Carbon emissions reduction using Material Circularity Indicator and Energy Value Stream Mapping

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Abstract. Increasing the productivity of a company is closely related to energy utilization activities which correlate to carbon emissions. It can drastically change the climate and harm the world community. The preferences of consumers who are aware of environmental impacts are also the main impetus for many companies to reduce carbon emissions in their business operations. This study aims to plan an improvement strategy for reducing sweeteners' company carbon emissions with the material circularity indicator (MCI)—a circular economy method—and the energy value stream mapping (EVSM)—a lean method. Those methods combined have shown their practicality in analyzing and triggering root cause analysis discussions with stakeholders. Results showed overall CWSS processing MCI value is 0.11 which is relatively low. Few potential actions were measured to increase its circularity. The EVSM method has prioritized corrective actions to reduce excessive energy consumption. Those methods conclude a few improvement strategies from material circularity and energy perspective, such as recover starch, reuse-recycle water, check the feasibility to sell out-of-specification CWSS as animal feed, replace PRV and implement SMED.

Keywords: carbon emissions, circular economy, energy efficiency, energy value stream mapping, lean, material circularity indicator

Introduction

Increasing operational productivity in a company often involves the use of energy, which lead to the carbon emissions that contribute to negative impacts on the environment and human health. It comes from various industrial activities, particularly the burning of fossil fuels like coal. Sustainability has been a significant concern in operational management since early 2000s. Implementing operational excellence strategy on reducing operational cost must be done by maintaining productivity levels while also environmentally friendly [1]. Production activities that require high levels of energy, such as those involving steam obtained by the burning from coal, can be challenging in this regard.

As a principle and methodology, Lean aims to identify and eliminate waste in production activities that do not provide value [2]. A similar concept was introduced by the circular economy, it aims at waste elimination by optimizing resource. Circular economy can be seen as an extension of Lean thinking, as both focus on the efficient use of resources and waste elimination [3].

Value stream analysis can be adapted to support the implementation of circular economy practices. EMF introduced Material Circularity Indicator (MCI) as a tool to assess the circularity of products and measure the progress towards a more circular model [4].

Several previous studies have varied methods and their suitability for use in certain industries. T J Roosen in 2013 integrated value stream with ISO 140001 [5]. N Verma in 2016 implemented a similar framework by Roosen, energy value stream mapping in a smaller manufacturing company [6]. Some approached energy utilization with categorization and performance indicators [7][8]. X Wen in 2021 developed a systematic energy value mapping approach consisted of 3 phases: energy loss modeling, lean energy analysis, and improvement strategy determination [9]. R A Qolbi in 2021 utilized MCI which is modified in its research to oversee the process of transitioning from a linear economy to a circular economy in B2B companies [10].

This research will focus on reducing carbon emissions with a combination of two methods, MCI and energy value stream mapping (EVSM) from two concepts/philosophies: lean and circular economy. By using a combination of these two methods, this research is expected to be able to target carbon emissions reduction in 2 subjects: materials circularity and energy utilization in processing unit.

Methods

Material Circularity Indicator (MCI)

For each stream of process and materials, Table 1 elaborates on the attributes to understand its circularity characteristics. The quantity of virgin feedstock used and unrecoverable waste in the intermediary to the final process affects its linearity, coupled with a utility factor to measure its usage intensity, then MCI is defined ranging from 0 to 1 scale (most linear to most circular) [4][9].

Table 1. Material Circularity Indicator (MCI) attributes and equation.

Attribute	Equation		Note
Mass of virgin feedstock (V)	$V = M(1 - F_R - F_U)$	(1)	**M** mass of material of the product. **F_R** mass fraction of recycled sources. **F_U** mass fraction of reused sources.
Mass of unrecoverable waste for intermediary materials (G)	$G_0 = M(1 - I_R - I_U)$	(2)	**G_0** intermediary waste to landfill. **G_F** intermediary waste from the recycling process for feedstock. **I_R** mass fraction of recycled intermediary. **I_U** mass fraction of reused intermediary.
	$G_F = M(1 - F_R)F_R/F_F$	(3)	
	$G = G_0 + G_F$	(4)	
Mass of unrecoverable waste for the final product (W)	$W_0 = M(1 - C_R - C_U)$	(5)	**W_0** waste to landfill. **W_C** waste from the recycling process. **W_F** waste from the recycling process for feedstock. **C_R** mass fraction of recycled product. **C_U** mass fraction of reused product. **E_C** recycling efficiency in the product lifetime. **E_F** recycling efficiency to generate feedstock.
	$W_C = M(1 - E_C)C_R$	(6)	
	$W_F = M(1 - E_F)F_R/E_F$	(7)	
	$W = W_0 + (W_F + W_C)/2$	(8)	
Linear flow index (LFI)	$LFI = \frac{V+W}{3M+(G_F+W_F-W_C)/2}$	(9)	
Utility factor (X)	$X = (L.L_{av}^{-1})(U.U_{av}^{-1})$	(10)	
Material circularity indicator (MCI)	$MCI_P = 1 - LFI \cdot f(X)$	(11)	**L** lifetime of a material. **L_{av}** average lifetime of material in market/industry. **U** usage intensity. **U_{av}** average usage intensity in market/industry.
	$f(X) = 0.9/X$	(12)	

