Available online at www.sciencedirect.com
ScienceDirect
Procedia Manufacturing 8 (2017) 112 – 120
Procedia MANUFACTURING

14th Global Conference on Sustainable Manufacturing, GCSM 3-5 October 2016, Stellenbosch, South Africa

Material efficiency measurement: empirical investigation of manufacturing industry

Sasha Shahbazi*, Mohammed Salloum, Martin Kurdve, Magnus Wiktorsson

[a]*School of Innovation, Design and Engineering, Mälardalen University, Smedjegatan 37, Eskilstuna, 63220, Sweden*

Abstract

Improving material efficiency contributes to reduce the volume of industrial waste as well as resource consumption. However, less has been published addressing on what to measure for material efficiency in a manufacturing company. This paper presents the current practice of material efficiency performance indicators in a manufacturing context through a bottom-up approach. In addition to literature review, the empirical data was collected via a multiple case study at seven global manufacturing companies located in Sweden. The results show that existing material efficiency indicators are limited and are mainly measured as a cost or quality parameter rather than environment. The limited number of measurements relates to the fact that material efficiency is not considered as a central business in manufacturing companies and is managed by environmental department with limited correlation to operation. Additionally, these measurements do not aim to reduce waste volume or improve homogeneity of generated waste.

Peer-review under responsibility of the organizing committee of the 14th Global Conference on Sustainable Manufacturing

Keywords: Material efficiency; performance indicator; manufacturing

1. Introduction

The European Commission [1], the World Economic Forum [2] and Mistra [3] emphasize on circular economy and resource efficiency as one of the most important strategic options to capture value in industry since these strategies will provide major economic opportunities, improve productivity, drive down costs, increase efficiency and effectiveness, and boost competitiveness. Material efficiency is a key element within circular economy and resource

* Corresponding author. Tel.: 46 (0)16 153715.
E-mail address: sasha.shahbazi@mdh.se

Peer-review under responsibility of the organizing committee of the 14th Global Conference on Sustainable Manufacturing
doi:10.1016/j.promfg.2017.02.014

efficiency, which reduces solid industrial waste, recoups a large portion of the original material value, helps the manufacturing industry to go up the waste hierarchy, and in a national and/or global perspective reduces the demand for virgin raw material, carbon emissions and total energy consumption.

Understanding the existing state and improvement potentials of an operation in term of material efficiency leads to a better waste segregation and higher recycling rate, and increases success rates of waste management initiatives. However, many factors contribute to the difficulties surrounding material efficiency [4], including the presence of numerous external and internal actors, low levels of information and knowledge, little correlation among the different actors' business models, the method of allocating gains and costs in the system, and the relationships between legal and regulatory systems and environmental and economic benefits. In addition to those barriers, our experience and empirical studies together with previous literature on material efficiency (e.g. [5]) show another important barrier towards improved material efficiency: lack of effective approaches to measure and evaluate material efficiency. Many of manufacturing companies miss material efficiency key performance indicators (KPIs), mainly due to the fact that productivity and efficiency, quality, cost and delivery KPIs are generally considered to be more important than sustainability KPIs to run the business and fulfil customer needs. Among sustainability measurement, material efficiency has lower priority at manufacturing companies and it is not considered as important as other sustainability aspects such as energy efficiency, energy consumption or CO_2 neutralization, which is mainly due to existing legislation and regulations. Even existing material and waste related measurements are reactively for reporting purposes for external stakeholders and authorities [6]. Therefore waste and material related issues such as waste homogeneity, and non-value adding materials (auxiliary and residual materials) are not measured and evaluated on regular basis. Looking at the most deployed frameworks in performance measurements such as the Balanced Scorecard [7] and the performance prism [8], material efficiency (together with many other aspects of sustainability) is not taken into account, while cost, quality, delivery and safety KPIs are dominant [9, 10]. Although academic publications have drawn attention to the area of material efficiency, less has been published addressing material efficiency in manufacturing, particularly material efficiency measurement and KPIs, i.e. what to measure for material efficiency in a manufacturing company, how to manage material efficiency performance, how other indicators interact with material efficiency measurements, and how they are connected to overall goal and strategy of company.

