A MOO-EDS Approach for Quantifying Energy Consumption and CO_2 Emissions for Manufacturing System Design and Evaluation

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***Abstract*—A sustainable manufacturing system design can be partially achieved by promoting an energy-saving production method in which energy consumption and amount of CO_2 emissions can be measured and reduced as minimal as possible. Thus, there is a need for developing a computer-based discrete event simulation (DES) tool which enables incorporating parameters of energy consumption and CO_2 emissions when it is used for manufacturing systems design and evaluation. Unfortunately, such a DES tool is unavailable in the existing market. This paper presents a hybrid Multi-Objective Optimization Enterprise Dynamic Simulation (MOO-EDS) approach that can be employed as an aid for manufacturing systems design and evaluation aiming to minimize energy consumption and amount of CO_2 emissions at an early stage. A real case study was examined for validating the applicability of the proposed approach. The research outcome demonstrates that the hybrid FMOO-EDS approach can be an effective decision-making tool by quantifying energy consumption and amount of CO_2 emissions towards a sustainable manufacturing system design.**

***Index Terms*—sustainable manufacturing systems, energy consumption, CO_2, modelling and simulation, multi-objectives**

I. Introduction

There has been a growing pressure of manufacturing industry promoting energy saving production and minimizing CO_2 (carbon dioxide) emissions due to ever strict regulations and rules on environmental issues. Development of sustainable manufacturing systems is considered as one of the effective solutions for a long-term strategy of manufacturing companies. The concept of lean approaches is also believed as an appropriate method for pursuing sustainability in manufacturing as it can reduce manufacturing wastes and increase system efficiency and productivity. However, the current lean approaches do not include reduction of environmental wastes in terms of such as energy consumption and amount of CO_2 emissions for production. To design a sustainable manufacturing system, manufacturing system designers need to not merely rely on applying traditional methods for improving efficiency and productivity of a manufacturing system but also need to examine the environmental impact on the developed system. Nevertheless, a traditional manufacturing system design is involved in the determination, analysis and optimization of, for example, system capacities, material flow, material-handling methods, production methods, system flexibilities, operations, and shop floor layouts. This can be partially achieved using the computer-based discrete event simulation (DES) tools as an aid for manufacturing systems design and evaluation [1, 2].

The existing DES tools allow an examination or prediction of a manufacturing system performance and these tools are particularly useful for facilitating a complex manufacturing system design by altering system parameters based on the developed DES model. However, these commercial DES tools cannot be used for measuring such as amount of energy consumption or CO_2 emissions providing alternative solutions for manufacturing system designers at an early stage. This is because the current DES tools do not provide functionalities that enable to investigate system performance by considering effects of environmental issues as described above. Hence, there is a need for requiring a DES tool that allows manufacturing systems designers to incorporate parameters of environmental considerations into their established DES models [3].

A few researchers applied the multi-objective optimization (MOO) approaches considering environmental aspects relating to a sustainable manufacturing system design. Jamshidi *et al* developed a MOO model aiming to minimize effects of nitrogen dioxide, carbon monoxide and volatile organic particles caused by facilities and transportation vehicles in a supply chain network [4]. Wang *et al* presented a MOO model used for determining a trade-off decision between total cost and total amount of CO_2 emissions in some facilities within a supply chain [5]. Shrouf *et al* proposed a MOO model used for minimizing the cost of energy consumption at machine levels [6]. Zhang *et al* proposed a dynamical optimization method for shop-floor material handling based on real-time multi-source manufacturing data to reduce transport costs and energy consumption [7]. Nujoom *et al* created a cost-effective approach towards a sustainable manufacturing system design using the MOO approach [8].

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This paper presents an integrated MOO-EDS approach, which is a combination of a MOO model incorporating a number of parameters of energy consumption and amount of CO_2 emissions into an EDS (Enterprise Dynamics Simulation) tool, which is a DES tool commonly used for manufacturing systems design and analysis. With this approach, a compromised solution can be made based on the pre-defined objectives towards minimization of total energy consumption and amount of CO_2 emissions for a sustainable manufacturing system design.

