx, SOx, and other significant air emissions Total water withdrawal by source Percentage and total volume of water recycled and reused Injury rate (number of injuries in a given time period) and type of injury Lost days (number of days lost due to injuries, occupational diseases, absenteeism etc. in a time period) Number and rate of near misses and hazards Lost time injury frequency rate Number of work-related fatalities (by region and gender) Job Satisfaction and motivation Average hour of training per year per employee Percentage of employees receiving regular performance and career development reviews Job-related experience and skills

6.2.2 Measure

One motivation of LeanMES for this exercise was to define the requirements for the future manufacturing IT-systems, such as MES. What information they need to collect and handle, in order to assist the companies in their sustainability measurement and management activities? What needs to be collected and from where? Therefore, in the second phase (measure) the measuring was made more concrete by visualizing the inputs and outputs that relate to certain processes accomplished with the resources included into the LeanMES Concept Factory simulation model. Three examples of such input-output analysis are shown in Figure 17. The actual measurement and indicator calculations have not been implemented to the Concept Factory simulation model.

Juhani Heilala, Marja Myllysilta, Saija Vatanen, VTT, Eeva Järvenpää, TTY, Kai Syrjälä, FIMECC

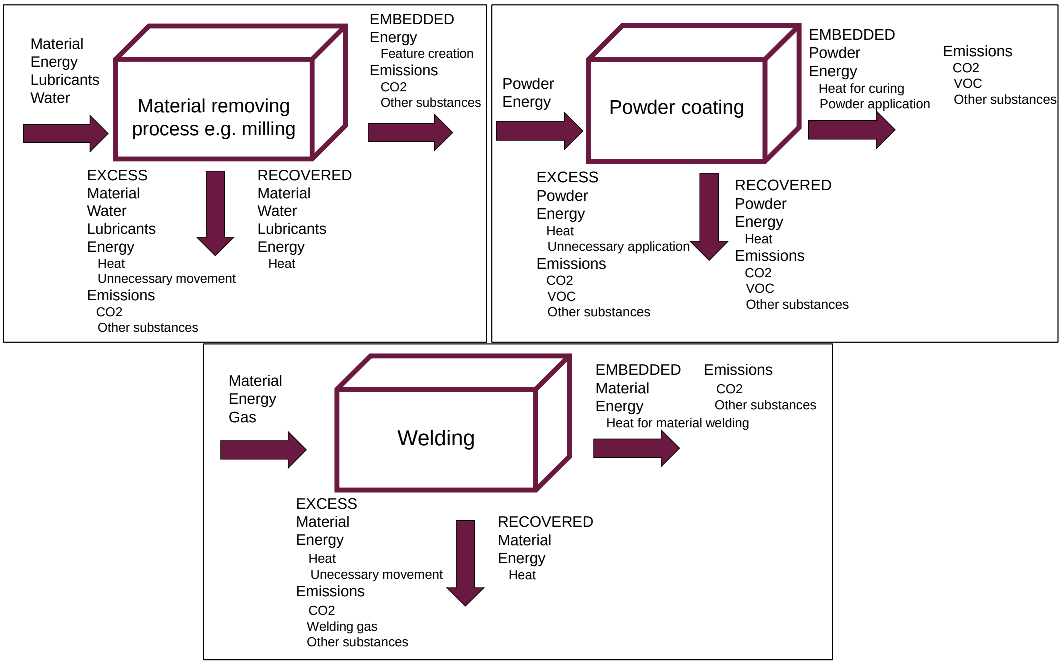


Figure 17. Example input-process-output graphs for material removing, powder coating and welding processes.

6.2.3 Analyze, improve and control

In the analysis phase, an evaluation was done on how the production planning, scheduling and control decisions can affect to the selected metrics, especially how they could improve and control the sustainability performance. Such an analysis involved identifying the cause-effect relationships between the production decisions and sustainability metrics. In general, as discussed in Koho et al. (2015a), prior-to-production decisions, such as investment decisions, procurement strategy, manufacturing location decision, product design and material selection, have a significant impact on the sustainability of the production, while the actual operative decisions have smaller possibilities to affect the sustainability performance.

The actual investment decision for machines to be included into the manufacturing system marks the boundaries for achieving sustainability in the process. For instance, the acquired machinery dictates the recoverable and consumed energy and materials for the process. The design decisions determine the features that need to be created and the processes that are needed to create those features. The designer has to understand that different manufacturing processes generally have different yields and different possibilities for material re-use. Therefore, the designer should target to design the product in such way that processes with good yield could be used. For instance, two-color painting is error-prone process and if it goes wrong, the material may not be re-used. The product designer has to also understand what tolerances are adequate, in order not to set too tight tolerances and thus avoid unnecessary scrap.

Material selection affects through required processing energy, as some materials are more energy consuming to modify than others. Procurement strategy affects to the lifecycle sustainability of the products. The suppliers and sub-contractors with sustainable manufacturing practices may be selected. The manufacturing location decision affects e.g. to the transporting distances and social responsibility aspects of sustainability. The location can also provide certain benefits through the origin of the energy. By changing location to places where renewable energy is available, the carbon footprint can be lowered.

Compared to those aforementioned prior-to-production decisions, the actual operative decisions have only a small role in the overall sustainability performance of production. The possibilities for improving the sustainability performance by production planning and control activities were analysed in two researcher workshops. The results are summarized in the following chapters.

6.2.3.1 Energy consumption and energy efficiency

The main identified means for reducing the energy consumption and increasing the energy efficiency of manufacturing were: Selecting the optimal processing parameters; Turning off the machines when there are no jobs; Allocating orders to the most energy efficient machines; and Reducing the energy consumption of lighting and heating. These will be discussed in the following sections.

