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Supply Chain Management in a Manufacturing Industry

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Abstract: *This research is focused on a supply chain management (SCM) of a manufacturing industry. In this present work, the SCM model consists of suppliers who provide raw materials to the manufacturing plants, warehouses/distribution centres and customer zones/retailers. Finished goods are shipped to various distribution centres using a particular mode of transportation, and finally to customers. A mixed integer, multi objective optimization model which simultaneously minimizes total cost through the supply chain, carbon dioxide emissions from trucks and manufacturing plants, and incidence rates during plant operations was formulated to create a sustainable supply chain. The model was solved by applying weights using the Analytic hierarchy process and using the branch and cut optimization algorithm of the Cplex solver, which combines the advantages of a pure Branch and Bound Scheme and the Gomory Cutting Planes. The model was tested with data from the case study. The outcomes from the optimization runs showed that environmental considerations can be taken without a huge effect on the Supply Chain costs. The objective cost function value minimizing total cost was ₦232, 615,300 while that of environmental and social objectives were 22.343 tonnes of CO2 and 5.68 respectively. The results obtained from this study indicated a successful supply chain management which minimized the total costs, CO2 emissions and incidence rates, thereby solving the conflicting problems created by the objective functions.*

Keywords: *Supply Chain Management, Manufacturing Industry, Supply Chain, Carbon Dioxide Emission, Analytic Hierarchy Process*

INTRODUCTION

Manufacturing industries worldwide are faced with a variety of problems. These problems or challenges, if not properly managed, may result in very high costs of making products available for customers, which subsequently affects the company's competitive advantage. Besides, it encounters an ever increasing and volatile demand rate from their product users. This has made the global market competition high, and to keep up competitive advantage, companies have explored innovative techniques to beat this rising competition through a proper integration of their supply chain management (SCM) concepts. A properly managed supply chain system can largely enhance both efficiency and product quality, and eventually enhance satisfaction of customers and profit making capabilities (Sotiris, 2000). So, it aims to bring together all those processes involved, to jointly cooperate with the firm as a means of productivity enhancement and deliver quality products to customers (Finch, 2006). A typical supply chain would involve procurement of raw materials, product manufacturing in manufacturing plants; shipment of these items to distribution centres and warehouses and further shipment to retailers or customer zones. Supply chain can be viewed as a network that is made up of raw materials suppliers, manufacturing plants, finished and unfinished product inventory, warehouses and distribution centres, and retail outlets or customers, materials and information that flow between the facilities. Consequently, to minimize cost and improve service levels, effective supply chain strategies must take into consideration the interactions in all levels along the SC.

Furthermore, a supply chain management is a set of approaches utilized to efficiently integrate suppliers, manufacturers, warehouses, and stores; so that merchandise is produced and distributed at the right quantities, to the right locations, and at the right time, in order to minimize system wide costs while satisfying service level requirements (Simchi-Levi *et al.,* 2003). So, SCM not only aims to minimize transportation cost or reduce inventories but, rather, takes on a systems approach to give better services to customers. However, a successful SCM in a typical manufacturing industry must be sustainable. Sustainability in SC has been a trending area lately and according to Ivanovski (2014) "the development that meets the needs of the present without compromising the ability of future generations to meet their own needs". It considers the environmental and social influences, together with the traditional economic (financial) metric of the SC, thus, giving a triple bottom line (TBL) approach. Sustainability in SCM entails adopting the triple bottom line approach. These three areas of sustainability that give rise to the triple bottom approach are sometimes called 3 Ps: profit, planet, and people (Halld´orsson *et al.,* 2009). Thus, it became necessary to evaluate supply chain management in a manufacturing industry. In this research work, the following issues will be tackle; high costs of purchasing and production, increased cost of shipment/ transportation (finished product and raw material), pollution of the environment due to manufacturing activities and high cost of energy consumption.

RESEARCH METHODOLOGY

2.1 Description of the Supply Chain Process

The supply chain process (SCP) can be viewed as comprising of organizational networks that are involved through upstream and downstream linkages and in the different processes and activities that produce value in the form of products and services in the hands of the ultimate consumer (Christopher, 2012). The system is concerned with management of suppliers, procurement and materials management, manufacturing, inventory management and facilities planning, and also customer service and transportation costs. In a typical supply chain management (SCM), materials/products flow downstream from supplier, down to the customer, while information flows upstream in the reverse direction as shown in Fig. 1.

