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An Integrated Method for Sustainable Manufacturing Systems Design

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Abstract. In the past decade, there has been an increasing awareness in development of sustainable manufacturing systems as governments in many countries have been enforcing ever-stricter environmental policies and regulations in industry by promoting energy saving and low emissions manufacturing activities. Lean manufacturing can be helpful for achieving a sustainable manufacturing system as it can reduce production wastes and increase manufacturing efficiency. Nevertheless, this lean approach does not include a consideration in energy consumption and carbon dioxide (CO_2) emissions when designing a lean manufacturing system. This paper presents a methodology which can be useful for measuring energy consumption and CO_2 emissions for a typical manufacturing system design at an early stage. A case study was carried out for obtaining computational results using the developed methodology based on data collected from a real production line.

1 Introduction

To develop a sustainable manufacturing system, system designers need not merely to apply traditional methods to improve system efficiency and productivity but also to examine the environmental impact on the developed system. This is because governments in many countries have been enforcing ever-stricter environmental policies and regulations by promoting energy saving and low-emission manufacturing activities in industry. A manufacturing system can be defined as a process or system of transforming raw materials, components or parts into final products that meet customer's needs and specifications [1]. The traditional manufacturing system design is involved in determination and analysis of such as material-handling methods, system capacities, production methods, material flow, shop-floor layouts, system flexibilities and operations. Nevertheless, there is an environmental consideration that needs also to be addressed today; this leads to a new challenge for manufacturing system designers to develop an effective approach by incorporating environmental parameters or constraints [2].

The concept of manufacturing sustainability may be defined as the creation of manufactured products by minimizing negative environmental impacts on usage of energy or natural resources. The environmental issues in manufacturing activities focus on energy consumption and CO_2 emissions. Koc and Kaplan presented an investigation on energy consumption for a particular ring type yarn manufacturing system [3]. Lind *et al.* developed a production simulation tool that was used for making a trade-off decision based on considerations of ergonomic constraints, levels of automation and environmental impacts [1]. Wang *et al.* proposed the process integration (PI) method that was used for evaluating CO_2 emissions for a steel industry [4]. Gutowski *et al.* conducted a thermodynamic analysis by examining the resources used in manufacturing processes [5]. Branham *et al.* used the quantitative thermodynamic analysis for quantifying energy in different categories applied into manufacturing processes or systems [6].

Lean concepts are widely adopted by many manufacturing plants as a popular model for improving system efficiency and productivity without additional investments. Lean manufacturing is a systematic approach to eliminate non-value added wastes in various forms and it enables continuous improvement [7]. These wastes are overproduction, waiting for parts to arrive, unnecessary movement of materials, the waste in processing, unnecessary inventory, excess motion and the waste of rework [8]. However, traditional lean manufacturing does not consider environmental wastes which also need to be identified as these wastes add no values on manufactured products. This paper presents an integrated method by incorporating parameters of energy consumption and CO_2 emissions into a manufacturing system design at an early stage. A case study was used for obtaining computational results based on data collected from a real production line.

2 Energy consumption and CO_2 emissions of a typical manufacturing system

In a manufacturing system, energy is used for operating machines, air conditioning systems, illumination systems and other supportive equipment such as compressors which supply compressed air to some machines [3].

Energy and CO_2 emissions are generated by either combusting fossil fuels directly or using electricity which is generated indirectly by using fossil fuels or renewable resources. To describe amounts of energy consumption and CO_2 emissions, the following notations are used:

Notations:

m: number of processes in a manufacturing system

n_i: number of machines involved in process i, where $i \in \{1, 2, ..., \text{m}\}$

E_i (kWh): energy consumption for a machine involved in process i

E_i^{cond} (kWh): energy consumption of an air conditioning system

E_i^{illum} (kWh): energy consumption of an illumination system

$E_i^{air\ comp}$ (kWh): energy consumption of a compressed air needed for a machine involved in process i

TE (kWh): total energy consumption of a manufacturing system

N_i (kw): installed power for a machine involved in process i

R_i (kg/h): manufacturing rate for a machine involved in process i

τ_i (hr): operating time for a machine involved in process i

μ_i (%): efficiency for a machine involved in process i

∂_i (kg): mass of materials transferred from a machine involved in process i

G_i(kg): mass production per month $\yen_i$ (%): total waste ratio for a machine involved in process i