II. The Integrated MOO-EDS Approach

Fig. 1 illustrates the integrated MOO-EDS approach that enables to quantify energy consumption and amount of CO_2 emissions of a manufacturing system at an early design stage. In this study, the parameters, which relate to amount of energy consumption and amount of CO_2 emissions, are formulated into a MOO model, which is also integrated with the EDS tool to investigate the performance of a manufacturing system so that energy consumption and amount of CO_2 emissions can be measured or quantified. With this approach, a trade-off decision can also be obtained by minimization of total energy consumption (equation 1) and minimization of amount of CO_2 emissions (equation 2) of a manufacturing system. Due to the limited page number, minimization of total cost Z1 relating to manufacturing system facilities used for production is not shown in this paper.

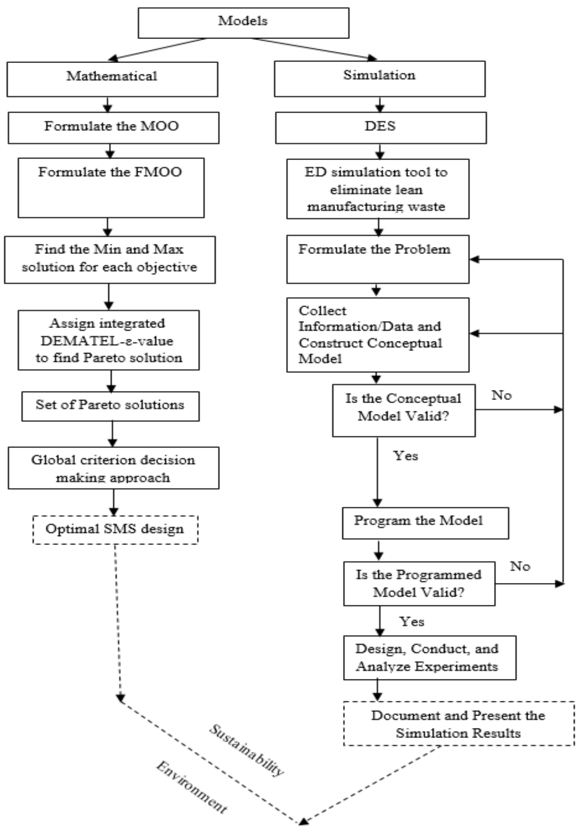

Figure 1. The integrated MOO-EDS approach.

By minimization of total energy consumption Z2, it is given:

$$Min\ Z_2 = \sum_{i=1}^{\Pi_f} \left(\begin{array}{l} \frac{q^r_{fi}}{\Re_{fi}\mu_{fi}} N^{mach}_{fi} n^{mach}_{fi} + N^{cond}_{fi} n^{cond}_{fi} \frac{q^r_{f(i+1)}}{\wp f} \\ + N^{bulb}_{fi} n^{bulb}_{fi} \frac{q^r_{f(i+1)}}{\wp f} + \frac{q^r_{fi}}{\Re_{fi}\mu_{fi}} \frac{N^{comp}_{fi}}{\rho^{comp}_{fi}} \upsilon^{comp}_{fi} n^{mach}_{fi} \end{array} \right) \tag{1}$$

By minimization of total CO_2 emissions Z3, it is given:

$$Min\ Z_3 = \sum_{i=1}^{\Pi_f} \left[\begin{array}{l} \omega_{f_i} \frac{q^r_{f_i}}{\Re_{f_i}\mu_{f_i}} N^{mach}_{f_i} n^{mach}_{fi} \\ +0.689 \left(\begin{array}{l} N^{cond}_{fi} n^{cond}_{fi} \frac{q^r_{f(i+1)}}{\wp f} + N^{bulb}_{fi} n^{bulb}_{fi} \frac{q^r_{f(i+1)}}{\wp f} \\ + \frac{q^r_{fi}}{\Re_{fi}\mu_{fi}} \frac{N^{comp}_{fi}}{\rho^{comp}_{fi}} \upsilon^{comp}_{fi} n^{mach}_{fi} \end{array} \right) \end{array} \right] + \sum_{s=1}^{S} \sum_{f=1}^{F} \left(\left(\frac{\omega^t_{sf}{}^{pes} + 2\omega^t_{sf}{}^{mos} + \omega^t_{sf}{}^{opt}}{4} \right) \frac{q^r_{sf}}{V} T_{sf} \right) + \sum_{f=1}^{F} \sum_{w=1}^{W} \left(\left(\frac{\omega^t_{fw}{}^{pes} + 2\omega^t_{fw}{}^{mos} + \omega^t_{fw}{}^{opt}}{4} \right) \frac{q^{mp}_{fw}}{V} T_{fw} \right) \tag{2}$$

