A Multi-Objective Optimization of Energy, Economic, and Carbon Emission in a Production Model under Sustainable Supply Chain Management

Biswajit Sarkar 1, Muhammad Omair 1 and Seok-Beom Choi 2,*

1 Department of Industrial & Management Engineering, Hanyang University, Ansan, Gyeonggi-do 15588, Korea; bsbiswajitsarkar@gmail.com (B.S.); muhamad.omair87@gmail.com (M.O.)
2 Department of International Business, Cheju Halla University, Jeju-do 63092, Korea
* Correspondence: sbchoi@chu.ac.kr; Tel.: +82-10-3854-2765

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Abstract: Nowadays, many industries are focusing on automation in manufacturing for high production and good quality to meet the needs of customers in a short period of time. This trend has produced a forward shift in technology in the form of advancement, which ultimately increases energy demand. For that reason, researchers have started working on sustainable development associated with cleaner-energy policies to avoid increasing energy consumption for enhanced manufacturing technology in developed countries. The other important issue affecting our world is global warming, which is the result of greenhouse gas emissions. That is the reason, renewable energies like solar energy have dramatically increased during recent years to compensate for the energy demand and reduced carbon footprint for cleaner production. This paper considers a supply chain management of automobile part manufacturing industry with suppliers to optimize the production quantity with multiple objectives i.e., minimizing the total cost of production including minimum quantity lubrication is a first objective, reduction of the carbon footprint is the second, and minimizing the cost of energy considering renewable energy is the last objective. This study considers a situation, where imperfect quality items are managed and controlled by the suppliers as outsourcing operations. A weighted goal programming methodology is utilized to solve the proposed mathematical model including sustainable suppliers. Sensitivity analysis of the model is performed for different scenarios with respect to the energy utilization. The optimal result of minimum production cost and carbon emissions is the evidence of successful pragmatic application in automobile industry. The results validate the model to provide the basis for sustainability in supply chain environment considering manufacturer and suppliers.

Keywords: carbon footprint; production model; sustainability; imperfect production

1. Introduction

The basic aim of manufacturing firms is to minimize the total cost of production. Likewise, many researchers optimized manufacturing models by considering sustainable free products and minimizing the total cost of production [1–6]. As customers have begun to value sustainable products, developed countries have adopted policies and strategies to attain sustainable manufacturing. On the other hand, developing countries are facing international market competition internationally due to lack of sustainable products, which produces potential research for manufacturers to adopt the concept of sustainable development. Such a sustainable manufacturing necessitates efforts on product, process and system levels including entire supply chain.

Sustainable development (SD) is defined by the Brundtland Commission in its 1987 report as a plan to fulfill the needs of the current generation without compromising the requirements of future
generations [7,8]. Energy as a catalyst of development is an essential indicator in the sustainable development of manufacturing and society [9]. Energy demand is rising day by day due to the increasing population and technological advancement in the industry. Globally, a large share of energy demand is generated by the industrial sector and consuming a significant amount of energy. The world energy consumption is analyzed by the U.S. energy information administration from the year 2012 to 2040 as given in Table 1. It is observed that energy consumption will continue to increase by 1.2% annually, on a global scale until 2040, which is lower than natural gas. However, the positive aspect of the analysis is the increasing share of renewable by 1.3% annually, which is more than the average but less than the natural gas. However, this share contributes more due to sustainable development by designing products and processes in manufacturing sector, which are eco-friendly and are accompanied by social support reduce carbon emissions [10]. In addition, there are numerous laws and regulations acted in different countries i.e., carbon tax, carbon trade-off, and carbon cap-and-trade [11,12]. The technology policies must be revised to increase the efficiency of energy consumption and reduce the carbon footprint for the benefit of people and society.

Table 1. World industrial sector energy consumption data, 2012–2040 (quadrillion Btu) [10].

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>2012</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
<th>2035</th>
<th>2040</th>
<th>% Change Annually</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total World</td>
<td>222.3</td>
<td>245.8</td>
<td>262.6</td>
<td>278.0</td>
<td>294.0</td>
<td>309.1</td>
<td>1.2</td>
</tr>
<tr>
<td>Liquid fuel</td>
<td>66.5</td>
<td>72.2</td>
<td>76.5</td>
<td>80.6</td>
<td>84.6</td>
<td>88.6</td>
<td>1.0</td>
</tr>
<tr>
<td>Natural gas</td>
<td>50.7</td>
<td>56.2</td>
<td>62.0</td>
<td>68.0</td>
<td>74.5</td>
<td>80.4</td>
<td>1.7</td>
</tr>
<tr>
<td>Coal</td>
<td>55.7</td>
<td>62.0</td>
<td>64.3</td>
<td>66.0</td>
<td>67.2</td>
<td>68.7</td>
<td>0.8</td>
</tr>
<tr>
<td>Electricity</td>
<td>31.9</td>
<td>37.2</td>
<td>40.0</td>
<td>42.2</td>
<td>44.3</td>
<td>46.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Renewable</td>
<td>17.4</td>
<td>18.2</td>
<td>19.7</td>
<td>21.3</td>
<td>23.0</td>
<td>25.1</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Due to rapid development and increasing population, the ecosystem has been damaged by greenhouse gas (GHG) emissions as a result of burning fossil fuels. Industries are working on strategies for reduction of energy consumption and carbon footprint for the clean and green environment. However, these policies in the form of investments increase the overall costs of products. Therefore, it is an urgent issue to select an eco-friendly energy source to fulfill the energy demand of present and future generations [13]. Providing sustainable energy access is one of the most critical global challenges [14]. However, the best option could be solar energy because of its great abundance [15]. Silicon technology is popular among solar cell designs due to its efficiency and suitability. Photovoltaic (PV) systems consist of cells that convert direct sunlight radiation into electricity [16]. Branker et al. [17] reviewed the levelized cost of electricity (LCOE) for solar renewable energy with the help of the case study based on Ontario power authority, Canada. It is concluded that the high initial cost of PV can be overcome by the combination of low-interest rate, long-term loans, and high discount rate.

Aiming to reduce the effect of high energy consumption, the industry should also focus on the process level of products. Sustainable machining is an important field of sustainable manufacturing aimed to reduce the machining cost, waste and power consumption provided in order to provide cleaner production. Sustainable machining involves cryogenic machining, dry machining, and near dry machining also called minimum quantity lubrication (MQL) [18]. MQL used in machining provides a major contribution to reduce carbon emission and energy consumption. MQL aims to minimize the force of friction and enhance the quality of a product. An MQL system is sustainable, improves the life of tools, provides a safe and hygienic environment to workers [19], and enhances the efficiency of machine tools in the form of minimum energy consumption [20]. A breakdown of machining costs is given in Figure 1 in terms of percentages of energy, cutting fluid, cutting tool, waste, etc. [21]. These results show the need to analyze the factor of cutting fluid carrying 15% cost, which is even more than the cost of the cutting tool. That is the reason, the selection of MQL in machining is highly significant for providing economic advantages along with environmental and societal benefits to the worker for sustainable machining.
This study is a step toward sustainable development in a manufacturing sector through the selection of MQL at the process level and utilization of cleaner-energy technology in manufacturer–supplier supply chain. The main contribution is to quantify the amount of carbon footprint reduction by the application of renewable energy. The analysis is providing a platform to adopt a renewable energy as a source in the automobile part industry for sustainable manufacturing. Globally, these tangible environmental advantages will help the policy makers to understand the positive impact of renewable energy to face the global warming challenge in production and supply chain management. The paper is structured as follows: Section 2 presents a literature regarding sustainability, renewable energy and carbon footprint. Furthermore, Section 3 shows the formulation of a mathematical model considering assumptions along with solution methodology, where weighted multiobjective goal programming (WGA) is revised for analysis of the model. Sections 4 and 5 depict the numerical example and results, respectively, to validate the practical applications of the proposed goal-oriented model. Section 6 presents the sensitivity analysis of the model to determine the effect of energy utilization on the manufacturing system in supply chain. Finally, Section 7 presents the conclusions of this study.

2. Literature Review and Research Gap

Energy consumption is one of the key criteria in life-cycle assessment (LCA) studies. There is enough information about energy usage during the manufacturing phase of LCA studies, and various assumptions must be made. According to statistics, the manufacturing sector consumes 90% of the total energy consumption of industry. As the resources of energy on earth are limited and steadily decreasing, sustainable manufacturing is gaining more and more attention. Energy efficient manufacturing is an important part of sustainable manufacturing aimed at processing products with less energy and the minimum carbon footprint [22]. Akpunar et al. [23] and Bortolini et al. [24] worked to minimize effectively the total energy utilized in the transportation of automated storage and retrieval system (AS/RS). Renewable energy is predicted to play a leading role in order to solve the issues related to energy demand and the environment. The energy payback time, net energy ratio, and the CO\textsubscript{2} emissions are calculated using methodologies based on LCA. Alsema [25] calculated the energy requirements and concerned CO\textsubscript{2} emissions for the manufacturing of grid-connected system. Ito et al. [26] have successfully analyzed the cost and life cycle of 100 MW solar systems in the Gobi desert, Mongolia. GHG emissions are best controlled by the methodologies of carbon footprint (CFP) assessment. CFP is based on the life cycle concept and is used to evaluate the GHG emissions during
extraction, manufacturing, and transportation of goods and services throughout the life cycle [27–29]. Accorsi et al. [30] and Lerher et al. [31] optimize the total cost and carbon footprint by designing the warehouse system of the production system.