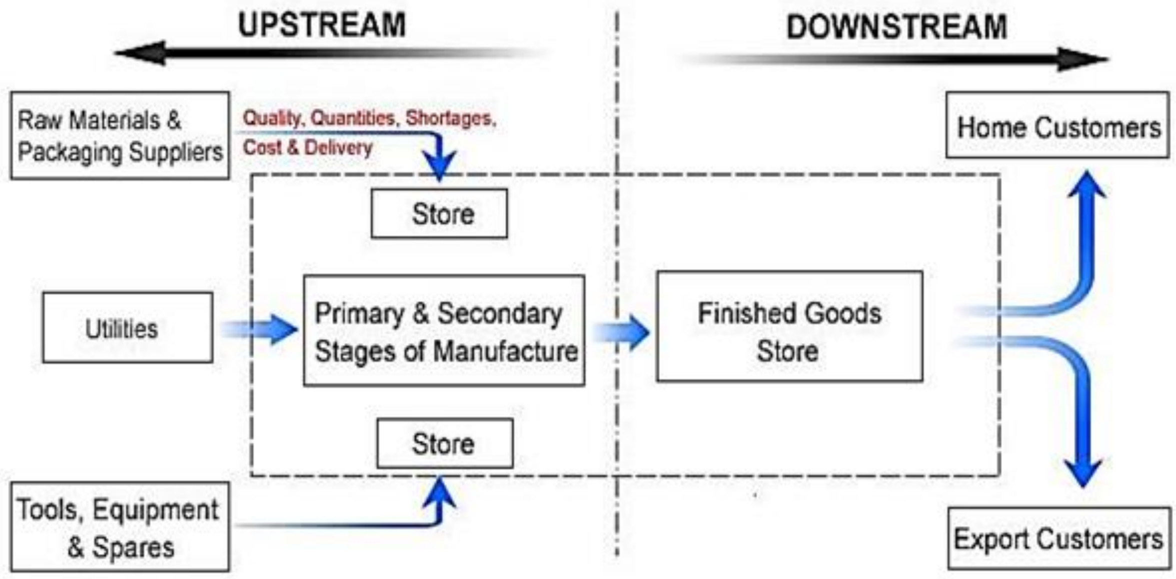

Fig. 1 Materials/information flow in SCM (Kittipong *et al.*, 2013)

In this research work, the SCM model consists of suppliers who provide raw materials to the manufacturing plants, warehouses/distribution centres and customer zones/retailers. Finished goods are shipped to various distribution centres using a particular mode of transportation, and finally to customers. Fig. 2 shows the network and interconnections of the components in the SCM process.