Selecting the optimal processing parameters
As discussed by Ikkala et al. (2015), the energy consumption of cutting process is dependent on the process parameters, processed material and the used tools. In MANU's DigiMap-project they studied the effects of cutting speed, feed speed and the cutting depth on the cutting power and to the machine tool power intake from the electric network. The energy efficiency was defined as the ratio of the necessary efficient cutting power and consumed power from the electric network. Based on the results the cutting depth and feed speed seems to have quite linear effect on the cutting power. The results showed that by increasing the material removal rate, the machine tool energy efficiency can be improved. Ikkala et al. (2015) also showed that machine tool energy efficiency is dependent on the cutting parameters. The same cutting power can be obtained by combinations of different cutting parameters, but the machine tool energy efficiency is not always the same. This is because, the motor's energy efficiency is not the same at different revolution speeds, the cutting forces and the frictions are different. The idle state power consumption often takes a significant part of the power consumption at low material removal rates. Figure 18 shows the results by Ikkala et al. (2015).

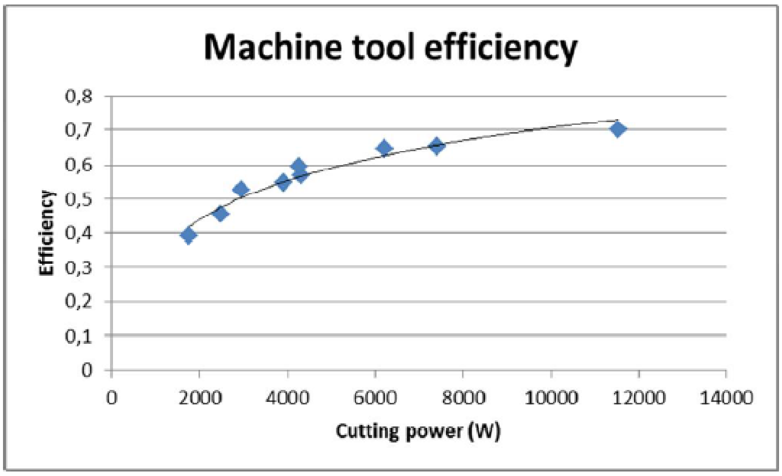


Figure 18. DMG Alpha 500 lathe's energy efficiency as a function of cutting power (Ikkala et al. 2015).

However, it has to be noted that the cutting process parameters also have an effect on the product quality. Therefore targeting to optimal energy efficiency by maximizing the cutting power may sacrifice the quality and lead to scrap, which again means waste both in the forms of raw material and consumed energy. Compromising the product quality for the sake of reduction in energy consumption may not be a very sustainable and wise move. The MES system should guide the operator in selecting proper cutting parameters. This guidance can be based either on systematic tests used to find the optimal processing parameters for certain material and tool combination, or it can be based on accumulated history data of used parameters, measured energy consumption and resulting quality.

Furthermore, optimising the cutting parameters has, alone, a small effect on the energy consumption of the manufacturing system. The fixed consumption, caused by e.g. unloaded motors, coolant pumps, controllers, fans and other peripheral equipment is significant. In general, it can be estimated that from the total energy consumption of a machine tool, only 30% is used for the actual material removing. E.g. in tests performed by (Lanz et al. 2010) the lathe's idle time's power consumption was 1.67 kW, which is 8.4% of the machines continuous drive power. Lanz et al. (2010) concluded that primary savings will come from good production planning, e.g. minimizing the non-productive time, such as CNC machine's idle time or long set-up times.

Turning off the machines when there are no jobs

The results from (Ikkala et al. 2015) suggested that increasing the material removing rate improves the energy efficiency of a machine tool. The results presented in (Lanz et al. 2010), on the other hand, highlighted that the machines idle energy consumption forms a remarkable portion of the total energy consumption of a machine. Therefore, the energy efficiency of machining will improve by running the jobs with full speed and turning off the machines, when there are no jobs to be performed in near future. This could be implemented by building a link between the MES and the individual resources on the factory floor so that the machines would know their own job list and would be programmed to turn themselves off if the production plan shows idle time of certain duration. However, the practice has shown, that machine tools' accuracy may decline when its temperature decreases below the optimal processing temperature. This may happen when the machine is turned off. However, the effect is seldom remarkable, but needs to be kept in mind in applications requiring high accuracy. Also, if machine is turned off for a long time, bacteria may start to grow in cooling fluid, which may corrode the sealants of the machine. Also, it has to be remembered that it takes some time (5–15) to turn the machines back on (electrics, hydraulics). In addition, running the machines with full speed in the morning and having no jobs in the afternoon may not sound appealing to the machine operators who would probably feel useless and get worried about the stability of their contract of employment.

Allocating orders to the most energy efficient machines

The allocation of jobs to the resources could be optimized based on their energy efficiency. In order to do this, the planning system should know the energy consumption of each machine for producing a specific feature of a specific material. By using this information the scheduling system could allocate the orders to certain resources, simultaneously respecting the given delivery dates and trying to minimize the overall energy consumption. Furthermore, smart energy grids could be utilized to optimize production plan based on the fluctuating energy availability and changing energy prices, e.g. by optimizing the order scheduling and utilization of resources based on their energy efficiency and current energy prices. However, maximizing the utilization of most energy efficient resources may lead to a situation in which some machines may stand unused for longer periods of time, which may cause deterioration of the cutting fluids and sealants, as discussed earlier. This, again, cause waste and time consuming maintenance. This problem can avoided by using dry cutting, which means that no cutting fluids are needed.