The literature has found that automation in manufacturing has a significant environmental impact due to the high consumption of electricity in machining [32]. Sarkaya and Güllü [33] used the Taguchi design method and concluded that MQL is better for machining operation in order to retain the surface quality of a cutting part. The automotive industry in Germany presented in a survey that cutting fluid comprises 7–17% of manufacturing costs, which was several times higher than the cost of cutting tools having a proportion of 2–4% [34]. Hadad and Sadeghi [35] analyzed the turning process using MQL and evaluated the performance of the machining process on the basis of force, the roughness of material, and temperature distribution. However, there is a need to consider MQL in production and manufacturing models for sustainable machining.

The general production models consider perfect quality items with constant demand in a manufacturing system. However, in real situations, it is not possible to adhere to the ideal assumptions. Due to long-term usage and breakdown of equipment, in addition to human errors, no production system can produce perfect items [36]. For this reason, researchers and scientists have extended the models by considering imperfect production. Kim et al. [37] derived a model for multi-stage production system considering defective items. Similarly, Cárdenas-Barrón et al. [38] developed an EMQ model for imperfect production associated with rework and multiple shipment strategies. Sarkar et al. [39] derived an economic manufacturing quantity (EMQ) model under the effects of reliability and inflation. Sarkar and Moon [40] presented an EPQ model considering inflation in an imperfect production system to maximize the profit function of production. Tayyab and Sarkar [41] worked on lean production in a manufacturing system by considering a random defect rate. Researchers also made contributions to develop different mathematical models considered energy utilization and carbon footprint using numerous analytical techniques. Soroudi et al. [42] developed a multiobjective planning model for expansion of a network with distributed energy using the immune genetic algorithm (I-GA) to minimize cost and carbon emission. Kahraman et al. [43] determined the best alternative among renewable energy resources using a fuzzy-based multi-criteria tool and an analytical hierarchical process (AHP). Zagrouba et al. [44] determined the electrical attributes of photovoltaic solar cells to obtain the corresponding maximum power point using GA. Kulkarni et al. [45] used optimization techniques to maximize the profit of water replenishment. A few researchers considered carbon footprint in supply chain models for manufacturers. Xiao et al. [46] optimized a supply chain to minimize the carbon footprint of the manufacturer and retailer. In this direction, Wu and Chang [47] projected a grey theory model that considers environmental impact in terms of tax in production planning to make decisions in uncertain conditions. Wang et al. [48] develop a multiobjective model for evaluating the association of costs with environmental guidelines in green supply chain. Wang et al. (2016) [49] proposed an electricity monitoring system considering multiobjective linear programming and carbon footprint and using electricity as a source of energy. The authors studied on automobile parts manufacturing to minimize the cost of manufacturing, carbon footprint from production and cost of electricity. The major sources of energy were electricity, diesel, and gasoline. Table 2 shows the contribution of previous authors to provide an opportunity for policy makers to save energy and minimize carbon footprint.
Table 2. Author contribution table.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Energy Resources</th>
<th>Cost Function</th>
<th>Greenhouse Gases Emissions</th>
<th>Minimum Quantity Lubrication</th>
<th>Mathematical Techniques</th>
<th>Imperfect Items</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soroudi et al. (2005) [42]</td>
<td>Non-renewable</td>
<td>Total cost of system</td>
<td>Emission from grid</td>
<td>Non-dominated sorting</td>
<td>genetic algorithm</td>
<td></td>
</tr>
<tr>
<td>Kahraman et al. (2009) [43]</td>
<td>Renewable energy</td>
<td></td>
<td></td>
<td>Fuzzy analytical</td>
<td>hierarchical process</td>
<td></td>
</tr>
<tr>
<td>Zagrouba et al. (2010) [44]</td>
<td>Renewable energy</td>
<td>Cost of energy</td>
<td></td>
<td>Genetic algorithm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sarkar, B and Moon, I (2011) [40]</td>
<td></td>
<td>Profit</td>
<td></td>
<td>Analytical technique</td>
<td></td>
<td>Rework</td>
</tr>
<tr>
<td>Wang et al. (2011) [46]</td>
<td>Non-renewable</td>
<td>Total cost of production</td>
<td>CO₂</td>
<td>Normalized</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wang et al. (2016) [49]</td>
<td>Non-renewable</td>
<td>Total cost of production</td>
<td>CO₂</td>
<td>constraint method</td>
<td>Rework</td>
<td></td>
</tr>
<tr>
<td>This paper (PV technology)</td>
<td>Renewable energy</td>
<td>Cost of Photovoltaic technology</td>
<td>CO₂</td>
<td>Fuzzy multiobjective goal programming</td>
<td></td>
<td>Rework and scrap</td>
</tr>
</tbody>
</table>
However, previous studies did not quantify the effect of renewable energy on total cost and carbon emissions in a manufacturing system. This paper extends the model of Wang et al. [49] to develop a multiobjective goal-oriented model. The main contribution of the paper is the incorporation of renewable solar energy, carbon cost (tax), and minimum quantity lubrication at process level in the production of the automobile part industry integrated with suppliers in supply chain. The concept of the carbon tax and levelized cost (LCOE) of solar energy showed positive economic advantages to industry experts and practitioners to provide a sustainable life in supply chain management. The tangible results are generated to trade off the cost of production in favor of minimum carbon emissions for a sustainable manufacturing. Such a sustainable manufacturing environment requires efforts/optimization in product design, manufacturing, and supply chain. A scenario is also considered where imperfect items are produced by the suppliers in the supply chain to make the given model more realistic. A weighted goal programming (WGP) technique is applied to obtain an optimal allocation policy for automobile part production to minimize the total cost of production, carbon emissions, and energy cost for sustainable manufacturing in supply chain.

3. Mathematical Model

Mathematical methods have been used to calculate the environmental impact of energy resources. In the past, managers were only focusing on the basic objectives i.e., cost, time and quality. Now, the current and future situations of the global warming compelled researchers and experts to set an eco-friendly objectives. This is the reason that managers are also manufacturing and dealing with sustainable elements including energy and carbon emissions in the supply chain. This paper deals with the supply chain management, which integrates multiobjective goal programming associated with the manufacturing phase of a Taiwan-based automobile part with integrated suppliers. The importance of proposed mathematical model is not only limited to the production system but also extended to the supply chain management by integrating sustainable suppliers to undertake the limitations of carbon footprint and renewable energy. Taiwan is known for manufacturers and exporters of a variety of auto parts among developing countries. The production flow diagram of automobile parts manufacturing is illustrated in two steps as in Figures 2 and 3, respectively.

![Figure 2. Production flow of automobile parts.](image-url)
Figure 3. Production flow of automobile parts.

The three parts A, B, and C are produced in-house by a sequence of manufacturing processes, i.e., sealing, bending, stuffing, stamping 1 and 2, cutting, cleaning, laser, coating, welding, fastening, and packaging. The sources of energy used in the manufacturing processes are electricity, solar, diesel, and gasoline. Solar energy as a renewable energy is considered to represent $h\%$ of the electricity consumed. By this consideration, the requirement of electricity is reduced to $1-h$ in each process category. The economic feasibility of solar energy as a renewable is analyzed by using the levelized cost of electricity (LCOE) generation to compare with other electricity technologies. LCOE calculates the cost of solar energy annually by considering the lifetime of the solar system using discounted cash flow techniques i.e., by calculating the present value of cash flows by mean of discount rate, $r$. Therefore the sum of present value of LCOE multiplied by the energy generated should be equal to the present valued net costs in Equation (1) [17,50,51]:

$$
\sum_{t=1}^{T} \left( \frac{LCOE_t}{(1+r)^t} \right) \times E_t = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t},
$$

where $C_t$ is the net cost of the solar system, consisting cash outflows in the form of initial investment ($I_t$), operations costs ($O_t$), maintenance cost ($M_t$), and fuel expenses ($F_t$) as given in Equation (2):

$$
LCOE = \frac{\sum_{t=1}^{T} \left( I_t + O_t + M_t + F_t \right) / (1+r)^t}{\sum_{t=1}^{T} E_t / (1+r)^t}.
$$

The limited capacity of resources and the aim of low operational cost compel manufacturing firms to outsource coating and laser operations to suppliers i.e., U, V, and W. There is an inspection workstation after each laser and coating operation to sort pass, rework and rejection parts. Pass parts move to the next station, rework parts backtracks to repeat the same operation and rejections move to scrap section, which are further salvaged at a low price. Let $\beta$ be the proportion of defective items of total production, and $\alpha$ is the percentage of scrap among defective items, then $\alpha \beta$ is the scrap quantity of total production, and $\beta - \alpha \beta$ represents the rework parts backtracked on the same workstation. The manufacturing industry evaluates the suppliers for outsourcing on the basis of quality, cost and carbon footprint. This model is proposed to replace MQL with cutting fluid in the cutting operations of the process flow to enhance environmental, societal, and economic fronts. Different techniques are used to find the optimal solution of a multiobjective mathematical model in the form of a system of equations. Goal programming (GP), developed by Charnes et al. [52], is a widely used methodology of
multi-criteria decision-making. The concept of GP is to satisfy the set objectives, i.e., to find a solution that comes as close as possible to each goal. This is the reason that a target value is obtained, which shows a level of achievement for each objective. Deviational variables are set in order to show the amount by which the results are numerically above or are below the corresponding goals. WGP is based on the assignments of weights to the objectives and a minimized total penalty in the form of deviational variables, which help decision makers to achieve the most important objectives of the desired goal [53].

