noted in Table 4 that the values of objective (1) and (3) are sensitive to the assigned values of ε_1 and ε_2 which vary between the minimum value and the maximum value for objectives (1) and (3), respectively. As an example, Pareto solution 1 obtained by an assignment of ε_1 = 9,639,090, and $\varepsilon_2 = 9.2\times10^9$ accordingly, the minimum total cost for establishing the manufacturing system is 9,639,090 GBP, the minimum total amount of energy consumed by the manufacturing system is 1,250,000 kWh and the minimum total amount of CO_2 emissions released from the manufacturing system is 9.2×10^9 kg. As shown in Table 5, each Pareto solution has a potential group of number of machines, number of air conditioning units and number of bulbs that are involved in process task *i* in the manufacturing system. For instance, in pareto solution 1, the number of machines involved in process task *i* in a manufacturing system $n_{f_i}^{mach}$ where $i \in \{1, 2, 3, 4, 5, 6, 7, 8\}$ are (4, 40, 3, 5, 13, 13, 60, 4), number of air-conditioning units involved in process task *i* $n_{f_i}^{cond}$ are (2, 20, 2, 3, 7, 7, 30, 2) and number of bulbs $n_{f_i}^{bulb}$ are (60, 600, 45, 75, 195, 195, 900, 60). A pairwise comparison among the three conflicting objectives is illustrated in Figure 2a and 2b.

Table 4. Pareto solutions obtained by using the integrated DEMATEL-ε-constraint approach

No of solutions	ε-values		Objective function solutions		
	ε_1	ε_2	Min Z_1	Min Z_2	Min Z_3
1	9,639,090	9.2×10^9	9,639,090	1,250,000	9.2×10^9
2	10,909,100	9.75×10^9	10,909,090	1,420,000	9.7×10^9
3	12,300,000	10.3×10^9	12,288,819	1,580,000	10.3×10^9
4	13,668,548	10.9×10^9	13,668,548	1,710,000	10.9×10^9

Table 5. Number of machines, air conditioning units and number of bulbs

From machines G up to machines Z that involved in process *i*, where $i \in \{1, 2, 3, 4, 5, 6, 7, 8\}$																								
Solution number	Number of machines involved in process *i* $n_{f_i}^{mach}$								Number of air conditioning units involved in process *i* $n_{f_i}^{cond}$								Number of illumination bulbs involved in process *i* $n_{f_i}^{bulb}$							
	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
1	4	40	3	5	13	13	60	4	2	20	2	3	7	7	30	2	60	600	45	75	195	195	900	60
2	5	40	4	5	14	14	60	4	3	20	2	3	7	7	30	2	75	600	60	75	210	210	900	60
3	5	45	5	6	16	16	60	5	3	23	3	3	8	8	33	3	75	675	75	90	240	240	900	75
4	5	50	6	7	16	16	60	5	3	23	3	3	8	8	33	3	75	675	76	90	270	270	900	75

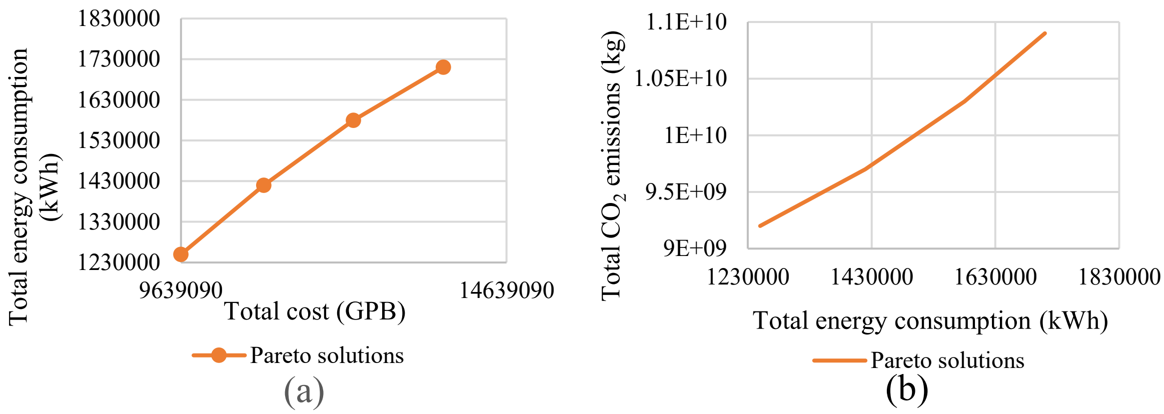

Figure 2. Comparison between solutions obtained

In order to design a SMS based on the obtained Pareto solutions using integrated DEMATEL-ε-constraint approach, one of these solutions needs to be selected based on the preferences of decision makers. Based on their experts to design the SMS, Pareto solution 1 is determined as the best solution. Furthermore, this Pareto solution shows the optimum input quantity of materials q^{r}_{fi}, the quantity of materials flow among the machines involved in process task i q^{r}_{fi+1} and then shipped as a final product q^{mp}_{fw}. As shown in Table 6, based on Pareto solution 1 the optimal decisions in the quantity of materials flows through the machines involved in process task 1, 2, 3, 4, 5, 6, 7, 8 are 1000,000 kg, 980,000 kg, 978,040 kg, 976,084 kg, 937,040kg, 918,299 kg, 889,824 kg, 868,344 kg, 850,660 kg, respectively before being shipped to the warehouse as a final products as 7655940 sacks per month.