Reducing the energy consumption of lighting and heating

The overall energy consumption of manufacturing operations can be reduced by cutting from the supporting facilities, such as lighting and heating, when they are not needed. For instance the lighting could be used only when needed, e.g. by utilizing motion recognition to detect human operators or tying the lighting hours to the production plan. Spotlights on top of the workstations could be utilized instead of ceiling lamps lighting the whole factory. This may affect positively to the ergonomics of the workstation as well, if the spotlights support the workers' activities. Lighting could also be worker and context-dependent. This would mean that the specific task to be performed and/or the person performing the task would affect to the level of lighting, i.e. the lighting would be adjusted based on the characteristics of the task and the operator. Similarly as lighting, also the heating of the factory could be adjusted based on the operating hours, i.e. reducing the factory temperature during unmanned time.

6.2.3.2 Material efficiency

The size of the billet material affects to the amount of material that has to be removed from the billet. In the design and planning phase the billet sizes should be optimized to minimize the wasted material, but still keep the amount of different billet sizes, and therefore the warehouse requirements, reasonable. The manufacturing IT-systems need to keep the material balances up to date and the purchasing should ensure the timely availability of the needed material. If there is a lack of proper billet size, bigger billet may be used to ensure the delivery reliability. This means that more waste is generated as originally planned.

Better utilization and recycling of the remainder material (e.g. after cutting) can increase the material efficiency. The MES system could collect the information of the remainder material and suggest to the operator to use those, when the size allows. After the cutting phase the MES could tell to the operator, if the remainder material could still have some further use in the company, or if it should be tossed to the recycling bin going out from the factory. It is important that the workers are given proper training and guidance for recycling and utilizing the remainder material. It should be clear to the operator, what material should be put to waste, what goes to recycling and what can still be utilized within the company's manufacturing process. MES could guide the user in that.

In sheet metal cutting the nesting has a huge effect on the material efficiency. Therefore nesting should be done as efficiently as possible. The production planner could try to optimize the plan in such way that the parts with same sheet thickness could be cut at the same time. The scheduling system should be able to nest the parts from multiple customer orders to the same sheet.

6.2.3.3 Generated waste

The generated waste is strongly dependent on the processes. Increasing the knowledge of workers regarding recycling and reuse can help to reduce the generated waste. Example of reducing waste is machining without cutting fluids and if cutting fluids are used, avoiding the deterioration of the cutting fluids. Rejected parts and products may also be regarded as waste, if they cannot be recycled. The processing should be done with proper good quality tools and processing parameters, so that the required tolerances and surface quality requirements can be respected. MES can help to reduce waste by supporting the condition monitoring of the machine and cutters, and recording the usage hours to support preventive maintenance. Proper instructions and worker training will also help to reduce the amount of rejected products. The MES with intuitive interfaces and new interaction technologies (e.g. Augmented reality), may be used to help the operator to perform the tasks right. It has to also be ensured that the prerequisites for good work exists, e.g. physical and cognitive ergonomics, which relate to the social aspects of sustainability.

6.2.3.4 Greenhouse gases, NOx, SOx, VOC, etc.

The generated greenhouse gases can be reduced by reducing energy consumption (as discussed earlier) and utilizing renewable energy sources. Other air emissions can be controlled by the selection of the process and materials involved in the process, for instance selecting paints which don't produce so much VOC. Local ventilation should be used to minimize the amount of toxic substances in the breathing air.

Transportation is one of the main causes of air emissions. The planning systems could help to optimize the material logistics in such way that the transportation distances and number of transports could be minimized. This could be done, e.g. by combining multiple orders to the same transport.

6.2.3.5 Accidents, injuries and occupational deceases

Attitudes, knowledge, training and experience of the workers affect to the risk of accidents and injuries in the workplace. Hurry often causes negligence. Therefore, the production plan should not put too much work load on the workers. By keeping the workers always aware of the status of the orders and resources will help them to be better prepared for reacting to change situations, i.e. reacting before it is too late. This is assumed to reduce stress. This can be implemented by bringing visual information from the MES onto the factory floor.

Regarding the injuries and work related deceases, the job rotation and changing the task during the day may help to strain different muscles from the body, and therefore reduce the effects of the ergonomic issues of the work (assuming that the worker has enough knowledge on the task and how to perform it right). For tasks which are extra straining, e.g. involving high vibrations, the production plan should allow the worker to have the needed breaks and remind him/her to actually have those breaks in certain time intervals. In the most extreme cases the manufacturing execution system could even force the breaks by not allowing the machines to be run if the breaks are not taken.

From ergonomic perspective, the workstations should be customized based on the characteristics of the worker. The factory system could recognize the worker and do automatically physical configuration to the system based on the anthropometric characteristics of the worker. Also the information display and the information content could be customized based on the experience level of the human and his/her cognitive capabilities (e.g. older person may require larger text).

6.2.3.6 Job satisfaction and motivation

Based on the interviews performed by (Järvenpää et al. 2015) the job rotation and variation in activities can increase the job satisfaction and keep up the motivation. This is not the case, however, with everybody. All the workers don't want job rotation. The production planning can affect to the worker motivation by giving them some level of freedom to choose tasks for which they have sufficient capabilities and interest. This can be supported by production planning and control approach, which doesn't allocate the orders to certain resources (humans), but the workers can dynamically select tasks from the job list. The job rotation will also affect positively to the flexibility of the organization through wider skill and experience level of the workers.

Another aspect increasing motivation, identified by (Järvenpää et al. 2015) was to increase the understanding of the workers on how their work and performance affects to the whole. This can be supported by providing visual information on the factory floor of the important metrics and also about the status of the orders and resources on the factory floor. Such information visibility would also give the operators an improved opportunity to plan ones tasks in advance, which is expected to improve the feel-of-control.