3.1. Assumptions

The following assumptions were used for the proposed model:

1. The model considers multiple types of products and a constant production rate with known demand i.e., no shortages are produced in the system.
2. Cost of production includes labor energy costs and labor costs, where energy sources are electricity, solar energy, gasoline and diesel.
3. Manufacturing processes are performed in-house except laser and coating operations, which are outsourced to suppliers. There is limited capacity for in-house and outsourced production.
4. Products can be reworked, but some imperfect items are produced after rework, which are sold at a discounted rate in the form of scrap.
5. MQL replaced conventional cutting fluid in the cutting operation. However, its cost is not considered in the manufacturing cost and is presented separately in the model.
6. Carbon footprint of production is also considered, and suppliers must also satisfy quality and environmental laws.
7. Solar energy is considered to represent h% of total electricity consumed in production to balance the total energy requirement of the system.
8. The levelized cost of electricity is considered as a regional weighted average of world-based statistical data [54].

3.2. Notation

The indices along with input parameters and decision variables of the model are comprehensively listed in Appendix A.

3.3. Formulation of the Mathematical Model

The multiobjective model is formulated to minimize the total production cost as the first objective, carbon emission as the second, and cost of energy as the third objective. The objective of the proposed WGP model is to minimize the deviations from the goals:

\[ \text{Minimize } w_1 d_1^+ + w_2 d_2^+ + w_3 d_3^+ . \]  

Equation (3) depicts the minimization of the deviations around the targeted goals. \( d_1^+ \), \( d_2^+ \) and \( d_3^+ \) indicate the deviational variables of total cost of production, carbon emission and energy cost goals, respectively. \( w_1 \), \( w_2 \) and \( w_3 \) are the corresponding weights. Since deviations have different units, i.e., $ and kg, it is not possible to sum them directly due to incommensurability. In order to add these factors, normalization methods are needed. The proposed model uses the percentage normalization method to standardize the different units to a single function and is represented by dividing the deviations by their corresponding target goals. Thus, the objective function of the proposed model using WGP is given in Equation (4):

\[ \text{Minimize } w_1 \frac{d_1^+}{\text{Goal}_A} + w_2 \frac{d_2^+}{\text{Goal}_B} + w_3 \frac{d_3^+}{\text{Goal}_C} . \]  

The first goal of the proposed model is to minimize the total cost of production, which covers fixed cost and variable cost. Fixed cost includes capital and setup cost, while variable cost includes
for manufacturing cost, crashing cost, maintenance cost, holding cost, warehousing cost, energy cost, rework with scrap, and cost of MQL along with deviational variables, as in Equation (5):

\[
\text{Total cost of production (A)} = \text{Fixed cost} + \text{Manufacturing cost} + \text{Crashing cost} + \text{Holding cost} + \text{Cost of solar energy} + \text{Cost of diesel} + \text{Cost of gasoline} + \text{Reworking cost} + \text{Outsourcing cost} + \text{Cost of MQL system} + \text{Scrap cost} + \text{Carbon emission cost} + d_{t}^{-} - d_{t}^{+}.
\] (5)

The ultimate objective of the industry is to minimize the production cost by any source. The managers need to verify each cost separately and carefully to determine which cost contributes the most to the total cost. This is why each must be defined and calculated individually, as given in Equations (6) to (19).

**Fixed cost (FC)**

The cost is related to the initial cost required to run the production system. It may include setup cost, changeover, and tool setting cost. This cost is fixed, independent of the production quantity. It is dependent on time and consists of initial investment and setup cost of the system in this production model, as given in Equation (6):

\[
FC = \sum_{j=1}^{J} \sum_{t=1}^{T} (FC_{jt}).
\] (6)

**Manufacturing cost (MC)**

Specifically, this is the cost incurred in the manufacturing operations of automobile parts, which is a variable cost and highly dependent on the production quantity. The cost comprises the sum of all costs utilized on resources required to manufacture product. It includes machining and processing cost, utilities required for machines, and labor cost. It is associated with the manufacturing operations of in-house manufacturing and can be formulated in the form of Equation (7):

\[
MC = \sum_{j=1}^{J} \sum_{t=1}^{T} (MC_{jt} \times MQ_{jt}).
\] (7)

**Crashing cost (CC)**

Crashing cost is used to improve the service level of the product by adding resources in the form of labor, machines, and energy. This cost is utilized to reduce the crashing lead time required to manufacture the given product. The crashing cost is incurred on the calculated amount of extra quantity required to avoid shortages. It is produced to compensate the extra demand in terms of backorders. The equation of crashing cost is given as in Equation (8):

\[
CC = \sum_{j=1}^{J} \sum_{t=1}^{T} (CC_{jt} \times CQ_{jt}).
\] (8)

**Holding cost (HC)**

Holding cost is the basic cost needed to understand the basic production model, which is variable and dependent upon the variable inventory at any instant of time. This is the carrying cost of holding inventory. Holding cost depends on production of semifinished and finished goods used as stock. It is incurred on production and crashing quantities in the proposed model and includes costs such as wedges, warehouse rent, and insurance. It also depends on the holding time of the product in inventory and can be expressed as in Equation (9) [55]:

\[
HC = \sum_{j=1}^{J} \sum_{t=1}^{T} HC_{jt} \times (MQ_{jt} + CQ_{jt}).
\] (9)
Maintenance cost (mC)

The ultimate objective to consider maintenance in this model is to reduce the effects of risk because of machine breakdown to enhance the service level of the manufacturing system. It is very important to improve the reliability of the system by planning for breakdown, malfunctioning, repairing, shutdown, and preventive measures. Maintenance cost includes spare parts, lubrication oils, maintenance kits, etc. It can be formulated as in Equation (10) [56]:

\[ mC = \sum_{j=1}^{J} \sum_{t=1}^{T} mC_{jt}. \]  

Warehousing cost (WC)

The warehousing cost is based on the storage and retrieval system of the production system. These costs are associated with the activities of warehouse inventory except holding cost and include cost of inventory control warehouse maintenance i.e., rent, utilities, salaries, and insurance. Warehousing cost can be calculated as in Equation (11) [31]:

\[ WC = \sum_{j=1}^{J} \sum_{t=1}^{T} WC_{j} \times (MQ_{jt} + CQ_{jt}). \]  

Energy cost (EC)

Energy costs are related to the source of energy, i.e., electricity (ECC), solar energy (SEC), diesel fuel (DC), and gasoline (GC), and the in-house manufacturing, reworking, and outsourcing operations. The basic energy requirement is fulfilled by regular grid-based electricity and renewable energy from PV, while diesel and gasoline are auxiliary types of energy resources. These individual costs are represented as in Equations (12)–(15), respectively [49]:

\[ EC = \sum_{j=1}^{J} \sum_{t=1}^{T} \gamma_{1} \times EP_{j} \times (MQ_{jt} + CQ_{jt}) + \sum_{j=1}^{J} \sum_{t=1}^{T} \gamma_{1} \times ER_{j} \times OQ_{ijt} \times (1 - \alpha_{ijt}) \times \beta_{ijt}, \]  

\[ SEC = \sum_{j=1}^{J} \sum_{t=1}^{T} \gamma_{4} \times SP_{j} \times (MQ_{jt} + CQ_{jt}) + \sum_{j=1}^{J} \sum_{t=1}^{T} \gamma_{4} \times SR_{j} \times OQ_{ijt} \times (1 - \alpha_{ijt}) \times \beta_{ijt}, \]  

\[ DC = \sum_{j=1}^{J} \sum_{t=1}^{T} \gamma_{2} \times DP_{j} \times (MQ_{jt} + CQ_{jt}) + \sum_{j=1}^{J} \sum_{t=1}^{T} \gamma_{2} \times DR_{j} \times OQ_{ijt} \times (1 - \alpha_{ijt}) \times \beta_{ijt}, \]  

\[ GC = \sum_{j=1}^{J} \sum_{t=1}^{T} \gamma_{3} \times GP_{j} \times (MQ_{jt} + CQ_{jt}) + \sum_{j=1}^{J} \sum_{t=1}^{T} \gamma_{3} \times GR_{j} \times OQ_{ijt} \times (1 - \alpha_{ijt}) \times \beta_{ijt}. \]  

Reworking cost (RC)

Inspection stations are located at supplier locations right after each laser and coating operation to inspect for defective items along the production flow. Rework parts are returned to same workstation for processing, which involves costs of processing, energy, labor, etc. Reworking cost can be expressed as in Equation (16) [40]:

\[ RC = \sum_{l=1}^{L} \sum_{i=1}^{I} VC_{ijt} \times OQ_{ijt} \times (1 - \alpha_{ijt}) \times \beta_{ijt}. \]  

Outsourcing cost (OC)

The role of suppliers is very significant in a sustainable manufacturing system for supply chain management. These suppliers are limited to provide environmental regulations (carbon emission tax) and quality law during manufacturing. Due to limitations of resources in terms of capacity, the manufacturing system bears the outsourcing cost for laser and coating operations from three suppliers
i.e., $U$, $V$ and $W$ to provide a continuous and smooth flow of material in supply chain as given in Equation (17) [57]:

$$OC = \sum_{i}^{T} \sum_{j}^{T} OC_{ij} \times OQ_{ij}. \quad (17)$$

**Costs of MQL (MQLC) and Scrap (SC)**

MQL includes installation cost, running cost, and maintenance cost, while scrap cost is based on those that are defective sorted after inspection and sold at a discounted price. As a result, cost is incurred due to loss of some proportion of defective items that can not be sold at the original price. Costs of MQL and scrap are represented as in Equations (18) and (19) [18]:

$$MQLC = \sum_{i}^{T} \sum_{j}^{T} MQL_{ij} \times (MQ_{ij} + CQ_{ij}), \quad (18)$$

$$SC = \sum_{i}^{T} \sum_{j}^{T} SC_{ij} \times OQ_{ij} \times \alpha_{ij} \times \beta_{ij}. \quad (19)$$