By focusing on the "what" aspect, this paper aims to present the current practice of material efficiency performance indicators through a bottom-up data collection approach i.e. operational level as oppose to organizational/enterprise level. Therefore, a single research question is formulated to fulfill this aim: what performance indicators are currently used at manufacturing companies that relates to material efficiency?

2. Methodology

Research presented in this paper was carried out as a part of an ongoing Swedish research project called Sustainable and Resource Efficient Business Performance Measurement Systems (SuRe BPMS). The project aims to develop a performance measurement system to support companies in development and redesign of performance measurement systems taking efficiency and sustainability into consideration. This paper however, within the area of sustainable manufacturing [11] focuses on material efficiency [12]. The paper contributes to industry and academia in different ways: (a) results can be used as a general set of common *performance* and *industry-generic* indicators [13] for material efficiency in research studies; (b) managers and practitioners can use the identified KPIs for evaluation and reporting purposes at their manufacturing companies, (c) helps companies to cut compliance costs to comply with upcoming guidelines and material efficiency legislations, (d) adds value to manufacturing sustainability and material efficiency literature by reviewing the most common material efficiency KPIs in manufacturing.

Due to lack of empirical studies on what to measure for material efficiency in manufacturing industry, a multiple case study methodology consist of real-time empirical studies at seven global manufacturing companies located in Sweden was adopted. Studied companies are mainly global companies within different manufacturing industry including heavy duty trucks, automobile, construction equipment, aerospace and metal cutting. These companies vary in terms of size, volume, complexity and waste management system; and their operations encompass machining, testing, assembly, painting, surface treatment, heat treatment and welding operations. Companies' participation was based on their intention to improve performance measurement system via SuRe BPMS research project.

With a limited understanding, the adopted case study methodology was appropriate [14] to comprehend the phenomenon (here the material efficiency performance indicators and measurements) and fulfil the research aim. Empirical data were gathered by means of direct observations, formal and informal discussions and document reviews. The observation included a bottom-up data collection approach for identifying material efficiency performance indicators (mainly relating to waste, material consumption, and waste segregation). The bottom-up approach incorporated investigating documentations/whiteboards in the meeting areas and production control measures on shop floor, where the KPIs are regularly presented, reviewed and discussed.

In order to better understand the measurements and validate the empirical findings, empirical data collection on material efficiency KPIs compounded with discussions with different organizational functions including environmental manager, area manager or production manager. This also helped capturing a broad perspective of material efficiency measurements in connection to different organizational levels. Documents were also briefly studied to get a basic insight about companies, their overall strategy and environmental target and current improvement (both environmental and operational) projects. The data analysis included data reduction, data displays, and conclusion drawing and verification, as suggested by Miles and Huberman [15]. Results were afterwards compared and analyzed in an iterative and explorative nature to increase understanding and generalizability of empirical findings.

3. Theoretical background

For many years financial, business and market performance indicators were in the center of measurement targets without taking sustainability performance (in particular environmental and social sustainability) into account. With publication of Our Common Future report [16], sustainability objectives gradually commenced in business strategies [17], environmental performance indicators were considered in managerial decision makings [18], and externally communicated in form of environmental reports [19]. The European Environmental Agency [20] and the Organization for Economic Co-operation and Development [21] define environmental indicator as an observed value representative of a phenomenon that is tracked over a certain period of time for progress, supporting, evaluation and informing the public. Environmental indicator demands qualitative or quantitative bits of information, visualizes change chronologically and communicates the phenomenon in an easier and more understandable way as an early warning of environmental damage. Among many environmental indicators to assess environmental performance of an operation or a product, Ecological Footprint, Carbon Footprint and Water Footprint have received more attention [22]: mainly due to their level of standardization and support of SETAC and ISO standards as well as their compatibility for environmental reporting purposes (in addition to measuring environmental performance). Water footprint in a manufacturing process is measured by calculating the total water consumption to manufacture a product throughout the entire supply chain [23]. Ecological footprint in a manufacturing process determines the space needed to provide the resources consumed, to produce a product, to dispose generated waste [24]. Carbon footprint in a manufacturing process measures the total greenhouse gas emission produced to manufacture a product; it is usually applied in energy-related studies and indicated in carbon dioxide and global warming equivalents.