6.3 Conclusions from LeanMES case study

A preliminary case study was introduced in adapting sustainability metrics to a virtual factory environment called LeanMES Concept Factory. The case study is expected to pave the way towards sustainability, as they assist both industry and academia in identifying the actions required to improve sustainability performance and realise sustainable production. Furthermore, the discussed case study is expected to provide ideas for the manufacturing IT-system developers to design new features to their systems, especially regarding the data collection and subsequent reasoning relating to sustainability performance.

In order to help the factory floor workers to make decisions contributing to sustainability improvements, it is important that the information related to the key metrics is clearly visible and understandable to the worker. The worker has to know how to affect to the metrics and how their own actions contribute to those. For instance, in order to reduce waste, the amount of waste and their origins should be visualized to the worker. Different competitions can be organized to support achieving the goals, especially in the learning phase. The manufacturing IT-systems can help by collecting the information needed to calculate those metrics, visualizing the metrics to the workers and providing information and instructions relating to the task at hand. Tracking and tracing functionalities will allow the work environment to be adapted or customized based on the needs and characteristics of the specific tasks and operators. This can contribute to improving the ergonomics of the workstations, both in physical and cognitive sense, and reduce the energy consumption of the facilities and machines when they are not needed.

It is important to notice that sustainability is a wide ranging issue covering the ecological, economical, technical, social and political aspects. Improving one metric can have a negative impact on some other metrics in either the same, or some of the other categories. Furthermore, the sustainability improvements done in one lifecycle phase of a product, may affect to the other lifecycle phases negatively. As pointed out in (Lanz et al. 2010), focusing solely on the difference between two alternative ways to produce a part based on energy consumption may shift the focus away from other more significant issues such as cycle time, idle time, material waste, toxic materials, material recycling and production facility in general. Efforts to make manufacturing more sustainable must consider issues at all relevant levels – product, process and system – and not just one of these in isolation. Therefore lifecycle assessment is needed to consider the total lifecycle sustainability of a product in a holistic way.

7 DISCUSSION AND FUTURE WORK

Sustainability started with the concept of being green, becoming more environmentally friendly, and paying more attention to conserving our planet's resources. Now sustainability has become much more than that. Focusing solely on environmental concerns while using the term sustainability is both misleading and improper as this concentration on one pillar of sustainability ignores the two other pillars, and can lead to designs that are not economical to produce or contain the potential for negative social impacts.

The number of regulations that are related to sustainability has been steadily growing, presenting new legal obligations to industry. Enterprises are also becoming increasingly aware of the importance of being able to credibly present facts about the

Juhani Heilala, Marja Myllysilta, Saija Vatanen, VTT, Eeva Järvenpää, TTY, Kai Syrjälä, FIMECC

sustainability of their performance to the public, which is increasingly aware of its importance.

The focus of engineering design on achieving a superior product, process or service, from the currently prevalent point-of-view of functional and economic factors, is now shifting towards sustainable design. Sustainability-related issues are increasingly important in business decision-making. Examples of the drivers of this development are:

- Cost savings, resource efficiency
- Society-set regulations, directives, standards, etc.
- Customer requirements, business reputation
- Organisation and others giving support

Sustainability requires simultaneous consideration of economic, environmental, and social implications associated with the production and delivery of goods. Sustainable development and manufacturing relies on descriptive metrics, advanced decision-making, and policy for implementation, evaluation, and feedback. This report shows Sustainability Measurement Framework for Finnish manufacturing companies as a process model.

The path towards sustainability is proving a struggle for Finnish manufacturing companies. Sustainability is a viable business strategy which takes into account economic considerations, governmental issues, as well as strongly voiced opinions from customers and stakeholders.

The concept for sustainability performance indicators, reporting and improvement has been developed, published and benchmarked in international conferences, including journal publication. One test case is on-going with LeanMES project as reported here also. The research partners are available for supporting Finnish manufacturing industry in their steps towards sustainable business.

ACKNOWLEDGEMENT

Support from the Finnish Metals and Engineering Competence Cluster (FIMECC) MANU (Future digital manufacturing technologies and systems) -research program, Tekes – the Finnish Funding Agency for Technology and Innovation, VTT Technical Research Centre of Finland Ltd, Tampere University of Technology and the participating companies is gratefully acknowledged. This report is done in collaboration with Next Generation Manufacturing and LeanMES projects in MANU program.

DISCLAIMER

No approval or endorsement of any commercial product by the authors is intended or implied. Certain commercial equipments, software, instruments, or materials are identified in this report to facilitate better understanding. Such identification does not imply recommendations or endorsement by the authors, nor does it imply the materials, software, or equipment identified are necessarily the best available for the purpose.

REFERENCE

Arnette, A.N.; Brewer, B.L.; Choal, T. (2014). Design for sustainability (DFS): the intersection of supply chain and environment. Journal of Cleaner Production 83, pp. 374–390. http://dx.doi.org/10.1016/j.jclepro.2014.07.021.

Bi, Z. (2011). Revisiting System Paradigms from the Viewpoint of Manufacturing Sustainability. Sustainability 3, 1323–1340. doi:10.3390/su3091323. ISSN 2071-1050. www.mdpi.com/journal/sustainability available at http://www.mdpi.com/2071-1050/3/9/1323/htm.

Bogue, R. (2014) "Sustainable manufacturing: a critical discipline for the twenty-first century". Assembly Automation 34(2), pp. 117–122. Permanent link to this document: http://dx.doi.org/10.1108/AA-01-2014-012.

Chen, D.; Schudeleit, T.; Posselt, G.; Thiede, S. (2013). A state-of-the-art review and evaluation of tools for factory sustainability assessment. 2nd CIRP Global Web Conference. Procedia CIRP 9, pp. 85–90. doi: 10.1016/j.procir.2013.06.173.