**Carbon emissions cost (CEC)**

Cost of carbon emissions is estimated when penalty is added to the production firms on the basis of CO$_2$ produced due to the burning of fossils fuel. The costs penalized on the carbon emission by the production, outsourcing and reworking operations are expressed as in Equation (20), where CE is the total carbon emission, which is represented in more detail in Equations (22)–(26) [51]:

$$CEC = \gamma_{5} CE. \quad (20)$$

From the costs given in Equations (6) to (20), total cost of production (TC) can be given as in the form of Equation (21):

$$TC \text{ (Goal A)} = \sum_{i}^{T} \sum_{j}^{T} (FC_{ij} + MQ_{ij} \times MQ_{ij} + CC_{ij} \times CQ_{ij}) + \sum_{i}^{T} \sum_{j}^{T} HC_{ij} \times (MQ_{ij} + CQ_{ij})$$

$$+ \sum_{i}^{T} \sum_{j}^{T} MC_{ij} + \sum_{i}^{T} \sum_{j}^{T} WC_{ij} \times (MQ_{ij} + CQ_{ij}) + \sum_{i}^{T} \sum_{j}^{T} T_{ij} \times EP_{ij} \times (MQ_{ij} + CQ_{ij})$$

$$+ \sum_{i}^{T} \sum_{j}^{T} \sum_{k}^{T} \sum_{m}^{T} \sum_{l}^{T} \sum_{n}^{T} \sum_{p}^{T} T_{ij} \times DR_{ij} \times OQ_{ij} \times \beta_{ij} \times \alpha_{ij} \times \beta_{ij} + \sum_{i}^{T} \sum_{j}^{T} \sum_{k}^{T} \sum_{m}^{T} \sum_{l}^{T} \sum_{n}^{T} \sum_{p}^{T} \sum_{q}^{T} T_{ij} \times SP_{ij} \times (MQ_{ij} + CQ_{ij})$$

$$+ \sum_{i}^{T} \sum_{j}^{T} \sum_{k}^{T} \sum_{m}^{T} \sum_{l}^{T} \sum_{n}^{T} \sum_{p}^{T} \sum_{q}^{T} \sum_{r}^{T} T_{ij} \times VQ_{ij} \times OQ_{ij} \times \beta_{ij} \times \alpha_{ij} \times \beta_{ij}$$

$$+ \sum_{i}^{T} \sum_{j}^{T} \sum_{k}^{T} \sum_{m}^{T} \sum_{l}^{T} \sum_{n}^{T} \sum_{p}^{T} \sum_{q}^{T} \sum_{r}^{T} \sum_{s}^{T} T_{ij} \times (MQ_{ij} + CQ_{ij})$$

$$+ \sum_{i}^{T} \sum_{j}^{T} \sum_{k}^{T} \sum_{m}^{T} \sum_{l}^{T} \sum_{n}^{T} \sum_{p}^{T} \sum_{q}^{T} \sum_{r}^{T} \sum_{s}^{T} \sum_{t}^{T} T_{ij} \times OQ_{ij} \times \alpha_{ij} \times \beta_{ij}$$

$$+ \gamma_{5} CE + d_{2} - d_{1}^{*}. \quad (21)$$

The second objective of the model is to minimize the carbon emissions generated by the manufacturing processes of the automobile industry. Carbon emissions are calculated as total carbon emissions from in-house, outsourcing and reworking operations depending on energy source. Carbon emissions for the complete manufacturing process can be optimized by the expression as given in Equation (22):

$$\text{Carbon emission goal (B) } = \text{ Carbon emission due to electricity in manufacturing, outsourcing, and reworking operations} + \text{ emission due to usage of solar energy}$$

$$+ \text{ emission due to burning of diesel} + \text{ emission by burning gasoline} \quad (22)$$

Similarly, Equation (22) represents the theoretical form to minimize the carbon emissions. To express this mathematically, it can be broken down into three equations: Equations (23) to (25). Carbon produced from in-house manufacturing (CEI) is the sum of emissions due to electricity, diesel, and gasoline utilized in-house production operations, given as in Equation (21):

$$CEI = \sum_{j=1}^{T} \sum_{i=1}^{T} (\alpha_{1} \times EP_{ij} + \alpha_{2} \times DP_{ij} + \alpha_{3} \times GP_{ij} + \alpha_{4} \times SP_{ij})$$

$$+ (MQ_{ij} + CQ_{ij}). \quad (23)$$
Carbon emissions due to consumption of electricity, diesel and gasoline in outsourcing operations (CEO) by the suppliers can be calculated as in Equation (24):

\[
CEO = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{t=1}^{T} \left( (a_1 \times EO_{ij} + a_2 \times DO_{ij} + a_4 \times SO_{ij} + a_3 \times GO_{ij}) \times OQ_{ijt} \right).
\]  

(24)

The proportion of carbon emissions is due to reworking operations (CER) generated by the supplier. In the model, a proportion of defective parts is transported to scrap because they cannot be reworked and are required to be sold at a discounted rate to be disposed of in a sustainable way. Such is not subjected to reworking operations and so will not generate carbon emissions, reducing the amount of emissions by \(OQ_{ijt} \times \beta_{ijt} \times \alpha_{ijt}\) quantity. Carbon emissions as a result of reworking operations can be given as in Equation (25):

\[
CER = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{t=1}^{T} \left( a_1 \times ER_j + a_2 \times DR_j + a_3 \times GR_j + a_4 \times SR_j \right) \times OQ_{ijt} \times \beta_{ijt} \times (1 - \alpha_{ijt}).
\]  

(25)

Using Equations (23) to (25), the total carbon emission (CE) produced by the system can be given as in Equation (26):

\[
CE \ (Goal \ B) = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{t=1}^{T} \left( a_1 \times EP_j + a_2 \times DP_j + a_3 \times GP_j + a_4 \times SP_j \right) \times (MQ_{ijt} + CQ_{ijt})
+ \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{t=1}^{T} \left( a_1 \times EO_{ij} + a_2 \times DO_{ij} + a_3 \times GO_{ij} + a_4 \times SO_{ij} \right) \times OQ_{ijt}
+ \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{t=1}^{T} \left( a_1 \times ER_j + a_2 \times DR_j + a_3 \times GR_j + a_4 \times SR_j \right)
\times OQ_{ijt} \times \beta_{ijt} \times (1 - \alpha_{ijt}) + d_2^3 - d_1^2.
\]  

(26)

The third objective is to optimize the model by minimizing the cost of energy consumed in manufacturing. Primary sources of energy are electricity and solar utilized to perform in-house, reworking, and outsourcing operation. Therefore, the objective function in the form of costs of electricity and solar energy is given as in Equation (27):

\[
\text{Energy cost goal (C)} = \text{Electricity utilized in manufacturing, outsourcing and reworking operations} + \text{Utilization of solar energy} \\
+ \ d_3^3 - d_1^2.
\]  

(27)

Electricity cost can be broken down into the portions of energy utilized in in-house manufacturing (EI), in reworking operations (ER) and to perform outsourcing operations (EO), as given in Equations (28)–(30):

\[
EI = \sum_{j=1}^{J} \sum_{t=1}^{T} (\gamma_1 \times EP_j \times (MQ_{ijt} + CQ_{ijt})),
\]  

(28)

\[
EO = \sum_{i=1}^{I} \sum_{j=1}^{J} (\gamma_1 \times EO_{ij} \times OQ_{ijt}),
\]  

(29)

\[
ER = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{t=1}^{T} (\gamma_1 \times ER_j \times (1 - \alpha_{ijt}) \times \beta_{ijt} \times OQ_{ijt}).
\]  

(30)

Similarly, the energy requirement of the production system is also fulfilled by a solar energy system to perform in-house (SI), reworking (SR), and outsourcing operations (SO), as given in Equations (31)–(33):

\[
SI = \sum_{j=1}^{J} \sum_{t=1}^{T} (\gamma_4 \times SP_j \times (MQ_{ijt} + CQ_{ijt})),
\]  

(31)

\[
SO = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{t=1}^{T} (\gamma_4 \times SO_{ij} \times OQ_{ijt}),
\]  

(32)

\[
SR = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{t=1}^{T} (\gamma_4 \times SR_j \times (1 - \alpha_{ijt}) \times \beta_{ijt} \times OQ_{ijt}).
\]  

(33)
From Equations (28)–(33), the overall equation to minimize total cost energy (TEC) is expressed as in Equation (34):

\[
TEC \text{ (Goal C)} = \sum_{j=1}^{J} \sum_{t=1}^{T} (\gamma_1 \times EP_j \times (MQ_{jt} + CQ_{jt})) + \sum_{j=1}^{J} \sum_{t=1}^{T} (\gamma_1 \times EO_{jt} \times OQ_{jt}) \\
+ \sum_{j=1}^{J} \sum_{t=1}^{T} \sum_{i=1}^{I} (\gamma_4 \times SP_{ij} \times (MQ_{jt} + CQ_{jt})) \\
+ \sum_{j=1}^{J} \sum_{t=1}^{T} \sum_{i=1}^{I} \sum_{t=1}^{T} (\gamma_4 \times SO_{ij} \times OQ_{ijt}) + \sum_{j=1}^{J} \sum_{t=1}^{T} \sum_{i=1}^{I} \sum_{t=1}^{T} (\gamma_4 \times SR_{ij} \times (1 - \alpha_{ijt}) \times \beta_{ijt} \times OQ_{ijt}) + d_j - d_j^+. \\
\] (34)

3.4. Constraints

The manufacturing system is restricted at in-house production, outsourcing, and reworking by a few limitations. The constraints of the proposed model are related to required demand, order quantity, and capacities of manufacturer and suppliers are given as in Equations (35) to (42).