Among the few articles investigating material efficiency in manufacturing context, Abdul Rashid [5] and Shahbazi [4] discuss existing barriers, including the lack of effective approaches to measure and evaluate material efficiency; which is in line with previous generic environmental studies e.g. by Al Zaabi et al. [25], Shi et al. [26] among others. However, past literature on material efficiency leaves practitioners with scant guidance on material efficiency measurement and relevant performance indicators.

Herva et al. [22] indicate *material input per unit service (MIPS)* as an appropriate material efficiency measure, although this indicator does not consider the material type i.e. combustible, inert, metals, fluids and their hazardousness. They also include *Life Cycle Assessment* (resource depletion) and *ecological footprint*. Based on supply chain operation, Bai and Sarkis [18] introduce *waste generation* from products and materials, and *percentage recycled material* as environmental performance measures that directly relate to material efficiency. In addition, other measurements including *mutual planning and assistance with supplier* for material efficiency improvement, *environmentally safe alternatives* (material substitution), *knowledge transfer* between suppliers, manufacturing company and waste handling company, and *new environmentally sound product or process* towards improved material efficiency can be indirectly perceived from their results as well. World Resources Institute [27] and the factor 10 club propose *material use*, *non-product output* (residual materials), *hazardous chemicals* and *net use of natural capital* as relevant material efficiency indicators. Based on eco-efficiency approach, World Business Council on Sustainable Development [28] name *material intensity of goods and services*, *material recyclability*, *sustainable use of renewable resources* (environmentally friendly material), *product durability* (component reuse, remanufacturing and repair) and *service intensity of goods and services* (through leasing, shared ownership and product service systems) that are relevant to material efficiency. Based on life cycle approach, Azapagic and Perdan name *resource use* (including resource depletion and land use), *solid waste*, *material intensity*, *recycling percentage of waste*, *product durability*, *service intensity* and *waste reduction* as indicators towards material efficiency [19]. The material intensity implies as total material consumption to produce the product, therefore it is equivalent to MIPS; in opposition to definition given by [29] as total wasted material per unit output (per kg of product, per SEK of revenue or per SEK value added). World Steel Association has also a material efficiency indicator as *% of by-products reused* [30]. Based on investigations on corporate social responsibility, global reporting initiative, rating systems and management systems, Rahdari and Rostamy list *waste productivity* (sales/tons of waste produced), *hazardous waste treatment* and *percentage of transported waste shipped internationally* as relevant material efficiency KPIs. Moreover, Vermeulen et al. [31] include *material intensity*, *waste recycling*, *waste/end products sent to energy recovery*, *waste sent to landfill* (land use), *human toxicity* (hazardous waste), *raw material consumption* and *waste treatment cost* as direct performance indicators related to waste treatment process. The indirect indicators for material efficiency include *upstream and downstream process* as well as *production of residuals* and *recovery of end products* (per unit of mass) and *transportation of materials* (per unit of mass multiples by unit of distance). In addition, Spangenbergh [32] discusses taking the *ecological rucksack* into account, which includes non-value adding materials (auxiliary materials) that are not physically included in the final product, but have been necessary for production, use, recycling and disposal.

4. Empirical findings

In total more than 3000 performance indicators were collected at seven manufacturing companies, of which only 80 indicators could be related to material efficiency. The majority of the identified material efficiency related KPIs are directly connected to waste generation and material consumption in the respective plant, although indirect KPIs such as supplier and customer issues, inventory and purchasing, rework/repair, deviations and product precision are also included. The identified material efficiency related KPIs are then clustered into five areas to achieve a better understanding, shown in the following table 1. These KPIs only identified at six companies, where one of the company had no environmental KPIs and no material efficiency related KPIs in operation and shop floor. Frequency in table 1 refers to the number of the same KPI in different operations/areas at different companies as well as different KPIs that have exactly the same goal but formulated differently. The performance indicators at each sites were structured in different categories including Cost, Quality, Environment, Delivery, Safety, People, Lean, Improvement, Leadership etc. Column Type in table 1 refers to these categorizations.

Almost one-third of identified material efficiency related KPIs within the studied companies were found under Environmental performance category e.g. chemical substitution, hazardous waste and volume of waste. Approximately 40% of material efficiency related KPIs were found under Cost performance category which are reported in SEK e.g. cost of consumable materials and scrap cost. Just above one-fourth of material efficiency KPIs were found under Quality performance category e.g. the number pallets demolished. The remaining 5% of material efficiency related KPIs are reported under Delivery, Inventory or the combination of thereof.