EFFRA. (2013). Factories of the Future 2020': Roadmap 2014–2020. Available at: http://www.effra.eu/attachments/article/129/Factories%20of%20the%20Future%2020 20%20Roadmap.pdf.

ELCD (European reference Life Cycle Database)
http://eplca.jrc.ec.europa.eu/ELCD3/.

Elkington, J. (2007). “Cannibals with Forks: The Triple Bottom Line of 21st Century Business”, In: American Management Association. Creating a Sustainable Future: A Global Study of Current Trends and Possibilities 2007–2017, American Management Association, New York, 2007.

ENEPLAN – “Energy Efficient Process pLAnning system” http://www.eneplan.eu/.

Environdec. 2015. EPD International (2015) General Programme Instructions of the International EPD® System. Version 2.5. Available at: http://environdec.com/The-International-EPD-System/General-Programme-Instructions/#.VYEouVXyVaQ. Accessed 17.06.2015. Dated 2015-05-11.

EPA, Sustainable Manufacturing” web pages. (http://www.epa.gov/sustainablemanufacturing/).

EPES – “Eco Process Engineering System for composition of services to optimize product life cycle” http://www.epes-project.eu/.

European Commission. (2008). “Sustainable consumption and production – a challenge for us all. Environmental fact sheet”, Available online at: http://ec.europa.eu/environment/archives/eussd/pdf/brochure.pdf (Accessed May 26, 2014).

Eurostat: “Sustainable Production and Consumption”, Available online at: http://epp.eurostat.ec.europa.eu/portal/page/portal/sdi/indicators/theme2 (Accessed August 15, 2014).

eVSM. electronic Value Stream Mapping), http://www.evsm.com/.

Feng, S.C.; Joung, C.; Li, G. (2010). “Development Overview of Sustainable Manufacturing Metrics”. Proceedings of the 17th CIRP International Conference on Life Cycle Engineering 2010, Hefei, China.

FIMECC. (2012). FIMECC MANU – programme, Available online at: http://www.fimecc.com/content/manu-future-digital-manufacturing-technologies-and-systems (accessed April 30th, 2015).

FIMECC. (2014a). Elinkaarinäkökulma liiketoiminnan kehittämisessä. Opas metalli- ja konepajateollisuudelle. RESULT PUBLICATIONS 2/2014 • FIMECC

Juhani Heilala, Marja Myllysilta, Saija Vatanen, VTT,
Eeva Järvenpää, TTY, Kai Syrjälä, FIMECC

PUBLICATIONS SERIES NO. 7. Available http://hightech.fimecc.com/results/a-roadmap-towards-sustainability.

FIMECC. (2014b). Elinkaariarviointi tuotesuunnittelussa. Opas metalli- ja konepajateollisuudelle. RESULT PUBLICATIONS 1/2014 • FIMECC PUBLICATIONS SERIES NO. 6. http://hightech.fimecc.com/results/a-roadmap-towards-sustainability.

FITMAN. (2013). D2.2 FITMAN Verification & Validation Business and Technical Indicators Definition. Available at: http://cordis.europa.eu/fp7/ict/netinnovation/deliverables/fitman/fitman-d22.pdf.

GaBi LCA software form PE International of Stuttgart, Germany. http://www.pe-international.com/nw-eu-english/index/ now http://www.thinkstep.com/.

Global Footprint Network. (2014). “Earth Overshoot Day”. Available online at: www.footprintnetwork.org/en/index.php/GFN/page/earth_overshoot_day/ (Accessed April 15, 2015).

Goodland, R. (1995). “The concept of environmental sustainability”. Annual Review of Ecology and Systematic 26, pp. 1–24.

GRI. (2013). Global Reporting Initiative. G4 Sustainability reporting guidelines. Available online at: https://www.globalreporting.org/resourcelibrary/GRIG4-Part1-Reporting-Principles-and-Standard-Disclosures.pdf (Accessed April 15, 2015).

Heilala, J; Vatanen, S.; Montonen, J.; Tonteri, H.; Johansson, B.; Stahre, J.; Lind, S. (2008). Simulation-Based Sustainable Manufacturing System Design. In: Mason, S.J.; Hill, R.R.; Mönch, L.; Rose, O.: Jefferson, T.; Fowler J.W. (Eds.). Proceedings of the 2008 Winter Simulation Conference. IEEE. Miami, Florida, U.S.A, 1922–1930. http://www.informs-sim.org/wsc08papers/237.pdf.

Heilala, J.; Majuri, M.; Sääski, J.; Pesonen, J.; Halme, J.; Hyötyläinen, R.; Hentula, M.; Paro, J.; Tuokko, R. (2011). Parhaat tuottavat – Valmistavan teknologia-teollisuuden tutkimusagenda 2020 (In Finnish). VTT. Espoo (2011), 63 p. + app. 10 p. http://www.vtt.fi/files/news/2011/parhaat_tuottavat_final.pdf.

Herrmann, C.; Thiede, S.; Kara, S.; Hesselbach, J. (2011). Energy Oriented Simulation of Manufacturing Systems – Concept and Application. CIRP Annals 60(1):45–48.

IEC 62264-1:2013 Enterprise-control system integration – Part 1: Models and terminology.

IISD Reporting Services: “Oslo Roundtable on Sustainable Production and Consumption”, Available online at: http://www.iisd.ca/consume/oslo00.html, (Accessed August 15, 2014).

Ikkala, K.; Lanz, M.; Kiviö, J.; Coatanéa, E. (2015). Energy efficiency evaluation method for machine tools. International Conference on Flexible Automation and Intelligent Manufacturing (FAIM 2015), June 22–26, 2015, Wolverhampton, UK.