3.4.1. Demand

The first constraint is based on the annual demand of the production from the market. It is a basic constraint used to limit the production system along the supply chain under the demand target. The capacity, resources, scheduling and planing are dependent on the annual demand of the system:

\[
\sum_{j=1}^{J} \sum_{t=1}^{T} (MQ_{jt} + CQ_{jt}) \sim D_j. \quad (35)
\]

3.4.2. Production Quantity

The second constraint is related to the outsourcing of the manufacturing processes i.e., laser and coating. The suppliers are carrying all the manufacturing items for outsourcing operation and returned all of them back after proposing work to in-house manufacturing through supply chain management. This constraint indicates that the production and outsourcing quantities are equal provided optimal quantity of each item are decided to send to each supplier to minimize the cost of production [57]:

\[
\sum_{j=1}^{J} \sum_{t=1}^{T} (MQ_{jt} + CQ_{jt}) = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{t=1}^{T} OQ_{ijt}. \quad (36)
\]

3.4.3. Manufacturing Limitation

The manufacturing facility is limited due to less resources in term of workers and machines. This is the reason that crashing quantity is produced to recover the shortages and minimize the lead time:

\[
MQ_{jt} \leq ML_{jt}, \quad (37)
\]

\[
MQ_{jt} \geq MU_{jt}. \quad (38)
\]

3.4.4. Supplier Capacity

Supplier capacity is also limited due to the same reason i.e., workers and machines. Therefore, it is not possible for one supplier to fulfill the demand alone and three suppliers are directed to work with the manufacturer in a supply chain management for sustainability [58]:

\[
OQ_{ijt} \leq AS_{ijt}, \quad (39)
\]

\[
OQ_{ijt} \geq BS_{ijt}. \quad (40)
\]
3.4.5. Crashing Quantity

The crashing quantity is also restricted to the maximum limit by the maximum budget available for the production to accommodate the possible shortages occurs in the system

\[ \sum_{j=1}^{J} \sum_{t=1}^{T} CQ_{jt} CC_{jt} \leq NT_{jt}. \]  

(41)

3.4.6. Non-Negativity

\[ MQ_{jt}, CQ_{jt}, OQ_{ijt} \geq 0. \]  

(42)

4. Numerical Example

A numerical problem is performed to present the real-time application of the proposed mathematical model. Research data was mostly collected from the research study of Wang et al. [49] except the data regarding solar energy, MQL system and scrap. An electricity monitoring system was integrated with a network system of machine tools to record the time scale and production parameters of manufacturing operations. Electricity consumed by the operations was collected from the units given by electric meters, while diesel and gasoline consumption was obtained from previous records. Suppliers were consulted for data regarding outsourcing and rework operations. Table 3 states the cost data related to the production system along with the demands. Major costs include fixed and variable costs including manufacturing, maintenance, holding, scrap, and MQL. Cost related to MQL system was assumed as \( m\% \) of the manufacturing cost for each item \( A, B, \) and \( C \), respectively. It is also reported that coolant management costs constitute 7.5% to 17% of the total manufacturing cost, such that \( m \) averaged 7.5 and 17, i.e., 12.25% of manufacturing cost [59].

**Table 3. Manufacturing data.**

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Item Type</th>
<th>Fixed Cost ($/Cycle)</th>
<th>Manufacturing Cost ($/Unit)</th>
<th>Crashing Cost ($/Unit)</th>
<th>Holding Cost ($/Unit)</th>
<th>Maintenance Cost ($/Cycle)</th>
<th>MQL Cost ($/Unit)</th>
<th>Warehousing Cost ($/Unit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>2307</td>
<td>0.32</td>
<td>0.42</td>
<td>0.25</td>
<td>510.5</td>
<td>0.0725</td>
<td>0.067</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>2307</td>
<td>0.29</td>
<td>0.39</td>
<td>0.21</td>
<td>255.26</td>
<td>0.0725</td>
<td>0.08</td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>2780</td>
<td>0.18</td>
<td>0.23</td>
<td>0.04</td>
<td>574.33</td>
<td>0.0725</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Table 4 shows reworking cost and scrap cost. Scrap cost for each item was assumed to be almost 3% of the average manufacturing cost, i.e., $0.083. Cost of energy sources and coefficients of carbon equivalent to electricity, solar, diesel, and gasoline usage are given in Table 5. PV systems can be divided into three main categories on the basis of energy generation i.e., residential rooftop (less than 20 kWe), commercial rooftop (from 20 kWe to 1 MWe), and large ground mounted (greater than 1 MW). To fulfill the h% requirement of energy from solar, a utility-scale solar system is considered for generation of electricity. They operate as any other power plant and provide power to the grid. Thousands of such solar system plants are currently in operation worldwide. The global average LCOE is considered as 0.195 $/kWh (average of 0.11–0.28) from the statistical analysis report of IRENA [45,54], based on the world energy data (considering life cycle = 25 years, discount rate = 7%, capacity factor = 12%, annual efficiency = 12%, overnight cost = 7284 $/kWe, and investment cost = 754 $/kWe). Carbon tax is applied on industries by the government for every ton of CO\(_2\), i.e., $25 to motivate for the reducing of carbon emissions [51]. The life-cycle carbon emissions for the PV system is considered as 32 CO\(_2\) $/kWh from the research work of [60]. The capacity limitation of manufacturing system and warehouse due to less resources is given in Table 6.
Table 4. Data of reworking operations with demand.

<table>
<thead>
<tr>
<th>Cycle Time</th>
<th>Item Type</th>
<th>Rework Cost ($/Unit)</th>
<th>Scrap Cost ($/Unit)</th>
<th>Additional ($/Unit)</th>
<th>Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>0.116</td>
<td>0.083</td>
<td>3500</td>
<td>800</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>0.116</td>
<td>0.083</td>
<td>2000</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0.15</td>
<td>0.083</td>
<td>500</td>
<td>400</td>
</tr>
</tbody>
</table>

Table 5. Energy cost and carbon emissions.

<table>
<thead>
<tr>
<th>Energy Source Type</th>
<th>Unit Cost ($)</th>
<th>kgCO$_2$e</th>
<th>Cost of CO$_2$ ($/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity (kWh)</td>
<td>0.1</td>
<td>0.536</td>
<td>0.025</td>
</tr>
<tr>
<td>Diesel fuel (L)</td>
<td>1.06</td>
<td>2.615</td>
<td></td>
</tr>
<tr>
<td>Gasoline (m$^3$)</td>
<td>0.6</td>
<td>1.881</td>
<td></td>
</tr>
<tr>
<td>Solar energy (kWh)</td>
<td>0.195</td>
<td>0.032</td>
<td></td>
</tr>
</tbody>
</table>

Table 6. Capacity limitation of manufacturing system and warehouse.

<table>
<thead>
<tr>
<th>Cycle Time</th>
<th>Item Type</th>
<th>Maximum Capacity (Units)</th>
<th>Minimum Capacity (Units)</th>
<th>Warehouse Capacity (m$^3$)</th>
<th>Unit Warehouse Space (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>570</td>
<td>80</td>
<td>480</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>290</td>
<td>80</td>
<td>480</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>345</td>
<td>70</td>
<td>256</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Data regarding energy consumption from electricity, diesel, solar, and gasoline utilized in manufacturing, reworking and outsourcing operations are presented as in Table 7. Solar energy as a renewable energy is considered to be added in the manufacturing system to reduce the requirement of electricity. In this numerical example, it is assumed as $h = 20\%$ of electricity consumed, which is why the requirement of electricity requirement is reduced to $1 - h$ in each activity i.e., electricity was fulfilling the requirement of 0.38 kWh for manufacturing item A. Due to addition of 0.0636 kWh of solar energy in the manufacturing system, the electricity consumption reduced to 0.2544 kWh. Similarly, the diesel and gasoline usage for item A are 0.3184 L and 0.0004 m$^3$, respectively. Outsourcing data is given in Table 8. Outsourcing data covers the capacity restrictions of suppliers, outsourcing cost, defective and scrap proportion. The proposed model’s considered defective rate of the items is assumed as $1.2\%$ and the scrap rate as $2\%$ to support realistic representation of the proposed model.

Table 7. Energy consumption data.