Adopting the role based equipment hierarchy from ISO 22400-2 (following figure 1) as an organizational hierarchy model, most of the identified material efficiency related KPIs exist on area and site levels and only one-third are related to work centers, even though the study performed via a bottom-up approach to capture lower level KPIs (shop floor and work center level). In addition, the majority of empirically identified material efficiency KPIs are measured on monthly basis with few exceptions: KPIs related to products are measured on daily basis, some of the KPIs related to scrap rate and paint consumption are measured once a week, and direct material related KPIs are reviewed in one-year interval.

Table 1 - Empirically identified material efficiency related KPIs

Categories	KPIs	Frequency	Type
Chemicals and lubricants (non-value adding)	Chemical substitution	2	Environment
	The number of reduced chemicals consumed	1	Environment
	The volume of hydraulic oils, cutting fluids, lubricants and solvents used	7	Environment and Quality
	The number of registered chemicals	1	Quality
	Paint consumption per unit	2	Cost
Solid consumable material (non-value adding)	Consumable material per unit	2	Cost
	The value of consumable (auxiliary) materials	7	Cost
	Repackaging	1	Cost
	Consumable material cost saved per month	1	Cost
Waste	Waste cost per ton	2	Environment
	Waste cost per produced unit	1	Environment
	Total waste generation	1	Environment
	The volume of hazardous waste generated in kg	1	Environment
	The volume of non-hazardous waste generated in kg	1	Environment
	The volume of hazardous waste sent to recovery in ton	1	Environment
	The volume of hazardous waste sent to other than recovery in ton	1	Environment
	The volume of non-hazardous waste sent to recovery in ton	1	Environment
	The volume of non-hazardous waste sent to other than recovery in ton	1	Environment
	Waste efficiency	1	Environment
	The number of pallets demolished	2	Quality
	Waste reused	2	Environment
	Waste to combustible	1	Environment
Scraps and quality rejected products	The amount of scrap produced	5	Environment and Quality
	Cost of produced scraps	9	Cost and Quality
	Scrap cost per unit	14	Cost
	Supplier rejection rate	1	Cost
	Number of scraps per employee	1	Cost
Products	Number of finished products	5	Quality and Delivery
	Obsolescence reserve	1	Inventory
	Material/products input	1	Delivery
	Direct material cost per unit (productive material)	1	Cost
	Direct material inventory (productive material)	1	Cost
	The amount of produced products in ton	1	Environment

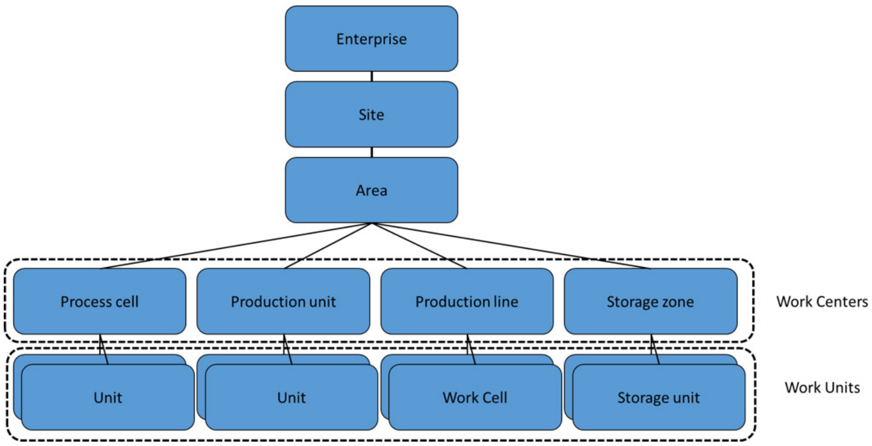

Figure 1 – Adopted role based equipment hierarchy as an organizational hierarchy model

5. Analysis and discussion

The largest proportion of KPIs at each case company measures operational activates i.e. productivity, flexibility, delivery, takt time and equipment effectiveness. This follows by quality, safety and human resource indicators. In general, environmental sustainability indicators found to be low; fewer than 5% of total KPIs. Although the size of the studied companies are different and they have different environmental priorities in their strategic goals, on average only 2% of KPIs at each case company can be directly and indirectly related to material efficiency i.e. waste generation and material consumption (excluding water). This proportion included even material efficiency KPIs existing under cost, quality and delivery indicator categories. Thus, the number of material efficiency KPIs belong to environmental indicators measuring material consumption and waste generation for the sake of environment is extremely low.