$Ȩ_i$ (kWh): energy consumption of air conditioning per month

$\check{E}_i$ (kWh): energy consumption of illumination per month

$\zeta_i^{air\ comp}$ (kWh/m^3): energy consumption per cubic meter of a compressor

υ_i (m^3/h): compressed air used for a machine involved in process i per hour

$\rho_i^{air\ \text{comp}}$ (m^3/h): capacity of compressed air in cubic meter per hour of a compressor

$N_i^{air\ \text{comp}}$ (kWh): installed power for a compressor

e_i (kg/kWh): amount of CO_2 emissions per kWh released from a machine involved in process i

Te_i (kg/kWh): amount of CO_2 emissions per KWh released from a machine, an air conditioning system and an illumination system, which involved in process i

ω : CO_2 emission factor using different energy sources

Te (kg/kWh): total amount of CO_2 emissions released from the manufacturing system

q_i (kg): mass of materials involved in process i

2.1 Energy consumption

The energy consumption E_i for a machine involved in process i is given by

$$E_i = \tau_i \times N_i \times n_i \tag{1}$$

The operating time τ_i for a machine involved in process i is calculated by:

$$\tau_i = \frac{q_i}{R_i \times \mu_i} \tag{2}$$

Mass of materials q_i transferred from a machine involved in process i is obtained by:

$$q_i = \partial_i \times (1 + \yen_i) \tag{3}$$

The energy consumption of an air conditioning system E_i^{cond} in a manufacturing system is given by:

$$E_i^{cond} = Ȩ_i \times \frac{\partial_i}{G_i} \tag{4}$$

The energy consumption of an illumination system E_i^{illum} is calculated by:

$$E_i^{illum} = \check{E}_i \times \frac{\partial_i}{G_i} \tag{5}$$

The energy consumption of a compressed air needed for a machine involved in process i $E_i^{air\ comp}$ is calculated by:

$$E_i^{air\ comp} = \tau_i \times \zeta_i^{air\ comp} \times \upsilon_i \times n_i \tag{6}$$

where $\zeta_i^{air\ comp}$ can be determined by:

$$\zeta_i^{air\ comp} = \frac{N_i^{air\ \text{comp}}}{\rho_i^{air\ \text{comp}}} \tag{7}$$

The total energy consumption TE for a manufacturing system is given below:

$$TE = \sum_{i=1}^{m} (E_i + E_i^{air\ comp} + E_i^{cond} + E_i^{illum}) \tag{8}$$

where $i \in \{1,2,...., \text{m}\}$

Hence, equation (8) will be as follows:

$$TE = \sum_{i=1}^{m} [\frac{\partial_i \times (1 + \yen_i)}{R_i \times \mu_i} \times \text{N}_i \times n_i$$
$$+ \tau_i \times \zeta_i^{air\ comp} \times \upsilon_i \times n_i$$
$$+ Ȩ_i \times \frac{\partial_i}{G_i} + \check{E}_i \times \frac{\partial_i}{G_i}]$$

2.2 CO_2 emissions

The amount of CO_2 emissions e_i released from a machine involved in process i is calculated by:

$$e_i = \omega \times E_i \tag{9}$$

where, the CO_2 emission factor ω can be defined as shown in table 1 [9].

Table 1. Amount of CO_2 emission factor per kWh using deferent energy sources.

Energy source	Emission factor ω kg/kWh
Oil as direct energy source when oil is combusted to generate thermal energy	0.5
Oil as indirect energy source to generate electricity	0.6895
Solar as indirect energy source to generate electricity	0.05

The total amount of CO_2 emissions *Te* can be calculated as follows [10].

$$Te = \sum_{i=1}^{m}[e_i \times q_i + 0.6895 \times (E_i^{air\ comp} + E_i^{cond} + E_i^{illum})] \qquad (10)$$

where $i \in \{1, 2, ..., m\}$

Hence, equation (10) will be as follows:

$$Te = \sum_{i=1}^{m}\{\omega \times \tau_i \times N_i \times n_i \times \partial_i \times (1+¥_i) + 0.6895 \times[\tau_i \times \zeta_i^{air\ comp} \times \upsilon_i \times n_i + E_i \times \frac{\partial_i}{G_i} + \check{E}_i \times \frac{\partial_i}{G_i}]\}$$