<table>
<thead>
<tr>
<th>Production Status</th>
<th>Item Type</th>
<th>Electricity (kWh)</th>
<th>Diesel Fuel (L)</th>
<th>Gasoline (m$^3$)</th>
<th>Solar Energy (% of Electricity, kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturing</td>
<td>A</td>
<td>0.2544</td>
<td>0.03184</td>
<td>0.0004</td>
<td>0.0636</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>B</td>
<td>0.2344</td>
<td>0.0937</td>
<td>0.0005</td>
<td>0.0586</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>C</td>
<td>0.364</td>
<td>0.0718</td>
<td>0.0005</td>
<td>0.091</td>
</tr>
<tr>
<td>Reworking</td>
<td>A</td>
<td>0.54</td>
<td>0.0055</td>
<td>0</td>
<td>0.135</td>
</tr>
<tr>
<td>Reworking</td>
<td>B</td>
<td>0.5616</td>
<td>0.0055</td>
<td>0</td>
<td>0.1404</td>
</tr>
<tr>
<td>Reworking</td>
<td>C</td>
<td>0.6056</td>
<td>0.011</td>
<td>0</td>
<td>0.1514</td>
</tr>
<tr>
<td>Outsourcing by U</td>
<td>A</td>
<td>0.5232</td>
<td>0.008</td>
<td>0</td>
<td>0.1308</td>
</tr>
<tr>
<td>Outsourcing by U</td>
<td>B</td>
<td>0.5096</td>
<td>0.008</td>
<td>0</td>
<td>0.1274</td>
</tr>
<tr>
<td>Outsourcing by U</td>
<td>C</td>
<td>0.576</td>
<td>0.015</td>
<td>0</td>
<td>0.144</td>
</tr>
<tr>
<td>Outsourcing by V</td>
<td>A</td>
<td>0.5784</td>
<td>0.007</td>
<td>0</td>
<td>0.1446</td>
</tr>
<tr>
<td>Outsourcing by V</td>
<td>B</td>
<td>0.5424</td>
<td>0.007</td>
<td>0</td>
<td>0.1356</td>
</tr>
<tr>
<td>Outsourcing by V</td>
<td>C</td>
<td>0.5928</td>
<td>0.015</td>
<td>0</td>
<td>0.1482</td>
</tr>
<tr>
<td>Outsourcing by W</td>
<td>A</td>
<td>0.56</td>
<td>0.01</td>
<td>0</td>
<td>0.14</td>
</tr>
<tr>
<td>Outsourcing by W</td>
<td>B</td>
<td>0.524</td>
<td>0.01</td>
<td>0</td>
<td>0.131</td>
</tr>
<tr>
<td>Outsourcing by W</td>
<td>C</td>
<td>0.5464</td>
<td>0.015</td>
<td>0</td>
<td>0.1366</td>
</tr>
</tbody>
</table>
Table 8. Outsourcing data.

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Supplier Type</th>
<th>Minimum Limit (Units)</th>
<th>Maximum Limit (Units)</th>
<th>Outsourcing Cost ($)</th>
<th>Defective Rate (%)</th>
<th>Scrap (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>U</td>
<td>100</td>
<td>1000</td>
<td>0.666</td>
<td>1.35</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>100</td>
<td>1500</td>
<td>0.666</td>
<td>1.45</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>150</td>
<td>2000</td>
<td>0.666</td>
<td>1.25</td>
<td>1.2</td>
</tr>
<tr>
<td>2</td>
<td>U</td>
<td>50</td>
<td>1000</td>
<td>0.6</td>
<td>1.45</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>50</td>
<td>1200</td>
<td>0.6</td>
<td>1.55</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>100</td>
<td>1200</td>
<td>0.6</td>
<td>1.45</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>U</td>
<td>50</td>
<td>800</td>
<td>0.833</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>50</td>
<td>500</td>
<td>0.833</td>
<td>1.55</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>100</td>
<td>1000</td>
<td>0.833</td>
<td>1.3</td>
<td>1.2</td>
</tr>
</tbody>
</table>

5. Numerical Results

The automobile part industry became more sophisticated due to advance manufacturing processes and automation. The consideration of solar renewable energy as a source of energy for production of automobile parts is necessary to provide a sustainable and cleaner manufacturing for resilient supply chain management. The system of equations generated by formulation of the proposed multiobjective model is linear. There are different methodologies available in literature to solve a multiobjective problem along with a subjective approach depending upon the will of the decision makers. Lexicographic programming includes the priority level of each goal, where the number of unwanted deviations is minimized. Chebyshev programming helps the decision makers to achieve a balance between the achievement of the set of goals by considering maximum deviation. Weighted goal programming contains a feature to assign each goal on the basis of importance. Weighted goal programming is selected to formulate the proposed model to allow decision makers for getting best result of particular goal on the basis of requirement. The optimal results of three goals in the form of production cost, carbon emission and cost of energy were calculated individually a $11333, 1585.67 kg and $194.51 respectively by using linear programming (LP) with the help of a MATLAB-16a tool, (United state) as given in Table 9. These goals are further considered as target values for the WGP model, where weights are also used for the priority of the objectives. The positive deviational variables of three objectives are expected to minimized around these target goals. Minimum optimal deviation for total cost of production (goal A) and carbon emission (goal B) are 104.56 and 65.16, respectively, but goal C in terms of cost of electricity is less deviated from its respective target values i.e., 8.85. The optimized solution of decision variables in terms of production quantity, crashing quantity and outsourcing quantity are calculated by application of linear programming and WGP as given in Table 10. These results will be beneficial for managers to allocate production at in-house, crashing and outsourcing activities. The production and crashing quantity manufactured at in-house were the same with little variation from their initial values, but the outsourced quantities have changed more in the case of WGP. These results also provide a decision for suppliers for the production of outsourcing quantity required by the manufacturer for a smooth supply chain. Since solar renewable energy is providing a proportion of electricity required by the manufacturing processes of the automobile part industry, the carbon footprint and cost of energy are therefore expected to show a positive impact on the environment of the manufacturing system. Possible optimal allocation policy is delivered by this model under the restriction of crashing and outsourcing quantity to meet the targeted demand. The large set of parameters and corresponding data provide a pragmatic application of the proposed model in the automobile part industry, where managers and practitioners can easily understand the concept. The optimal results and solutions are the evidence of successful pragmatic application of photovoltaic technology in the automobile part industry. Indeed, the validation of the model with the help of a numerical example compel the managers to adopt the photovoltaic technology for the production of a new product in the form of a sustainable product. Overall, these results show successful reduction of a
carbon footprint in the automobile part manufacturing system and can be highly incorporated in a decision-making tool for the evaluation of sustainable environment technologies in supply chains.

Table 9. Optimal results of the mathematical model.

<table>
<thead>
<tr>
<th>Objective Function</th>
<th>Target Value (Goal)</th>
<th>Deviational Variable ($d^+$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total cost of production ($)</td>
<td>Goal A 11333</td>
<td>$d_1^+$ 104.56</td>
</tr>
<tr>
<td>Carbon emission (kg)</td>
<td>Goal B 1585.67</td>
<td>$d_2^+$ 65.16</td>
</tr>
<tr>
<td>Total energy cost ($)</td>
<td>Goal C 194.51</td>
<td>$d_3^+$ 8.85</td>
</tr>
</tbody>
</table>

Table 10. Optimal solution of the mathematical model.

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Item Type</th>
<th>Production Status</th>
<th>Decision Variable</th>
<th>LP Goal A</th>
<th>LP Goal B</th>
<th>LP Goal C</th>
<th>WGP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>Manufacturing</td>
<td>MQ_{11}</td>
<td>570</td>
<td>557</td>
<td>539</td>
<td>555</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>Manufacturing</td>
<td>MQ_{22}</td>
<td>290</td>
<td>249</td>
<td>247</td>
<td>274</td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>Manufacturing</td>
<td>MQ_{32}</td>
<td>345</td>
<td>336</td>
<td>342</td>
<td>345</td>
</tr>
<tr>
<td>4</td>
<td>A</td>
<td>Crashing</td>
<td>CQ_{11}</td>
<td>230</td>
<td>243</td>
<td>261</td>
<td>267</td>
</tr>
<tr>
<td>5</td>
<td>B</td>
<td>Crashing</td>
<td>CQ_{22}</td>
<td>110</td>
<td>150.8</td>
<td>153</td>
<td>158</td>
</tr>
<tr>
<td>6</td>
<td>C</td>
<td>Crashing</td>
<td>CQ_{32}</td>
<td>55</td>
<td>65</td>
<td>59</td>
<td>63</td>
</tr>
<tr>
<td>7</td>
<td>A</td>
<td>Outsourcing</td>
<td>OQ_{111}</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>252</td>
</tr>
<tr>
<td>8</td>
<td>B</td>
<td>Outsourcing</td>
<td>OQ_{211}</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>304</td>
</tr>
<tr>
<td>9</td>
<td>C</td>
<td>Outsourcing</td>
<td>OQ_{311}</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>265</td>
</tr>
<tr>
<td>10</td>
<td>A</td>
<td>Outsourcing</td>
<td>OQ_{122}</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>131</td>
</tr>
<tr>
<td>11</td>
<td>B</td>
<td>Outsourcing</td>
<td>OQ_{222}</td>
<td>250</td>
<td>50</td>
<td>50</td>
<td>123</td>
</tr>
<tr>
<td>12</td>
<td>C</td>
<td>Outsourcing</td>
<td>OQ_{322}</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>177</td>
</tr>
<tr>
<td>13</td>
<td>A</td>
<td>Outsourcing</td>
<td>OQ_{132}</td>
<td>100</td>
<td>300</td>
<td>300</td>
<td>167</td>
</tr>
<tr>
<td>14</td>
<td>B</td>
<td>Outsourcing</td>
<td>OQ_{232}</td>
<td>50</td>
<td>250</td>
<td>250</td>
<td>123</td>
</tr>
<tr>
<td>15</td>
<td>C</td>
<td>Outsourcing</td>
<td>OQ_{332}</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>118</td>
</tr>
</tbody>
</table>

6. Sensitivity Analysis

The total cost of production, carbon emission and cost of energy as objectives of the proposed model are influenced by utilization of solar energy. The initial investments of the solar system are huge; however, it is estimated that the costs of running a PV system are comparatively less for a whole life cycle. In addition, in some developing countries, government and environmental agencies are contributing to subsidizing the percentage of initial investments of the solar system due to its sustainable nature to avoid the global warming issue worldwide. Recent research has assured to reduce the maximum limitation of capacity and efficiency of solar systems. Solar energy systems are now replacing non-renewable sources of energies at residential, commercial and industrial levels. For that instance, additional tests are necessary to cover different scenarios for the usage of solar systems. Sensitivity analysis of the proposed model undertaking 10 cases to see how much the usage of solar energy instead of other sources of electricity affects the goal values of total cost of production, carbon emission and cost of energy. The first four cases are related to the sensitivity of energy consumption in the production system. The data regarding energy consumption of energy from the solar system and electricity with variations are illustrated completely in the form of four cases as given in Table 11.
Table 11. Data showing different cases of energy utilizations in the automobile part industry.