The existence of environmental KPIs on the lowest operational level is dependent on companies' production system and strategic goals. For instance one of the company's current strategic focus and goal lies on cost effectiveness and finance; hence no environmental KPIs are currently measured on the shop floor. In the majority of case companies, production system and strategic goals primarily focus on quality improvements and cost effectiveness, consequently cost, quality and productivity KPIs are the most common measurements on their shop floor. Since material efficiency is closely connected to cost (e.g. scrap cost) and quality (e.g. defects rate), the material efficiency KPIs might be placed under any of these categories on the shop floor, as long as they are measured, evaluated and improvement actions are taken place. However, on enterprise and site level, it is vital to put material efficiency indicators under environmental performance measurements; consequently the material and waste related performances are communicated to authorities and stakeholders, and necessary actions are planned and cascaded down to the lower levels.

The small proportions of environmental and material efficiency indicators on the shop floor can be correlated to the deployed bottom-up approach, whereas environmental sustainability indicators are mostly on enterprise, site or area level i.e. top-down approach [33]. Thus environmental sustainability indicators are mostly aggregated for the whole site on a yearly basis, and reactively stated for reporting purposes to authorities and external stakeholders [6]. Additionally, environmental performance indicators (including material efficiency) are managed and reported by environmental department which is mostly a separate function and regarded as an independent system, rather than an integrated function within production. As a result, environmental indicators, particularly material efficiency KPIs are not taken into consideration in the operational level as much as they should, and environmental improvement actions are not usually taken place continuously. To be able to identify improvements opportunities, it is recommended to have measurements on lowest operative level [34, 35], which is in line with 'go to gemba' concept.

In addition, existing KPIs have mainly financial goals. In relation to financial or non-financial measures as well as external or internal measures, following figure 2 maps empirically identified material efficiency related KPIs in table 1. The bubbles' sizes represent the frequency while the color of each bubble indicate the type of material efficiency KPIs. As shown, external KPIs include mainly environmental KPIs with reporting purposes to external authorities. Internal KPIs with focus on finance include cost KPIs to a large extent, although quality, environment and delivery KPIs also contribute. The number of non-financial material efficiency KPIs which are communicated internally for continuous improvement (as opposed for reporting purposes) is low. The blue bubble in non-financial and internal area is the "paint consumption per unit" which has environmental purposes but measures under cost category.

Among identified material efficiency indicators in literature, *material intensity* has been mentioned the most, for instance by [19, 28, 29, 31, 36]. This measurement is being used in the studied companies in different forms e.g. taking only consumable material (indirect/auxiliary materials) into account, or only volume of chemicals as part of auxiliary materials, or direct material inventory (productive materials). However the total material consumption is not aggregately calculated per produced unit. In addition, results show that waste related KPIs are mainly measured under cost indicators category for financial purposes and not for the sake of environment, hence environmental cost of using material and generating waste (for example through life cycle cost assessment) is not included in any KPIs. Furthermore, very few indicators measure consumable materials (auxiliary materials) including packaging materials, maintenance material/tools or personal protection equipment, etc. Recycling of auxiliary materials is as environmentally beneficial as the recycling of metals, but are mainly more complex, costly and energy consuming [4]. Moreover, the waste related KPIs in the studied companies mostly measure chemicals and lubricant consumption (in five out of seven companies) and scraps rate (in six out of seven companies), which can be justified with the high return revenue of selling metal scraps and high environmental requirements and regulations on reporting hazardous materials. Scrap rate was also mainly reported under cost performance, although few scrap rate indicators were identified under environmental performance.