IMS2020 Roadmap on Sustainable Manufacturing, Energy Efficient Manufacturing and Key Technologies (2010) (www.ims2020.net).

Institute for Sustainability (2011). Available at: http://theinstituteforsustainability.com/ (Accessed 28 May 2015).

ISO (International Organization for Standardization, http://www.iso.org/iso/home.html).

ISO 13374-1:2003. Condition monitoring and diagnostics of machines – Data processing, communication and presentation – Part 1: General guidelines.

ISO 13374-2:2007. Condition monitoring and diagnostics of machines -- Data processing, communication and presentation -- Part 2: Data processing.

Juhani Heilala, Marja Myllysilta, Saija Vatanen, VTT,
Eeva Järvenpää, TTY, Kai Syrjälä, FIMECC

ISO 14045:2012 Environmental management – Eco-efficiency assessment of product systems – Principles, requirements and guidelines.

Järvenpää, E. (2015). LeanMES Concept Factory. MANU LeanMES project documentation, FIMECC. 5 p.

Järvenpää, E.; Lanz, M.; Tokola, H.; Salonen, T.; Koho, M. (2015). Production planning and control in Finnish manufacturing companies – Current state and challenges. Proceedings of the 25th International Conference on Flexible Automation and Intelligent Manufacturing, FAIM2015, 23rd–26th June, 2015, Wolverhampton, UK. 8 p.

Järvinen, P. (2008). “Mapping research questions to research methods”, In: Avison, D.; Kasper, G.M.; Pernici, B.; Ramos, I.; Roode, D. (Eds.). Advances in Information Systems Research, Education and Practice. Springer; Boston, Vol. 274, pp. 29–41, 2008.

Jawahir, I.S.; Dillon, O.W.; Rouch, K.E.; Joshi, K.J.; Venkatachalam, A.; Jaafar, J.H. (2006). “Total Life-cycle considerations in product design for sustainability: A framework for comprehensive evaluation”, Proceedings of 10th Int. Research/Expert Conf, Barcelona, Spain.

Jawahir, I.S.; Rouch, K.E.; Dillon, O.W.; Holloway, L.; Hall, A. (2007). Design for sustainability (DFS): new challenges in developing and implementing a curriculum for next generation design and manufacturing engineers. Int. J. Eng. Educ. 23(6), pp. 1053–1064.

Jayal, A.D.; Badurdeen, F.; Dillon, O.W. Jr.; Jawahir, I.S. (2010). Sustainable manufacturing: Modeling and optimization challenges at the product, process and system levels. CIRP Journal of Manufacturing Science and Technology 2(3): 144–152. doi:10.1016/j.cirpj.2010.03.

Jovane, F.; Westkämper, E.; Williams, D. (2008a). “The ManuFuture Road: Towards Competitive and Sustainable High-Adding-Value Manufacturing”. Springer, Berlin, Germany.

Jovane, F.; Yoshikawa, H.; Alting, L.; Boër, C.R.; Westkamper, E.; Williams, D.; Tseng, M.; Seliger, G.; Paci, A.M. (2008b). “The incoming global technological and industrial revolution towards competitive sustainable manufacturing”. CIRP Annals – Manufacturing Technology 57, pp. 641–659.

Kelvin, Baron William Thomson. (26 Jun 1824–17 Dec 1907). Scientific Quatations.

Kibira, D.; Jain, S.; McLean, C. (2009). A System Dynamics Modeling Framework for Sustainable Manufacturing. Proceedings of the 27th Annual System Dynamics Society Conference. http://www.nist.gov/customcf/get_pdf.cfm?pub_id=903291.

Koho, M.; Tapaninaho, M.; Heilala, J.; Torvinen, S. (2014). Measures and a concept for realizing sustainability in the manufacturing industry. International Conference on Sustainable Design and Manufacturing, SDM 2014, 28–30 April 2014, Cardiff, Wales, United Kingdom. KES Transactions on Sustainable Design and Manufacturing, Special Edition – Sustainable Design and Manufacturing 2014, Part 1. Future Technology Press 1(1), pp. 432–443.

Koho, M.; Tapaninaho, M.; Heilala, J.; Torvinen, S. (2015a): “Towards a concept for realizing sustainability in the manufacturing industry”. Journal of Industrial and Production Engineering 32(1), pp. 12–22. DOI: 10.1080/21681015.2014.1000402.

Koho, M.; Tapaninaho, M.; Järvenpää, E.; Lanz, M.; Heilala, J. (2015b). Sustainability Performance Measurement and Management: Process Model. FAIM2015, June 2015.

Labuschagne, C.; Brent, A.C. (2005). Sustainable Project Life Cycle Management: the need to integrate life cycles in the manufacturing sector. International Journal of Project Management 23, pp. 159–168. doi:10.1016/j.ijproman.2004.06.003.

Lanz, M.; Mani, M.; Leong, K.; Lyons, K.; Ranta, A.; Ikkala, K.; Bengtsson, N. (2010). Impact of energy measurements in machining operations. Proceedings of the ASME 2010 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDTC/CIE 2010), August 15–18, 2010, Montreal, Quebec, Canada.

Lanz, M.; Järvenpää, E.; Nylund, H.; Tuokko, R.; Torvinen, S.; Georgoulias, K. (2014). “Sustainability and Performance Indicators Landscape”. Proceedings of the 24th International Conference on Flexible Automation and Intelligent Manufacturing, FAIM2014, 20th–23rd May, San Antonio, Texas.