Energy Value Stream Mapping (EVSM)

This method has 3 phases of analysis to identify, quantify, visualize, analyze, and reduce energy losses related to productivity variables.

Energy Loss Modelling. Following lean principles, energy losses refer to energy consumption that is non-value-added activities that are not involved in the conversion of raw materials into products.

The energy loss modelling phase includes 3 steps: classification, characterization, and visualization of energy losses. (a) *Classification of energy losses* is divided into 2 categories: planned losses and unplanned losses. Unplanned losses are further categorized into independent losses and dependent losses. (b) *Characterization of energy losses* describes the operating conditions of the machine (standby, idle, processing). In contrast to Wen's work, which explains the characteristics of electric power, this study applied the same framework to steam usage because of the availability of data. (c) *Visualization of energy losses* utilizes an alternative form of current-state-map from VSM, namely energy loss-embedded CSM (EL-CSM) initiated by Wen [10].

Lean Energy Analysis. It started by using the Pareto principle to take the highest 20% energy loss, then create the production-oriented energy performance indicators (PEPI). Overall energy (OE) has many energy consumption level compositions which defined in Table 2. Production-oriented energy performance indicators (PEPI) are divided into production-oriented indicators (PEI) and production-oriented key energy indicators (PKEI). PEI consists of 4 indicators and PKEI consists of 4 indicators which are defined in Table 3.

Table 2. Energy breakdown structure parameter definition.

Parameter	Definition
Theoretical energy (TE)	The amount of energy required for chemical or physical production activities by carrying out certain operations.
Operational energy optimum (OEO)	Minimum energy to produce a unit of product under certain conditions (buildings, technology, operators, etc.).
Value-added energy (VAE)	Actual energy consumption to produce several products beyond planned losses and unplanned losses. VAE is not the same as energy consumption due to several losses such as sampling.
Effective energy (EE)	Actual value-creation and operational energy consumption of the organization that meets the needs of external and internal consumers (intermediate processes).
Independent energy (IE)	The amount of actual energy except for energy losses caused by external production disturbances. Internal and external boundaries need to be defined.
Overall energy (OE)	Actual consumption of energy to produce the appropriate number of products. To calculate OE, all the energy consumed at the process boundary needs to be considered.

Table 3. Production-oriented energy performance indicator (PEPI) for lean energy analysis.

Indicator	Ratio	Definition
PEI-1	OEO/VAE	Changes in operational conditions and identification of undetected energy-saving potential.
PEI-2	VAE/EE	Energy saving potential by reducing planned losses.
PEI-3	EE/IE	Independent losses related to the effect of internal disturbances.
PEI-4	IE/OE	Dependent losses are caused by external disturbances.
PKEI-1	VAE/OE	The level of energy efficiency by only considering the status of value creation.
PKEI-2	EE/OE	The level of energy efficiency from the perspective of the level of energy demand.
PKEI-3	OEO/IE	Energy loss caused by internal factors potentially represents an energy efficiency bottleneck.
PKEI-4	OEO/OE	Lean energy indicator – overall energy efficiency.

Improvement Strategies Prioritization

EMF suggested several potential strategies to increase MCI, such resale, use period extension, refurbishment, and recycling. Resale has the potential for companies to enter new markets. If there is no potential for resale/reuse and refurbishment, the material in the product can be recycled.

In the context of improving the efficiency of energy utilization, there are two improvement techniques: engineering techniques and lean techniques. It can be evaluated by considering implementation ease, low cost, and low risk of affecting productivity. *Potential engineering techniques*: equipment optimization, maintenance, refurbishing, retuning, engine replacement, retrofitting components. *Potential lean techniques*: focus on increasing productivity time.

In selecting a project or appropriate corrective steps, several criteria need to be considered: energy benefits, feasibility that considers technical and economic aspects in their implementation, as well as non-energy benefits that are not included in the benefits of energy efficiency and production management, for example, the impact of emissions of carbon.