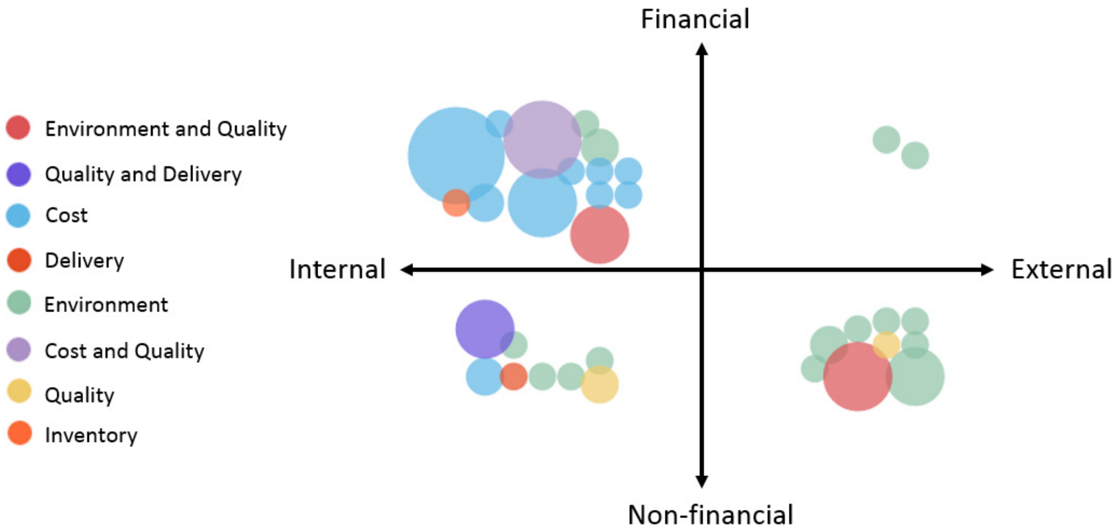

Figure 2 - Material efficiency KPIs' visualization

Despite recommendations on literature to measure end-of-life scenarios of waste flows including material recycling rate, product durability and waste transportation [28, 31], very few indicators and only at two companies monitor the end-of-life stage of wasted material. In general, waste hierarchy perspective i.e. waste recycling rate, material reuse, zero waste to landfill and energy recovery from waste is not measured or assessed. In addition, waste homogeneity is not measured under any circumstances at shop floors, while increasing the homogenous quality of the residual materials lessens price volatility, increases selling potentials and provides economic and environmental benefits [4]. According to Kurdve et al. [34] waste sorting rate (Σ sorted / (Σ mixed + Σ sorted)) ought to be calculated for each waste segment to measure and monitor waste homogeneity of each segment.

Three-fourth of identified KPIs at companies are not normalized to the physical flows in the system (e.g. ton of product output or produced unit) or to a measure of economic performance (e.g. cost or value added) [19], i.e. many of identified KPIs are absolute that measure performance regardless of input variables, e.g. the volume of oils and lubricants, the volume of generated waste (hazardous and non-hazardous or combination) and the amount of scrap produced. The value of these measurements depends on the size of the companies, company growth and production volume, without indicating any improvement or deterioration of process. Some specific hazardous materials must have an absolute KPI because hazardous materials need to be limited regardless of production rate due to their environmental and health impacts or legislation requirements [37]. One-fourth of identified KPIs are relative, mostly normalized per produced unit that helps monitoring the production over time and enables comparing different companies and divisions of the same company.

According to Schwarz et al. [29] the sustainable metrics need to be simple, useful for management decision making, understandable for different functions, cost-effective in term of data collection, reproducible with consistent and comparable results, stackable along the supply chain, robust and non-perverse to indicate progress towards sustainability, and protective of information. These characteristics are essential to initiate any change/improvement in operation. Relevant, understandable and reliable KPIs enable environmental performance monitoring over time, find improvement potentials, pursuing defined environmental goals, communicate the results, and benchmarking against other operations [22].

Taking environmental indicator classification by Azapagic and Perdan [19] into account, table 2 suggests relevant material efficiency indicators. In addition to presented indicators in table 2 which have environmental purposes, economic indicators can be also included such as average segment treatment cost (SEK/ton) [34], cost of waste treatment per produced unit (SEK/#) or cost of consumable material per produced unit (SEK/#).