Lee, J.Y.; Kang, H.S.; Noh, S.D. (2014). MAS2: an integrated modeling and simulation-based life cycle evaluation approach for sustainable manufacturing. Journal of Cleaner Production 66, 1 March 2014, pp. 146–163. http://dx.doi.org/10.1016/j.jclepro.2013.11.029.

Lind, S.; Johansson, B.; Stahre, J.; Berlin, C.; Fasth, Å.; Heilala, J.; Helin, K.; Kiviranta, S.; Krassi, B.; Montonen, J.; Tonteri, H.; Vatanen, S.; Viitaniemi, J. (2009). SIMTER - A Joint Simulation Tool for Production Development. VTT Working Papers : 125. VTT, Espoo. 49 p. ISBN 978-951-38-7185-7 http://www.vtt.fi/inf/pdf/workingpapers/2009/W125.pdf.

LIPASTO – a calculation system for traffic exhaust emissions and energy consumption in Finland http://lipasto.vtt.fi/.

Lowell Center for Sustainable Production. University of Massachusetts Lowell. http://www.sustainableproduction.org/index.php.

Lu, T.; Gupta, A.; Jayal, A.D.; Badurdeen, F.; Feng, S.C.; Dillon, O.W.; Jawahir, I.S. (2010). A Framework of Product and Process Metrics for Sustainable Manufacturing. Proceedings of the Eighth International Conference on Sustainable Manufacturing, Abu Dhabi, November 22–24, 6 p. Available at: http://www.nist.gov/customcf/get_pdf.cfm?pub_id=907261.

Martins, A.A.; Mata, T.M.; Cost, C.A.V.; Sikdar S.K. (2001). “Framework for Sustainability Metrics”, Ind. Eng. Chem. Res. 46, pp. 2962–2973.

May,G.; Barletta, I.; Stahl, B.; Taisch, M. (2015). Energy management in production: A novel method to develop key performance indicators for improving energy efficiency. Applied Energy 149, pp. 46–61. http://dx.doi.org/10.1016/j.apenergy.2015.03.065.

Myllysilta, M.; Vatanen, S.; Heilala, J. (2015) Ekotehokkuuden arvioinnilla tukea päätöksentekoon – Opas arviointimenetelmästä yrityksille. FIMECC MANU Report 2015.

NACFAM (National Council for Advanced Manufacturing). 2012. Sustainable manufacturing. www.nacfam.org/PolicyInitiatives/SustainableManufacturing/tabid/64/Default.aspx.

NIST National Institute of Technology “Sustainable Manufacturing Portal”. http://www.nist.gov/sustainable-manufacturing-portal.cfm.

NIST. (2010). National Institute of Technology “Sustainability Standards Portal”, http://www.mel.nist.gov/msid/SSP/index.html.

OECD. (2001). OECD Environmental Indicators: Towards Sustainable Development 2001, OECD Publishing, Paris. DOI: http://dx.doi.org/10.1787/9789264193499-en.

OECD. (2010a). "Tracking Performance: Indicators for Sustainable Manufacturing", in OECD, Eco-Innovation in Industry: Enabling Green Growth, OECD Publishing, Paris. DOI: http://dx.doi.org/10.1787/9789264077225-6-en.

OECD. (2010b). Eco-Innovation in Industry: Enabling Green Growth, OECD Publishing, Paris. DOI: http://dx.doi.org/10.1787/9789264077225-en.

OECD. (2011). OECD Sustainable Manufacturing Toolkit, available at http://www.oecd.org/innovation/green/toolkit/. (Accessed May 26, 2015).

Paju, M.; Heilala, J.; Hentula, M.; Heikkilä, A.; Johansson, B.; Leong, S.; Lyons, K. (2010). Framework and indicators for a sustainable manufacturing mapping methodology. In: Johansson, B.; Jain, S.; Montoya-Torres, J.; Hugan, J.; Yücesan, E. (Eds.). Proceedings of the 2010 Winter Simulation Conference, pp. 3411–3422. 2010 Winter Simulation Conference 2010, WSC '10, Baltimore Marriot Waterfront, Baltimore, Maryland, USA, 5–8 Dec. 2010. Available at following http://www.informs-sim.org/wsc10papers/315.pdf.

Paju, M. (2012). Eco-efficient production. In: Production matters. VTT in global trends. Häkkinen, K. (Ed.). VTT Research Highlights : 3, VTT , Espoo, pp. 58–61. http://www.vtt.fi/inf/pdf/researchhighlights/2012/R3.pdf.

Peng, T. (2014). A Novel Approach Towards Energy-efficient Machining. Phd thesis. Department of Mechanical Engineering, Faculty of Engineering. University of Auckland. New Zealand. Available at:
https://researchspace.auckland.ac.nz/handle/2292/22581.

Peng, T.; Xun Xu, X.; Heilala, J. (2012). Energy-efficient machining via energy data integration. Conference Proceeding of APMS 2012. International Conference on Advances in Production Management Systems (APMS). "Competitive Manufacturing for Innovative Products and Services", Rhodes, Greece, 24–26 September 2012 Athena Research and Innovation Center.

PTC Windchill . http://www.ptc.com/product/windchill/lca.

SCOR. (2008). The Supply Chain Operations Reference model.

Shuaib, M.; Seevers, D.; Zhang, X.; Badurdeen, F.; Rouch, K.E.; Jawahir, I.S. (2014). Product Sustainability Index (ProdSI). A Metrics-based Framework to Evaluate the Total Life Cycle Sustainability of Manufactured Products. Journal of Industrial Ecology 18(4). DOI: 10.1111/jiec.12179.

Singh, R.K.; Murty, H.R.; Gupta, S.K.; Dikshit, A.K. (2009). “An overview of sustainability assessment methodologies”. Ecological Indicators 9, pp. 189–212.