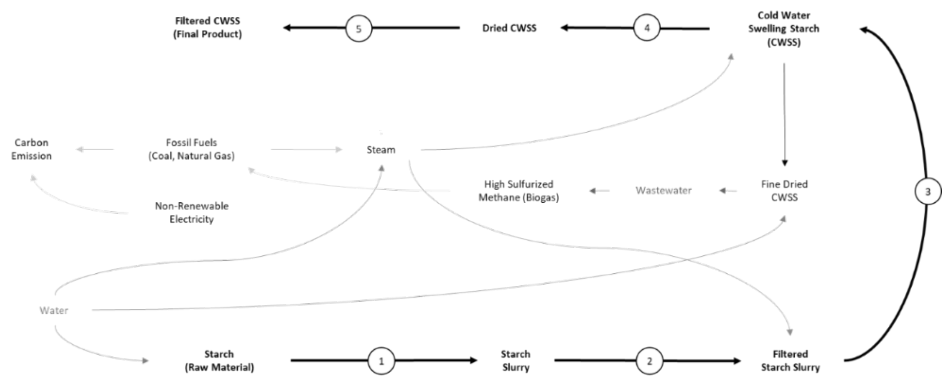
Result and Discussion

In this case of study, cold-water swelling starch (CWSS) as one of product in a sweeteners company was being used. *Energy* term that being used in this study is limited to steam. *Materials* term that being used in this study are limited to raw material and supporting chemicals. This study is limited up to generating suggestions.

Material Circularity Indicator

Determining the circularity of each material at each stream begins by reviewing its bill of materials. As shown in Figure 1, modified corn starch is mixed with water to form slurry before being filtered then sprayed through nozzle. Virgin feedstock is calculated with equation (1) and calculation of unrecoverable waste in intermediate material targets material circularity in the middle of the process cycle using equation (2) to (8). LFI measures the amount of material used linearly (single use) or circularly using equation (9). LFI has a value ranging from 0-1 with 1 meaning the material has high linearity (low circularity).

Figure 1. Process flow production of CWSS with its supporting materials.



MCI value then is defined by considering LFI and utility, as two factors affecting the degree of material circularity, calculated with equation (11). Those calculations are then applied to all material at each stream. CWSS processing obtained overall MCI 0.11 which was relatively low. To improve its circularity, there are few potential actions:

Recover spilled starch. Spilled starch in the dumping process is often disposed of as waste and it is avoided to be used because it had been on the ground. If the concern about food safety issues can be eliminated, maximizing starch recovery can be realized.

Sell out-of-specification CWSS. CWSS products that do not meet customer specifications have the potential to be extend its lifetime by selling them as animal feed

Energy Value Stream Mapping (EVSM)

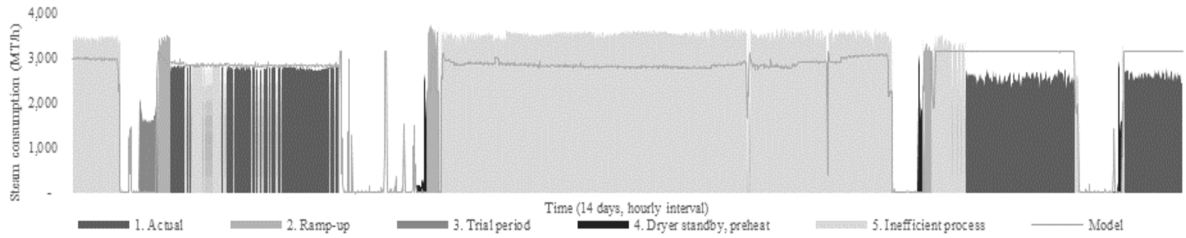


Figure 2. Example of spray drying steam consumption against a model with loss classification.

An empirical model is used to identify the actual energy consumption performance of a unit compared to 1-year historical data. It is used as the baseline of the unit process' personal best and helps with energy losses characterization as an example shown in Figure 2 for a spray drying unit. It is then visualized into *energy losses-embedded current state map (EL CSM)*, an example shown in Figure *2*.