<table>
<thead>
<tr>
<th>Production Status</th>
<th>Item Type</th>
<th>Case 1 (Solar $h = 0%$)</th>
<th>Case 2 (Solar $h = 10%$)</th>
<th>Case 3 (This Paper) (Solar $h = 20%$)</th>
<th>Case 4 (Solar $h = 30%$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-house</td>
<td>A</td>
<td>0.318</td>
<td>0.0318</td>
<td>0.0636</td>
<td>0.0954</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0.293</td>
<td>0.0293</td>
<td>0.0586</td>
<td>0.0879</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0.455</td>
<td>0.0455</td>
<td>0.091</td>
<td>0.1365</td>
</tr>
<tr>
<td>Rework</td>
<td>A</td>
<td>0.675</td>
<td>0.0675</td>
<td>0.135</td>
<td>0.2025</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0.702</td>
<td>0.0702</td>
<td>0.1404</td>
<td>0.2106</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0.757</td>
<td>0.0757</td>
<td>0.1514</td>
<td>0.2271</td>
</tr>
<tr>
<td>Outsourced to supplier U</td>
<td>A</td>
<td>0.654</td>
<td>0.0654</td>
<td>0.5886</td>
<td>0.1308 0.5232</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0.637</td>
<td>0.0637</td>
<td>0.5733</td>
<td>0.1274</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0.72</td>
<td>0.072</td>
<td>0.648</td>
<td>0.144</td>
</tr>
<tr>
<td>Outsourced to supplier V</td>
<td>A</td>
<td>0.723</td>
<td>0.0723</td>
<td>0.6507</td>
<td>0.1446 0.5784</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0.678</td>
<td>0.0678</td>
<td>0.6102</td>
<td>0.1356</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0.741</td>
<td>0.0741</td>
<td>0.6669</td>
<td>0.1482</td>
</tr>
<tr>
<td>Outsourced to supplier W</td>
<td>A</td>
<td>0.7</td>
<td>0.07</td>
<td>0.63</td>
<td>0.14 0.56 0.21 0.49</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0.655</td>
<td>0.0655</td>
<td>0.5895</td>
<td>0.131</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0.683</td>
<td>0.0683</td>
<td>0.6147</td>
<td>0.1366</td>
</tr>
</tbody>
</table>
In each case, the percentage of solar energy consumption is different in the form of $h\%$ to vary the requirement of electricity. Case 1 illustrates the scenario that is taken by the research work done by Wang et al. [49], where the only main source of energy is electricity and no energy is used from solar PV for manufacturing, while Case 3 shows the initial values as considered in this proposed model having $h = 20\%$. Cases 2 and 4 represent that solar energy fulfills $h = 10\%$ and $h = 30\%$ demand of electricity in the manufacturing system, respectively. In this way, the consumption of electricity also reduces in terms of $1-h$ in each case. By using linear programming, the results are found and given in Table 12, which shows an intense change in carbon emission (goal $B$) with reference to case 3 ($h = 20\%$). By comparing Case 1 against Case 3 (this paper), it is clear that there is very less negative effect observed in total cost of production i.e., $-0.1\%$ but a significant change of $-16.7\%$ and $+10.6\%$ occur in cost of energy and carbon emissions, when there is no solar energy utilization in the system. The result is very meaningful to understand the impact of positive solar energy utilization on the environment but this increases the cost of production, which can be a trade-off. On the other hand, when solar energy utilization is escalated by 30% as in Case 4, energy cost increases and ultimately affects the total cost of production by almost 0.04% rise. From these results, it is concluded that the utilization of renewable energy from the solar system in the production system is very essential to reducing the carbon footprint of the automobile part industry, but, on the other hand, it slightly increases the total cost of production. The cost of the production increases because of initial investments, which is incorporated in calculating the global weighted average LCOE of utility scale solar system i.e., 0.195 $/kWh. It is estimated that the global average LCOE of utility scale solar PV has fallen by half in four years from 2010–2014. The most competitive utility scale system is generating electricity for just 0.08 $/kWh without financial support and even up to 0.06 $/kWh if low-cost finance is provided [54]. It is also estimated that the solar system will reach grid parity from year 2031 to 2042, when solar electricity costs will equal those of conventional electricity. The grid parity can be achieved faster under favourable conditions depending upon the government policies (to subsidies, low interest rates against loans for PV, maximize carbon tax etc.), region (high solar resources), and less discount rate [51].

A trade-off policy can be developed for sustainably aware manufacturers and customers with less economic loss and high environmental benefits to select sustainable energy and sustainable products for cleaner production. These results will ensure that decision makers develop policies for adopting the solar renewable energy for the betterment of future generations to avoid global warming.

### Table 12. Percent change observed in the objectives of the model with variations of solar energy utilization.

<table>
<thead>
<tr>
<th>Case</th>
<th>Goal</th>
<th>Result</th>
<th>Change %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Total cost of production ($)</td>
<td>11324</td>
<td>$-0.1$</td>
</tr>
<tr>
<td></td>
<td>Carbon emissions (kg)</td>
<td>1753.60</td>
<td>10.6</td>
</tr>
<tr>
<td></td>
<td>Total energy cost ($)</td>
<td>162.09</td>
<td>$-16.7$</td>
</tr>
<tr>
<td>2</td>
<td>Total cost of production ($)</td>
<td>11329</td>
<td>$-0.04$</td>
</tr>
<tr>
<td></td>
<td>Carbon emissions (kg)</td>
<td>1671.9</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td>Total energy cost ($)</td>
<td>178.3</td>
<td>$-8.33$</td>
</tr>
<tr>
<td>3 (This)</td>
<td>Total cost of production ($)</td>
<td>11333</td>
<td>Initial</td>
</tr>
<tr>
<td>(paper)</td>
<td>Carbon emissions (kg)</td>
<td>1585.67</td>
<td>values</td>
</tr>
<tr>
<td></td>
<td>Total energy cost ($)</td>
<td>194.51</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Total cost of production ($)</td>
<td>11338</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>Carbon emissions (kg)</td>
<td>1508.6</td>
<td>$-5.1$</td>
</tr>
<tr>
<td></td>
<td>Total energy cost ($)</td>
<td>210.72</td>
<td>8.33</td>
</tr>
</tbody>
</table>

Further tests are also necessary to check the sensitivity of the proposed model on the basis of costs related to the energy, carbon emission and other basic costs of production. Cost of carbon emission and LCOE for solar system is changing with respect to the region and government policies. Other factors like inflation, degradation rate, discount rate and efficiency of the system may also be influencing the
total cost of production and carbon emissions over the life cycle. To deal with these scenarios, Cases 5 to 10 are recommended for analysis for the sensitivity of the model, which are given in Table 13.

### Table 13. Sensitivity analysis of the key parameters of the production model.

<table>
<thead>
<tr>
<th>Case</th>
<th>Parameters</th>
<th>Initial Value</th>
<th>% Change (in Value%)</th>
<th>% Effect on Total Cost, TC ($)</th>
<th>% Effect on Energy Cost, TEC ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>$\gamma_4$ ($/kWh$)</td>
<td>0.195</td>
<td>−50</td>
<td>−0.10</td>
<td>−14.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>−25</td>
<td>−0.04</td>
<td>−8.96</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+25</td>
<td>+0.05</td>
<td>+7.29</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+50</td>
<td>+0.10</td>
<td>+15.42</td>
</tr>
<tr>
<td>6</td>
<td>$\gamma_1$ ($/kWh$)</td>
<td>0.10</td>
<td>−50</td>
<td>−0.20</td>
<td>−33.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>−25</td>
<td>−0.10</td>
<td>−16.67</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+25</td>
<td>+0.11</td>
<td>+16.67</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+50</td>
<td>+0.20</td>
<td>+33.33</td>
</tr>
<tr>
<td>7</td>
<td>$\gamma_5$ ($/kg$)</td>
<td>0.025</td>
<td>−50</td>
<td>−0.18</td>
<td>No effect</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>−25</td>
<td>−0.09</td>
<td></td>
</tr>
<tr>
<td></td>
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<td>+25</td>
<td>+0.09</td>
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</tr>
<tr>
<td></td>
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<td></td>
<td>+50</td>
<td>+0.18</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>$MC_{jt}$ ($/unit$)</td>
<td>0.26</td>
<td>−50</td>
<td>−1.45</td>
<td>No effect</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>−25</td>
<td>−0.72</td>
<td></td>
</tr>
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<td></td>
<td></td>
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<td>+25</td>
<td>+0.72</td>
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<td></td>
<td>+50</td>
<td>+1.39</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>$CC_{jt}$ ($/unit$)</td>
<td>0.35</td>
<td>−50</td>
<td>−0.78</td>
<td>No effect</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>−25</td>
<td>−0.34</td>
<td></td>
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<td></td>
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<td>+25</td>
<td>+0.34</td>
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<td></td>
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<td></td>
<td>+50</td>
<td>+0.68</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>$HC_{jt}$ ($/unit$)</td>
<td>0.17</td>
<td>−50</td>
<td>−1.34</td>
<td>No effect</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>−25</td>
<td>−0.67</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<td>+0.67</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+50</td>
<td>+1.39</td>
<td></td>
</tr>
</tbody>
</table>

1. In Case 5, by changing the LCOE of the solar energy from −50% to +50%, the results exhibit an inverse relation, showing a slight change from +0.1% and −0.1% in the total cost (TC). However, a huge change of +14% and −14% occurs in the total energy cost (TEC). The original value is at equilibrium, showing symmetric positive and negative effects on TC and TEC.