3 A case study

Figure 1 illustrates a process flow chart or precedence diagram for producing plastic and woven sacks at a company. The study was carried out for analysing the energy consumption and CO_2 emissions for a manufacturing system consisting of machines for carrying out process tasks, an air conditioning system, an illumination system and a compressor system. Air conditioning is necessitated to maintain reasonable temperatures required for operators, effective machining operations and quality of products. The production line comprises 10 different processes tasks, each process task involves a number of machines and each machine has energy, mass inputs and different specifications. Table 2 shows the symbols representing the manufacturing processes used by the factory.

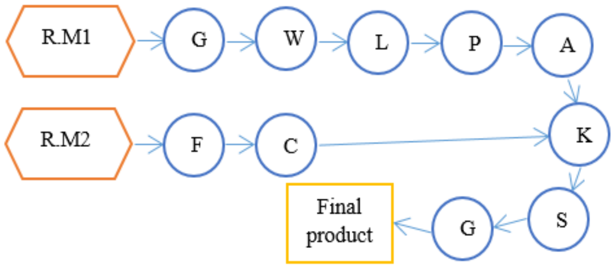

Figure 1. The process flow of plastic and woven sacks.

Table 2. Manufacturing processes tasks for producing plastic and woven sacks.

Tasks	Description	Predecessors
R.M$_1$	Raw material (Polypropylene)	None
R.M$_2$	Raw material (Polyethylene)	None
G	Extruding the Polypropylene to make stands	R.M$_1$
W	Weaving the strands into rolls of sacks	G
L	Laminating the rolls	W
P	Printing and branding	L
A	Cutting the rolls into bags	P
F	blowing the polyethylene into Inner-film bags	R.M$_2$
C	Cutting blown inner-film in to bags	F
K	Liner stick, inserts and smoothes out blown film	F,C
S	Film sewn into bag	K
B	End product compressed using baling machines	S

Table 3 shows collected data from the company. These include the mass of materials involved in process *i* per month, number of machines involved in process *i*, waste ratio, manufacturing rate and installed power.

Table 3. Data collected from a plastic and woven sacks company.

Tasks	∂_i (kg/month)	n_i	$¥_t$ (%)	R_i (kg/h)	N_i (kW)
G	254800	4	0.02	408	200
W	244608	40	0.04	392	14
L	300309	3	0.015	481	70
P	297306	5	0.01	476	20
A	291360	13	0.02	467	7
F	11050	3	0.002	18	40
C	11028	2	0.002	18	7
K	301536	13	0.003	483	0
S	298521	54	0.01	478	0.8
B	298521	4	0	478	4

4 Comparative results

Table 4 shows computational results in energy consumption and CO_2 emissions of machines involved in a process task and Figure 2 illustrates these results. Energy consumption of the machines involved in a process task of a manufacturing system depends on the installed power *Ni* and the operating time τ_i. As shown in Figure 2, the machines for completing process task *G* have the largest energy consumption and the machines for completing process task *K* have the least energy consumption. This is because the machines involved in process task *G* have the highest installed power *Ni* (200 kw) and the highest operating time τ_i (646 h), while the machines involved in process task *K* have the lowest installed power *Ni* (zero kw) as this process is a manual task.

CO_2 emissions released from the machines involved in a process task of a manufacturing system depends on the energy consumption used by the machines, the emission factor and the energy source. Table 4 alos shows the amount of CO_2 emissions which are subject to the CO_2 emission factor ω using different energy sources and Figure 3 illustrates these results. As shown in Figure 3, the machines in completing process task *G* have the highest amount of CO_2 emissions Te_i (91244910178 kg/kWh using oil as indirect energy to generate electricity, 66167449497 kg/kWh using oil as direct thermal energy and 6616751966 kg/kWh using solar as indirect energy to generate electricity), respectively.This is because the machines involved in process task *G* have the highest amount of energy consumption. By contrast, the machines involved in process task *K* generate zero CO_2 emissions as this process is a manual task. The amount of CO_2 emissions that released from this task is released from the air conditioning and illumination system only which is 4431 kg/kWh. The results in Table 4 also show that using the solar source of energy has the lowest total of CO_2 emissions *Te* of 15679203081 kg/kWh, followed by oil as a direct energy source to generate thermal energy of 1.6×10^{11} kg/kWh and oil as indirect energy source to generate electricity of 2.2×10^{11} kg/kWh, because solar energy has the least emission factor ω (0.05 kg/kWh) followed by oil as direct energy source (0.5 kg/kWh) and oil as indirect energy source (0.6895 kg/kWh). The amount of total CO_2 emissions *Te* using oil as indirect energy source is higher than using oil as direct energy source because electricity is already generated through oil and the emission factor ω for using oil as indirect energy source is higher than the emission factor for using oil as direct energy source.