Table 6. The quantity of materials flows through the system

$q^{r}_{f_i}$ (kg), where $i \in \{1, 2, 3, 4, 5, 6, 7, 8\}$										q^{mp}_{fw} (unit)
Solution number	0	1	2	3	4	5	6	7	8	
1	1000000	980000	978040	976084	937040	918299	889824	868344	850660	7655940 sacks
2	1020000	1002000	996100	994084	955150	928300	904824	883344	865660	7790940 sacks
3	1045000	1027000	1009000	991100	973050	940200	919700	898400	883660	7952940 sacks
4	1066000	1048000	1033000	1015000	997040	955100	934824	919344	901660	8114940 sacks

Table 7 shows the number of machines, the number of air-conditioning units, the number of bulbs and quantity of materials that need to be involved in processes task *i* to achieve the SMS design based on Pareto solution 1.

Table.7. The best Pareto solution for a sustainable manufacturing system

The best solution for a sustainable manufacturing system design				
Number of process task i	Number of machines involved in process i $n_{f_i}^{mach}$	Number of air conditioning units involved in process i $n_{f_i}^{cond}$	Number of bulbs involved in process i $n_{f_i}^{bulb}$	Quantity of materials involved in process i $q_{f_i}^{r}$
0	-	-	-	1000000
1	4	2	60	980000
2	40	20	600	978040
3	3	2	45	976084
4	5	3	75	937040
5	13	7	195	918299
6	13	7	195	889824
7	60	30	900	868344
8	4	2	60	850660
Number of manufacturing products q_{fw}^{mp} Units				850660≈ 7,655,940 sack

Finally, Figure 3 shows the optimal sustainable manufacturing system design model based on the determined Pareto solution 1, which is obtained with ε_1= 9,639,090, and $\varepsilon_2 = 9.2\times10^9$ that yields a minimum total cost of 9,639,090 GBP with the minimum total amount of energy consumption of 1,250,000 kWh and the minimum total amount of CO_2 emissions of 9.2×10^9 kg.

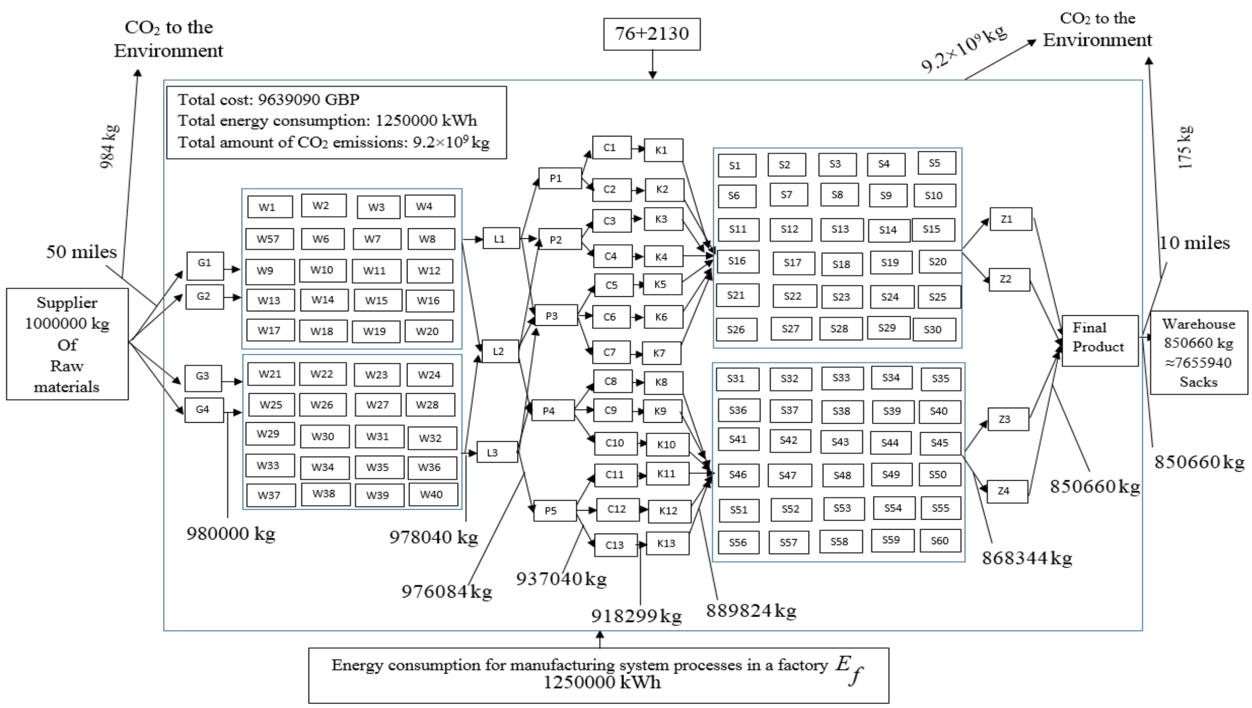

Figure 3. An optimal sustainable manufacturing system design model

4. Conclusion

When designing a manufacturing system, engineers used to focus on the key performance indicators in terms of system productivity and capacity; environmental considerations are often overlooked. This paper presents the development of a three-objective mathematical model for optimizing a sustainable manufacturing system design which addresses environmental sustainability relating to manufacturing activities. The developed multi-objective mathematical model can be used as a reference for manufacturing system designers in finding a trade-off solution in minimizing the total investment cost, minimizing the total energy consumption and minimizing the total CO_2 emissions released from the manufacturing system. The computational results were validated based on data collected from a real industrial case. The initial results indicate that this is a useful and effective aid for optimizing traditional manufacturing system design in order to achieve sustainability under economic and ecological constraints.

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