Table 2 - Suggested material efficiency KPIs

Environmental indicators	Environmental efficiency	Voluntary indicators
Total non-value adding (auxiliary) material per produced unit (kg/#)	Product output/(productive material + auxiliary material)	The volume of hazardous materials used per produced unit (kg/#)
Total waste generated per produced unit (kg/#)	Sorting rate: waste sorted/ segment waste total	Consumable material (auxiliary) used per produced unit (kg/#)
Total material consumption (both productive and auxiliary) per produced unit (kg/#)	Recycling per total generated waste (%)	Scrap produced per produced unit (kg/#)
		Hazardous waste/total waste (%)

6. Conclusion and future work

Material efficiency is an essential part of sustainable manufacturing that regains a large portion of the original material value, and reducing industrial waste and material consumption [35]. However, few articles has been published addressing material efficiency in manufacturing, particularly material efficiency measurement and KPIs, which leaves practitioners with scant guidance to measure and improve it. The purpose of this paper was to present the current practice of material efficiency performance indicators identified through a bottom-up data collection approach at seven global manufacturing companies located in Sweden. The material efficiency KPIs directly connects to function of the operations and are particularly useful to decision-makers who focus on environmental performance, waste management and process improvements. KPIs calculated with the financial numerator incorporate excellent information relative to the production cost, providing vital information for strategic business decisions. Presented KPIs in this paper also provides guidance to managers on how their operation is performing in terms of material consumption and waste generation, and to track material efficiency improvement over time to extract more value from their processes.

The performed study presented in this paper had a bottom-up approach to identify material efficiency KPIs. Further research will investigate material efficiency KPIs from a top-down approach i.e. data collection through semi-structured interviews of environmental coordinators, plant directors and production managers who has a deep knowledge about environmental reporting, companies' manufacturing and environmental strategies and overall plant goals. Furthermore, this paper concentrated on what to measure for material efficiency in manufacturing industry. Performing top-down approach also enables answering why these KPIs are measured i.e. purpose and objective to each measure, and aids understanding how top-down and bottom-up measures interact with each other, and how strategies and environmental goals are cascaded down to production in terms of KPIs. Additionally, the participating case companies are predominantly large companies in Sweden that are the leading manufacturers in their respective industries. Their products are manufactured, assembled and sold worldwide, and their international reputations and success have forced them to maintain tighter control of environmental issues, including material flows. Therefore, future researchers might include SMEs.

References

[1] European Commission, A resource-efficient Europe – Flagship initiative under the Europe 2020 Strategy (EN), in: EUROPEAN COMMISSION, Brussels, 2011.
[2] World Economic Forum, More with less: Scaling sustainable consumption and resrouce efficiency, in, Geneva, Switzerland, 2012.
[3] Mistra, Closing the Loop: From Waste to Resource, in, The swedish foundation for strategic environmental research, Sweden, 2011.
[4] S. Shahbazi, M. Wiktorsson, M. Kurdve, C. Jönsson, M. Bjelkemyr, Material efficiency in manufacturing: Swedish evidence on potential, barriers and strategies, Journal of Cleaner Production, doi:10.1016/j.jclepro.2016.03.143 (2016).
[5] S.H. Abdul Rashid, An investigation into the material efficiency practices of UK manufacturers, in: School of applied sciences, Cranfield University, UK, 2008.
[6] S. Shahbazi, Material efficiency management in manufacturing, in: Innovation, Design and Engineering, Mälardalen University, Sweden, 2015.
[7] R.S. Kaplan, D.P. Norton, The balanced scorecard: measures that drive performance, Harvard business review, 83 (2005) 172.