2. In Case 6, a similar inverse relation is found for the electricity cost, but the difference is that it has a little more impact of ±0.20% on TC and a huge impact of ±33% on TEC as compared to Case 5.

3. Carbon tax in the form of carbon emissions cost affects TC by ±0.18% and has no effect on TEC as shown in Case 7.

4. In Cases 8 and 9, the manufacturing cost and crashing cost are having small effects from −1.45% to +1.39% and −0.78% to +0.68%, respectively, on TC by changing these costs from −50% to +50%.

5. The holding costs are showing a small impact around ±1.40% on TC and is independent of TEC as given in Case 10.

### 7. Conclusions

Global warming due to increasing carbon emissions as a result of the applications of non-renewable energy resources is a serious issue for current and future generations. This is the reason that researchers and experts are searching for a sustainable solution. This study proposed a multiobjective model to simultaneously minimize total production cost, carbon emissions, and cost of energy for manufacturing processes in order to develop a production policy for manufacturers and suppliers in a supply chain. It was observed that the addition of renewable energy as a cleaner environmental technology produced a positive impact on the environment by reducing carbon emission in a manufacturing system. On the other hand, the total cost of production had slightly increased due to initial investments of renewable energy from the solar system, although running costs are more
feasible. LCOE for solar PV overcome the impact of the initial investment. The policies of government play a vital role for greater adoption of solar systems by providing incentives and policies to achieve long-term objectives for sustainable development. Customers are also required to prefer sustainable products made up of clean energy technology for supporting the government to meet energy targets. In addition, the application of MQL at the process level of machining is also vital for sustainable machining. Optimal production cost, carbon emission, and cost of energy using the WGP technique ensured that the proposed goal-oriented model is significant for suppliers and manufacturers to achieve sustainable production in terms of MQL and renewable energy, which is a step towards sustainable supply chain management. Economically, there is a little difference between the cost of PV-based energy and other renewable energy. The costs of energy generated from renewable energy are going down each year and are cost-effective for long-term manufacturing systems. Research is also required in order to develop a tool for the evaluation of different energy technologies on the basis of LCOE. Warehousing activities in the inventory and storage system are also required to be more efficient on the basis of energy consumption to minimize the carbon emissions. Research work is further required to minimize the resources (material and energy) for the installation and setup activities of PV system. Other analytical methods should be tested to analyze the model for better results. Production costs can be fuzzy, thus more solutions in terms of cost and carbon footprint can be obtained to increase the generality of the proposed model. Renewable energies generated from wind and water-based technologies are also important for analysis and could be incorporated for gap analysis based on optimal results. To attain a competitive advantage, manufacturing firms must develop sustainable systems by attaining low-carbon manufacturing. Overall, this research will create awareness among manufacturers to understand the importance of sustainability among supply chain players in terms of renewable energy, carbon footprint, and MQL to fulfill the needs of today’s customers for sustainable products.

Author Contributions: B.S. conceptualized and supervised the proposed research work, whereas M.O. has collected the data, analyzed the methodology, and wrote the original draft and S.B.C. helped in review writing and editing with validation of research work.

Conflicts of Interest: The authors declare no conflict of interest

Appendix A

The list of notations to represent the production quantities of manufacturer and suppliers are represented as follows.

Indices

\( i \) supplier index, \( i = 1, 2, \ldots, I \)

\( j \) item index, \( j = 1, 2, \ldots, J \)

\( t \) cycle time index, \( t = 1, 2, \ldots, T \)

decision variables

\( CQ_{jt} \) units of \( j \)th item crashed in \( t \)th time cycle (units)

\( MQ_{jt} \) quantity of \( j \)th item manufactured in \( t \)th time cycle (units)

\( OQ_{ijt} \) number of \( j \)th item outsourced to \( i \)th supplier in \( t \)th time cycle (units)

Parameters

\( AS_{ijt} \) minimum available \( j \)th item from \( i \)th supplier in \( t \)th time cycle (units)

\( BS_{ijt} \) maximum available \( j \)th item from \( i \)th supplier in \( t \)th time cycle (units)

\( CC_{jt} \) cost of crashing \( j \)th item in time cycle \( t \)th ($/unit)

\( CE \) carbon emission produced from production system (kg)

\( D_{jt} \) demand for \( j \)th item in \( t \)th time cycle (units)
DO_{ij} \quad \text{diesel consumed to manufacture } j\text{th item from } i\text{th supplier (L/unit)}

DP_{ij} \quad \text{consumption of diesel to manufacture } j\text{th item (L/unit)}

DR_{ij} \quad \text{usage of diesel for reworking } j\text{th item (L/unit)}

EO_{ij} \quad \text{required electricity to manufacture } j\text{th item from } i\text{th supplier (kWh/unit)}

EP_{ij} \quad \text{usage of electricity to manufacture } j\text{th item (kWh/unit)}

ER_{ij} \quad \text{electricity consumed to rework } j\text{th item (kWh/unit)}

FC_{jt} \quad \text{fixed cost for production of } j\text{th item in } t\text{th time cycle ($)}

GO_{ij} \quad \text{gasoline consumed to manufacture } j\text{th item from } i\text{th supplier (m}^3\text{/unit)}

GP_{ij} \quad \text{gasoline for manufacturing of } j\text{th item (m}^3\text{/unit)}

GR_{ij} \quad \text{required gasoline to rework } j\text{th item (m}^3\text{/unit)}

HC_{jt} \quad \text{holding cost for } j\text{th item in } t\text{th time cycle ($/unit)}

mC_{jt} \quad \text{cost of maintenance for } j\text{th item in } t\text{th time cycle ($/unit)}

MC_{jt} \quad \text{manufacturing cost of } j\text{th item in } t\text{th time cycle ($/unit)}

ML_{jt} \quad \text{minimum number of } j\text{th items in } t\text{th time cycle (units)}

MQL_{jt} \quad \text{cost of MQL for } j\text{th item in } t\text{th time cycle ($/unit)}

MU_{jt} \quad \text{maximum number of } j\text{th items in } t\text{th time cycle (units)}

OC_{jtt} \quad \text{outsourcing cost for } j\text{th item in } t\text{th time cycle to } i\text{th supplier ($/unit)}

S_j \quad \text{per unit scrap cost ($/unit)}

SO_{ij} \quad \text{solar energy consumed to manufacture } j\text{th item from } i\text{th supplier (kWh/unit)}

SP_{ij} \quad \text{solar energy used to manufacture } j\text{th item (kWh/unit)}

SR_{ij} \quad \text{utilization of solar energy for reworking } j\text{th item (kWh/unit)}

TC \quad \text{total cost of production ($/unit)}

TEC \quad \text{total cost of energy utilized ($/unit)}

VC_{jtt} \quad \text{cost of reworking for } i\text{th supplier and } j\text{th item in } t\text{th time cycle ($/unit)}

WC_{jt} \quad \text{warehousing cost ($/unit)}

a_1 \quad \text{electricity coefficient equivalent to carbon emission}

a_2 \quad \text{diesel fuel coefficient equivalent to carbon emission}

a_3 \quad \text{gasoline coefficient equivalent to carbon emission}

a_4 \quad \text{solar energy coefficient equivalent to carbon emission}

a_{ijt} \quad \text{proportion of scrap produced in defective } j\text{th item, manufactured by } i\text{th supplier in } t\text{th time cycle (%)}

\beta_{ijt} \quad \text{defective rate for } j\text{th item, manufactured by } i\text{th supplier in } t\text{th time cycle, percentage (%)}

\gamma_1 \quad \text{unit cost of electricity ($/kWh)}

\gamma_2 \quad \text{per unit cost of diesel oil ($/kWh)}

\gamma_3 \quad \text{cost of gasoline per unit ($/m}^3\text{)}

\gamma_4 \quad \text{unit cost of solar energy ($/kWh)}

\gamma_5 \quad \text{carbon emission cost ($/kg)}

NT_{jt} \quad \text{additional cost limit } j\text{th item in } t\text{th time cycle (units)}

d_{1+} \quad \text{achieving production cost over above the target goal}

d_{1-} \quad \text{achieving production cost below the target goal}

d_{2+} \quad \text{carbon emission achieved above the target}

d_{2-} \quad \text{to achieve the carbon emission below the target value}

d_{3+} \quad \text{energy cost achieved over above the required target}

d_{3-} \quad \text{cost of energy under the target goal}

deviational variables
References


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