Where

$N^{mach}_{f_i}$	installed power (kw) for a machine involved in process *i* at factory *f*.
$\Re_{f_i}$	manufacturing rate (kg/h) for a machine involved in process *i* at factory *f*.
μ_{f_i}	efficiency (%) for a machine involved in process *i* at factory *f*.
$N^{cond}_{f_i}$	installed power (kw) for an air-conditioning unit involved in process *i* at factory *f*.
$N^{bulb}_{f_i}$	installed power (kW) for a light bulb involved in process *i* at factory *f*.
$N^{comp}_{f_i}$	installed power (kw) for a compressor at factory *f*.
$\upsilon^{comp}_{f_i}$	compressed air (m^3/h) used for a machine involved in process *i* at factory *f*.
ω_{f_i}	CO_2 emission factor (kg/kWh) at factory *f*.
ω^t_{sf}, ω^t_{fw}	CO_2 emission factor (kg/mile) released for transportation from supplier *s* to factory *f* and from factory *f* to warehouse *w* respectively
q^r_{fi}	mass of material (kg) involved in process *i* in factory *f* where, $i \in \{1, 2, ..., \Pi_f\}$.
$q^r_{f(i+1)}$	mass of material (kg) transferred from the machines involved in process *i* in factory *f*.
q^r_{sf}, q^{mp}_{fw}	mass of material (kg) transported from supplier *s* to factory *f* and products transported from factory *f* to warehouse w, respectively.
$n^{mach}_{f_i}$	number of machines (unit) involved in process *i* in factory *f*.
$n^{cond}_{f_i}$	number of air-conditioning units (unit) involved in process *i* in factory *f*.
$n^{bulb}_{f_i}$	number of light bulbs (unit) involved in process *i* in factory *f*.

III. A Case Study

For examining the applicability of the integrated MOO-EDS approach as previously described, a real case study was applied. Table 1 shows manufacturing tasks of a production line at a woven sacks company. The production line consists of 8 different processing tasks; for each of these tasks to be processed it is involved in a number of machines, air-conditioning units and multiple illuminating bulbs. The production line is powered by electricity that is generated using oil as an indirect energy sources, which are then compared with solar as an indirect energy source to generate electricity. LINGO[11] software was also used for obtaining an optimal solution based on the developed MOO.

TABLE I. Manufacturing Tasks for Production of Plastic and Woven Sacks

Tasks	Description	Predecessors
R.M	Raw material (Polypropylene)	None
G	Extruding the Polypropylene to make stands	R.M
W	Weaving the strands into rolls of sacks	G
L	Laminating the rolls	W
P	Printing and branding	L
C	Cutting the rolls into bags	P
K	Liner stick, inserts and smoothest out blown film	C
S	Film sewed into bag	K
Z	End product compressed using baling machines	S

Fig. 2 shows the proposed plastic and woven sacks production line, which was built using the EDS software. It shows part of raw material source and the first process (extrusion process) of a woven sacks production line at the company.

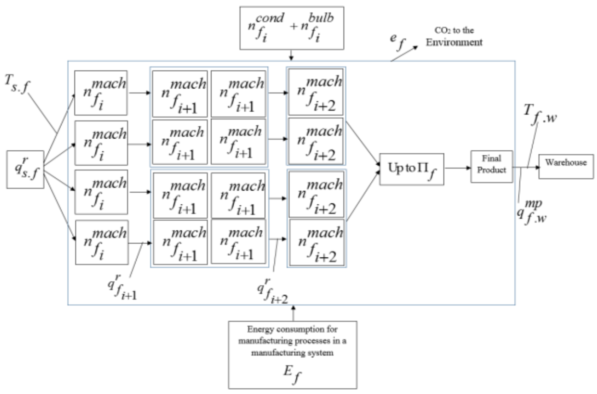

Figure 2. The plastic and woven sacks production line.