Singh, R.K.; Murty, H.R.; Gupta, S.K.; Dikshit, A.K. (2012). “An overview of sustainability assessment methodologies”. Ecological Indicators 15, pp. 281–299.

SolidWorks Sustainability. (2010). http://www.solidworks.com/sustainability/.

Stamatis, D.H. (2004). “Six Sigma Fundamentals: A Complete Guide to the System, Methods and Tools”. Productivity Press, New York.

SULCA. https://www.simulationstore.com/SULCA.

Sustainable Minds. http://www.sustainableminds.com/product.

SUSTAINVALUE – “Sustainable Value Creation in Manufacturing Networks” http://www.sustainvalue.eu/.

Takeda, H.; Veerkamp. P.; Tomiyama, T.; Yoshikawa, H. (1990). “Modeling Design Processes”. AI Magazine 11, pp. 37–48.

Tapaninaho, M.; Koho, M.; Nylund, H.; Heilala, J.; Torvinen, S. (2013). Sustainability performance indicators for supporting the realization of sustainable and energy-efficient manufacturing. 23rd International Conference on Flexible Automation &

Intelligent Manufacturing, FAIM13, 26–28 June 2013, Porto, Portugal. In: Advances in Sustainable and Competitive Manufacturing Systems, Part VI. Lecture Notes in Mechanical Engineering. Springer, pp. 1677 – 1688. DOI: 10.1007/978-3-662-44736-9_77.

Tapaninaho, M.; Koho, M.; Pihkola, H.; Heilala, J. (2014). Developing a concept for sustainability indicators and reporting systems for Finnish manufacturing industry. The sixth Swedish Production Symposium, SPS14, 16–18 September 2014, Göteborg, Sweden. Proceedings of The 6th International Swedish Production Symposium 2014, 9 p. Available at: http://conferences.chalmers.se/index.php/SPS/SPS14/paper/viewFile/1690/363.

Thiede, S.; Seow, Y.; Andersson, J.; Johansson, B. (2013). Environmental aspects in manufacturing system modelling and simulation – State of the art and research perspectives. CIRP Journal of Manufacturing Science and Technology 6, pp. 78–87. http://dx.doi.org/10.1016/j.cirpj.2012.10.004.

UNEP. (2007). United Nations Environment Programme. Life Cycle Management. A Business Guide to Sustainability. ISBN: 978-92-807-2772-2, DTI/0889/PA. http://www.unep.org/pdf/dtie/DTI0889PA.pdf. (Accessed 23.3.2014).

UNEP. (2011). United Nations Environment Programme. Towards a Life Cycle Sustainability Assessment: Making informed choices on products. ISBN No: 978-92-807-3175-0. DTI/1412/PA.
http://www.unep.org/pdf/UNEP_LifecycleInit_Dec_FINAL.pdf
http://www.unep.org/publications/contents/pub_details_search.asp?ID=6236.

U.S. Department of Commerce. (2008). How does Commerce define Sustainable Manufacturing?
http://www.trade.gov/competitiveness/sustainablemanufacturing/how_doc_defines_SM.asp. (Accessed 28 May 2015).

U.S. Department of Commerce's "Sustainable Manufacturing 101 Module" (http://www.trade.gov/green/sm-101-module.asp).

Valkokari, K.; Valkokari, P.; Palomäki, K.; Uusitalo, T.; Reunanen, M.; Macchi, M.; Rana, P.; Liyanage, J.P. (2014). "Road-mapping the business potential of sustainability within the European manufacturing industry". Foresight 16(4), pp. 360–384. Permanent link to this document: http://dx.doi.org/10.1108/FS-05-2012-0037.

Veleva, V.; Ellenbecker, M. (2001). "Indicators of sustainable production: Framework and methodology". J. Cleaner Prod. 9, pp. 519–549.

Visual Components. http://www.visualcomponents.com/.

VTT Sustainability Assessment.
http://www.vttresearch.com/services/bioeconomy/industrial-process-efficiency-and-management/concept-development-and-evaluation/sustainability-assessment.

WBCSD World Business Council for Sustainable Development, http://www.wbcsd.org/home.aspx. (Accessed 7.1.2015).

WBCSD. (1997). WBCSD – World Business Council for Sustainable Development: "Signals of Change: Business Progress Toward sustainable Development", Geneva, Switzerland, 1997.

WCED. (1987). Report of the World Commission on Environment and Development: Our Common Future, Oxford University Press, Oxford.

Wiktorsson, M.; Bellgran, M.; Jackson, M. (2008). "Sustainable Manufacturing - Challenges and Possibilities for Research and Industry from a Swedish perspective", In: Mitsuishi, M.; Ueda, K., Kimura, F. (Eds.). Manufacturing Systems and Technologies for the New Frontier. Springer, London, pp. 119–122.

Winroth, M.; Almström, P.; Andersson, C. (2014). “Indicators of sustainable production – A survey among Swedish manufacturing industry”. Proceedings of the 1st EurOMA Sustainable OM & SCM Forum, Groningen.

WWF. (2012). “Living Planet Report 2012”. WWF International. Gland: Switzerland.

Zendoia, J.; Woy, U.; Ridgway, N.; Pajula, T.; Unamuno, G.; Olaizola, A.; Fysikopoulos, A.; Krain, R. (2014). A specific method for the LCI of machine tools and its demonstration with two manufacturing case studies. Journal of Cleaner Production 78, 1 September, pp. 139–151.

We create strategic renewal – together

FIMECC Ltd.

Åkerlundinkatu 11 A
33100 Tampere, Finland
www.fimecc.com

VAT-number (Finland) 2179030-4