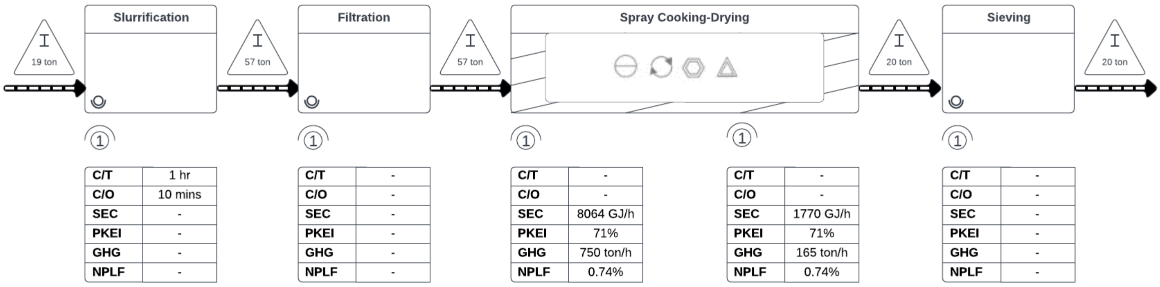


Figure 3. Energy losses-embedded current state map (EL CSM).

It is then further analyzed using lean energy analysis with PEPI for a spray drying unit shown in Figure 3. Spray cooking-dryer process unit has a value PKEI of 71% with the lowest indicator PKEI-3 (72%) which has energy losses due to internal operational factors. It can indicate a declining level of energy efficiency, changes in operating conditions and internal factors, so that improvements can be focused on stabilizing operational conditions.

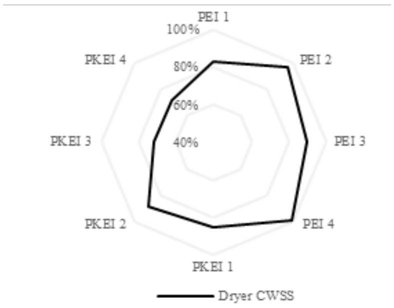


Figure 4. Production-oriented energy performance indicator (PEPI) for CWSS.

Potential suggestions for improvement are prioritized based on non-energy benefits, feasibility (possibility to be executed in a short period), and energy benefits (energy efficiency) as shown in Table 4. Three corrective measures are prioritized: 1, 4, and 6. Energy losses-embedded future state map (EL FSM) with its Kaizen event then can be visualized as shown in Figure 4 below.

Table 4. Corrective measures with its estimated impact.

Corrective Actions	Energy Reduction (GJ/h)	Non-energy benefit/feasibility
[1] SMED Implementation	780	Low/Low
[2] Pull system strategy optimization	366	Low/Low
[3] Parameter optimization by Taguchi Method	134	Low/Low
[4] PRV replacement in Evaporator	776	Medium/Medium
[5] Trial instruction with energy cons. impact	89	Low/High
[6] PRV replacement in Spray Cooking-Drying	1020	High/Medium

Both MCI and EVSM combined are showing a good practicality in identifying losses and generating suggestions. Only for a manufacturing company which already well equipped with measurement instruments, it can be a powerful tool to identify its symptoms earlier as real-time metrics if it's integrated to cloud and being monitored as a single dashboard for operations team and middle management.

Conclusion

In terms of emission, each material attained its carbon emission footprint through energy utilization throughout the process chain. Based on MCI calculation and EVSM analysis, few actions to reduce carbon emission have been identified and prioritized from 2 perspectives: material circularity and energy utilization. In terms of material circularity, it is suggested to recover starch and check the feasibility to sell out-of-specification CWSS as animal feed. In terms of energy utilization, PRV replacement and SMED implementation were prioritized.

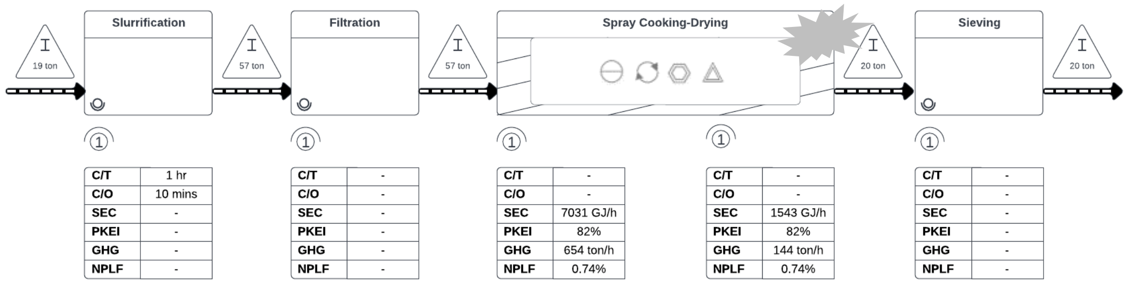


Figure 5. Energy losses-embedded future state map (EL FSM).

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