Fig. 3 and 4 show the simulation results using alternative energy solutions; these energy solutions are categorised as oil as a direct source of energy for generating thermal energy, oil and solar as an indirect source of energy, respectively for generating electricity that drives the manufacturing system facilities as previous described for production.

As shown in Fig. 3, the machines, air-conditioning units and light bulbs, which are involved in process task G, have the highest energy consumption and those equipment, which are involved in process task K, have the lowest energy consumption. This is due to the machines involved in process task G have the highest installed power (200 kw), while the machines involved in process task K have the lowest installed power (zero kw) as this process is largely involved in a manual task.

Fig. 4 also indicates comparable simulation results using the integrated MOO-EDS approach relating to amount of CO_2 emissions using oil as a direct source of energy and an indirect source of energy, and solar as an indirect source of energy for generating electricity. It shows that the equipment, which are involved in completing process task G, release the highest amount of CO_2 emissions, which are 4.08×10^9 kg) using oil as an indirect source of energy for generating electricity, 2.9×10^9 kg using oil as a direct source of energy for generating thermal energy and 3×10^6 kg using solar as an indirect source of energy for generating electricity, respectively. This is because the equipment involved in process task G consume the highest amount of energy. By contrast, the equipment involved in process task K generate the lowest amount of CO_2 emissions as those equipment consume less energy.

The simulation results in Fig. 4 also show that using the solar source of energy generates the lowest amount of total CO_2 emissions, which is 7×10^6 kg, followed by oil as a direct source of energy for generating thermal energy, which is 6.5×10^9 kg and oil as an indirect source of energy for generating electricity, which is 8.4×10^9 kg. This is because solar energy has the lowest emission factor where ω_{f_i} =0.05 kg/kWh, followed by oil as a direct source of energy (0.5 kg/kWh) and oil as an indirect source of energy (0.6895 kg/kWh), respectively.

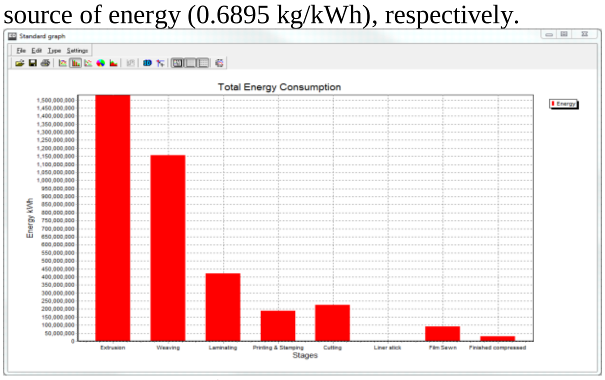

Figure 3. Screenshot of energy consumption results obtained using the integrated MOO-EDS approach.

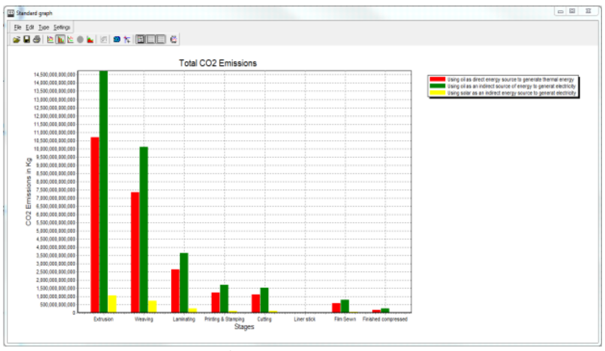

Figure 4. Screenshot of results obtained using the integrated MOO-EDS approach relating to amount of CO_2 emissions using oil as a direct source of energy and an indirect source of energy and solar as an indirect source of energy for generating electricity.