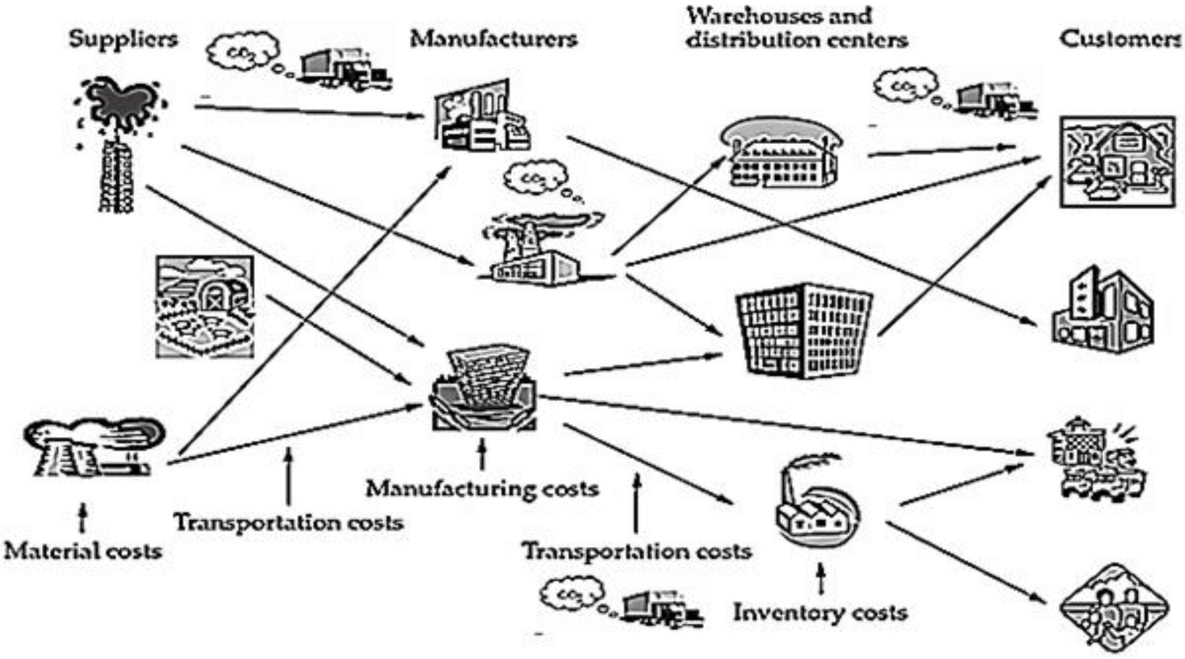

Fig. 2 Supply Chain Network in a Manufacturing Industry (Large and Thomsen, 2011)

The following assumptions were made:

i. There are different raw materials for all products.
ii. The suppliers can provide the required quantities that are required for production.
iii. Just-in-time approach is assumed; therefore raw materials inventory is neglected.

iv. The suppliers, manufacturing plants and distribution centres have constraints in their capacities.
v. The demands from customer zones are known.
vi. Cost of transportation is a function of the distances from suppliers to plants, plants to warehouses and quantity shipped as well.

The sustainability aspect of SCM ensures that the overall performance of the system is improved by considering all three dimensions together. This simply means that the environmental and social factors should be considered, plus the traditional economic dimension. Cetinkaya *et al.* (2011) employed a three-dimensional metrics system to describe the sustainability. That is, social, economic, and environmental dimensions, and each of the dimensions is broken down into three other sub dimensions (Fig. 3). They stated that an improvement in one of the aspects, without negatively affecting the other dimensions, will result in a positive and sustainable supply chain.

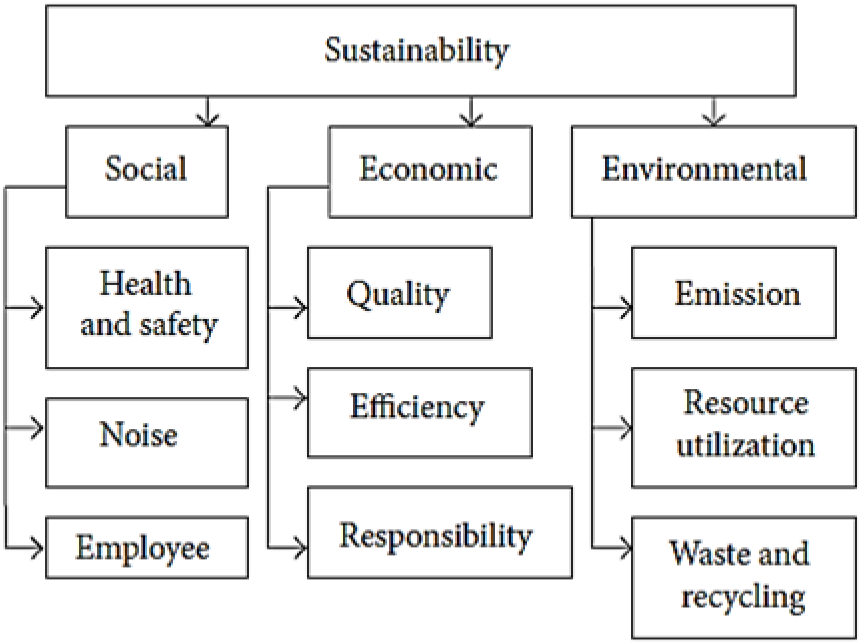

Fig. 3 Dimensions and Sub-Dimensions in a Sustainable Supply Chain (Cetinkaya *et al.*, 2011)

2.2 Description of Model

The supply chain problem is modelled with functions of different variables such as raw materials and production costs, inventory and transportation costs, environmental and social considerations also. The model is designed as a triple bottom, multi-objective optimization (MOO) problem to take care of some of the conflicting goals present in the system. Multi-Objective Optimization (MOO) or Pareto optimization involves the simultaneous optimization of problems with at least two objective functions. No single optimum solution exists in MOO rather we have a number of solutions that are optimal called Pareto fronts. Moreover, the model is designed as a mixed integer linear program (MILP), with three objective functions defined.