[8] A. Neely, C. Adams, M. Kennerley, The Performance Prism: The Scorecard for Measuring and Managing Business Success, Prentice Hall, Harlow, UK, 2002.
[9] A. Davéa, K. Salonitisa, P. Balla, M. Adamsb, D. Morganc, Factory Eco-Efficiency Modelling: Framework Application and Analysis, in: 13th Global Conference on Sustainable Manufacturing - Decoupling Growth from Resource Use, 2016.
[10] K. Salonitis, P. Ball, Energy efficient manufacturing from machine tools to manufacturing systems, in: Forty Sixth CIRP Conference on Manufacturing Systems 2013, Procedia CIRP, 2013, pp. 634-639.
[11] S. Rahimifard, A.J. Clegg, Aspects of sustainable design and manufacture, International Journal of Production Research, 45 (2007) 4013-4019.
[12] J.M. Allwood, M.F. Ashby, T.G. Gutowski, E. Worrell, Material efficiency: providing material services with less material production, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 371 (2013) 20120496.
[13] S.K. Sikdar, Sustainable development and sustainability metrics, AIChE Journal, 49 (2003) 1928-1932.
[14] R.K. Yin, Applications of Case Study Research, Sage Publications, 2003.
[15] M.B. Miles, A.M. Huberman, Qualitative Data Analysis: An Expanded Sourcebook, SAGE Publications, 1994.
[16] G. Brundtland, World Commission on Environment and Development, Our Common Future, in, Oxford University Press, Oxford, UK, 1987.
[17] A. Möller, S. Schaltegger, The Sustainability Balanced Scorecard as a Framework for Eco-efficiency Analysis, Journal of Industrial Ecology, 9 (2005) 73-83.
[18] C. Bai, J. Sarkis, Determining and applying sustainable supplier key performance indicators, Supply Chain Management: An International Journal, 19 (2014) 275-291.
[19] A. Azapagic, S. Perdan, Indicators of Sustainable Development for Industry: A General Framework, Process Safety and Environmental Protection, 78 (2000) 243-261.
[20] EEA (European Environment Agency), Environmental indicators: typology and overview, in: Technical report No 25, Copenhagen, Denmark, 1999.
[21] OECD (The Organization for Economic Co-operation and Development), key environmental indicators, in, Paris, France, 2004.
[22] M. Herva, A. Franco, E.F. Carrasco, E. Roca, Review of corporate environmental indicators, Journal of Cleaner Production, 19 (2011) 1687-1699.
[23] J.A. Allan, Virtual Water: A Strategic Resource Global Solutions to Regional Deficits, Ground Water, 36 (1998) 545-546.
[24] J. Venetoulis, J. Talberth, Refining the ecological footprint, Environment, Development and Sustainability, 10 (2008) 441-469.
[25] S. Al Zaabi, N. Al Dhaheri, A. Diabat, Analysis of interaction between the barriers for the implementation of sustainable supply chain management, The International Journal of Advanced Manufacturing Technology, 68 (2013) 895-905.
[26] H. Shi, S.Z. Peng, Y. Liu, P. Zhong, Barriers to the implementation of cleaner production in Chinese SMEs: government, industry and expert stakeholders' perspectives, Journal of Cleaner Production, 16 (2008) 842-852.
[27] D. Ditz, J. Ranganathan, Measuring up: toward a common framework for tracking corporate environmental performance, in, World Resources Institute, 1997.
[28] M.I. Winn, Book: Eco-Efficiency - The Business Link to Sustainable Development, by Livio D. DeSimone and Frank Popoff, Journal of Industrial Ecology, 3 (1999) 147-149.
[29] J. Schwarz, B. Beloff, E. Beaver, Use sustainability metrics to guide decision making, Chemical engineering progress, 98 (2002) 58-63
[30] Worldsteel Association, Sustainable Steel Policy and Indicators 2012, in: I. 978-2-930069-71-5 (Ed.), 2012.
[31] I. Vermeulen, C. Block, J. Van Caneghem, W. Dewulf, S.K. Sikdar, C. Vandecasteele, Sustainability assessment of industrial waste treatment processes: The case of automotive shredder residue, Resources, Conservation and Recycling, 69 (2012) 17-28.
[32] J.H. Spangenberg, Environmental space and the prism of sustainability: frameworks for indicators measuring sustainable development, Ecological Indicators, 2 (2002) 295-309.
[33] M. Kurdve, M. Wiktorsson, Green performance map: visualizing environmental KPI's, in: European Operations Management Association (EurOMA), 2013.
[34] M. Kurdve, S. Shahbazi, M. Wendin, C. Bengtsson, M. Wiktorsson, Waste flow mapping to improve sustainability of waste management: a case study approach, Journal of Cleaner Production, Vol. 98 (2015) P. 304–315.
[35] L. Smith, P. Ball, Steps towards sustainable manufacturing through modelling material, energy and waste flows, International Journal of Production Economics, 140 (2012) 227-238.
[36] A.A. Martins, T.M. Mata, C.A. Costa, S.K. Sikdar, Framework for sustainability metrics, Industrial & engineering chemistry research, 46 (2007) 2962-2973.
[37] M. Kurdve, Chemical Management Services: Safeguarding Environmental Outcomes, in: S. Schaltegger, M. Bennett, R.L. Burritt, C. Jasch (Eds.) Environmental Management Accounting for Cleaner Production, Springer Netherlands, Dordrecht, 2008, pp. 209-229.