IV. CONCLUSIONS

For design of a manufacturing system, engineers used to focus on conventional indicators of system performance in relation to its productivity and capacity, environmental considerations were often overlooked. This paper presents a hybrid MOO-EDS approach incorporating parameters of energy consumption and amount of CO_2 emissions in the relevance to manufacturing activities associated with facilities for production into an EDS tool with the simulation results being optimised via LINGO[11] software. The developed hybrid MOO-EDS can be a useful decision-making tool as a reference for manufacturing system designers to determine a trade-off solution aiming for minimization of total energy consumption and amount of CO_2 emissions towards a sustainable manufacturing system design or evaluation at an early stage.

A real case study was employed for examination of the applicability of the developed hybrid MOO-EDS approach that can be used for quantifying energy consumption and amount of CO_2 emissions within a sustainable manufacturing system design. The comparative simulation results demonstrate that the hybrid FMOO-EDS approach can be a useful decision-making tool as an aid for manufacturing systems design and analysis by considering effects of energy consumption and amount of CO_2 emissions during production. The results also revealed that oil as indirect source of energy to operate facilities for production has the highest amount of CO_2 emissions. By comparison, using solar as an indirect source of energy leads to a lowest CO_2 emissions. From an industrial managerial perspective, this approach can be a useful and effective way for re-configuring current traditional manufacturing system design in order to achieve the aim of sustainability in accordance with both the ecological and economic constraints.

On the other hand, the current commercial DES packages offer only dedicated application object libraries (or atoms of the EDS tool used for this study) for developing DES models and these tools can be characterised as limited functionalities in the usage or purpose of manufacturing systems design and evaluation. The future challenges or trends in developments of DES tools are to introduce cloud-based technologies to facilitate the mobility of applications and the interoperability between different users. Currently, there are only few commercial tools that have integrated this function. In addition, more efforts need to be focused on creation of running established DES models for users using multiple and mobile devices. The extended use of open and cloud-based tools can address these issues and it can result in high performance in computing at a minimum cost.

Another major problem is that there is a lack of data exchange among different domains or users using different DES packages as there are no common standards or integrated frameworks, which cause difficulties in interoperability and collaboration between systems or partners. Application of building incremental models allows in-process debugging but often this does not work properly and this also increases the complexity of finding out the problems of the developed DES models.

All the above issues can be addressed further with the development and utilisation of multi-disciplinary and multi-domain integrated DES tools. As far as the lifecycle simulation is concerned, the poverty of adequate DES tools ought to be noted. There were only few applications that take into serious considerations of product life-cycle costs and environmental issues. In addition, some DES tools are usually aimed at the re-manufacturing of specific product types and these tools are still insufficient for de-manufacturing of products. Hence, researchers should focus on the development of DES tools for the field of lifecycle management as one case. Currently, object-oriented, hierarchical models of plants encompassing business, logistic and production processes exist but the direct integration of modelling tools with CAD, DBMS (ORACLE, SQL Server, Access, etc.) and direct spreadsheet link in/out, XML, HTML reports are still limited.

As a result, DES tools that will assure the multi-level integration among them should be developed as priority. Gradually, enterprises are starting to adopt the concepts and the models of virtual factory. But, the technologies or tools related to virtual factory especially with data acquisition, control and monitoring are still expensive, complicated and hard to apply in manufacturing industry. Thus, the research should also move towards the direction of real-time virtual factory by developing applicable and affordable tools. Efforts may also be made to create smart, intelligent and self-learning DES tools incorporating inbuilt algorithms for automated optimisation of system parameters providing optimised solutions for manufacturing system design, unfortunately, the current DES tools cannot offer optimised solutions but replicate existing manufacturing systems for evaluation or analysis. Moreover, there are applications that base on empirical or past data and some knowledge-based advisory systems. Although satisfactory and analytical simulation capabilities in continuous processing units can be noticed, research is required in order to develop more intelligent tools that will lead to autonomous self-adapting systems [3].

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Reda Nujoom conducted the research, the real case study in industry, data collection and analysis, the simulation work and the draft paper; Ahmed Mohammed was involved in development of multi-objective model and analysis; Qian Wang supervised the research work and re-configured the paper. All authors had approved the final version.

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