Table 4. Calculated results for energy consumption and CO_2 emissions

			Source of energy		
			Oil		Solar
			Indirect energy to generate electricity	Direct energy when oil is combusted to generate thermal energy	Indirect energy to generate electricity
Tasks	E_i (kWh)	τ_i (h)	Amount of CO_2 emissions (kg/kWh)		
			Te_i	Te_i	Te_i
G	509184	646	91244910178	66167449497	6616751308
W	363417	640	63744725119	46225327628	4622536751
L	133005	636	27953731584	20271018351	2027108300
P	63024	633	13048677512	9462422354	946249157
A	57919	625	11868414917	8606547911	860689587
F	75029	630	572799149	415374486	41542833
C	8753	625	66700011	48370533	4844068
K	0	624	4431	0	0
S	27226	623	5660055586	4104465022	410450490
B	9984	620	2055013982	1490221654	149026153
$E_i^{\text{air comp}}$	69309				
E_i^{cond}	41184				
E_i^{illum}	23088				
(TE)	1381125				
		(Te)	2.2×1011	1.6×1011	15679203081

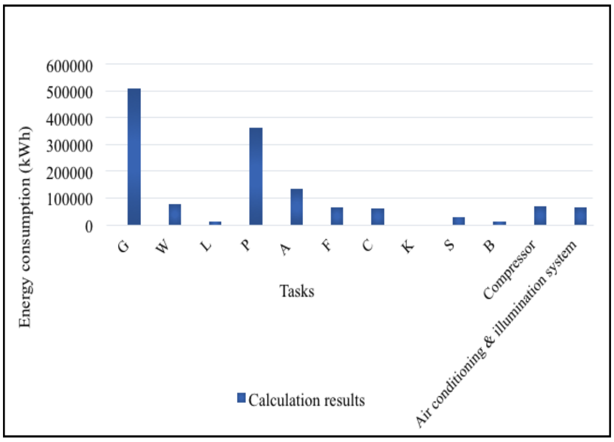

Figure 2. Energy consumption calculated results.

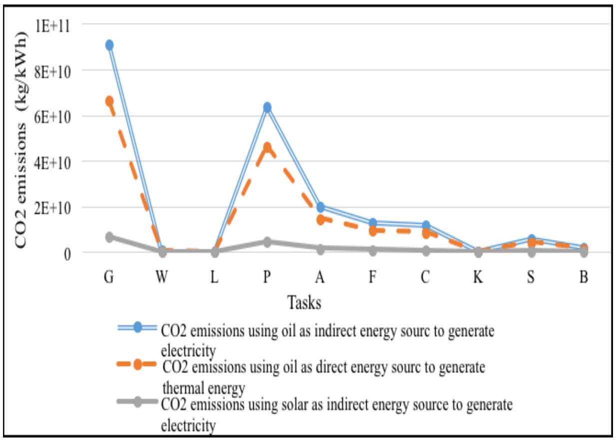

Figure 3. The amount of CO_2 emissions using oil as direct energy source and indirect energy source and solar as indirect energy source to generate electricity.

5 Conclusions and discussions

When designing a manufacturing system, engineers used to focus on key performance indicators in terms of system productivity and capacity; environmental considerations are often overlooked. This paper presents an integrated method which addresses environmental sustainability relating to manufacturing activities. The developed method was aimed at helping decision-makers to design a manufacturing system incorporating a number of environmental parameters in terms of energy consumption and CO_2 emissions. The computational results were validated based on data collected from a real case in industrial case. In addition, the developed method allows a joint analysis of the system performance using environmental constraints.

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