A. Economic Model

This contains the system wide costs including the fixed costs for opening plants and distribution centres, raw material purchasing and production costs, cost of inventory and transportation costs between the respective nodes.

B. Environmental Factor

It minimizes the greenhouse gas emission, in this case, carbon dioxide (CO_2), from the production plants and from trucks carrying raw material and finished goods. It also minimizes consumption of energy and industrial wastes generated and its environmental effects. This is to make sure the firm operates its supply chain within internationally accepted environmental standards.

C. Social Impact of the Supply Chain Operations

A sustainable process ensures at all times that the system thrives in all the challenges it faces. It is worth noting that measuring all the social factors in a single process of decision-making will be extremely difficult. Pishvaee *et al.* (2012) developed some standards to plan and implement corporate social responsibility in organizations, but a standard framework developed by the ISO termed the "International Guidance Standard on Social Responsibility-ISO 26000" (Montoya-Torres, 2015) is adopted. The classifications which are relevant to SCM are presented in Table 1. The safety factor (number of lost days caused by injuries at work) is considered by reducing the incidents/accident rates.

Table 1. ISO Measure of Social Impacts in Supply Chain Design Decisions (Pishvaee *et al.,* 2012)

Social impact	Measure	ISO 26000 Core Subject
Safety	Number of lost days caused by injuries at work	Labour Practices
Community development	Number of created job opportunities	Community involvement and development

2.3 Mathematical Models

The following sets and parameters are used for the formulation of the mathematical model.

Sets/indices:

P	Product type, p = 1, . . . , P (P = 3)
R	Raw material type, r = 1, … , R (R = 4)
F	Plant, f = 1, … , F (F = 3)
D	Distribution centres, d = 1, … , D (D = 4)
C	Customer zone, c = 1, … , C (C = 4)
S	Supplier, s = 1, … , S. (S = 4)
T	Time period, t = 1, …, T

Parameters

KF_{fpt}	Fixed costs of running plant *f* for product type *p* in time period *t*
KD_{dpt}	Fixed costs of running distribution centre (DC) *d* for product *p* in time period *t*
KR_{rsft}	Unit cost of raw material *r* supplied by supplier *s* to plant *f* in time period *t*
KP_{pft}	Unit cost of production for product *p* in plant *f* in time period *t*
TP_{rsft}	Unit transportation cost of raw material *r* from supplier *s* to plant *f* in time period *t*
KT_{pfdt}	Unit transportation cost of product *p* from plant *f* to DC*d* in time period *t*
TY_{pdct}	Unit transportation cost of product *p* from DC*d* to customer zone *c* in *t*
UK_{pdt}	Unit cost of inventory for product *p* at distribution centre *d* in time period *t*
DE_{pct}	Average demand for product *p* by customer zone *c* in time period *t*
$CO2_{sft}$	CO_2 emission from truck supplying raw materials to plant *f* in time period *t*
$CO22_{fdt}$	CO_2 emission from truck supplying products from plant *f* to DC *d* in time period *t*
$CO23_{dct}$	CO_2 emission from truck supplying products from DC *d* to customer zone *c* in *t*
L_{fpt}	Plant capacity for product *p* at plant *f* in time period *t*
EG_{pft}	Emissions from using diesel powered generators to produce product *p* in plant *f* in *t*
EP_{ft}	Emissions from other electrical equipment running in plant *f* in time *t*

WG_{pft}	Quantity of wastes generated for product p in plant f in time t
BS_{rst}	Supplier capacity for supplying raw material *r* in time period *t*
J_{pdt}	Capacity of distribution centre *d* for product *p* in time period *t*
INJ	Number of injuries and illnesses recorded
HRS	Employee hours worked

Decision variables

$X1_{rsft}$	Quantity of raw material *r* shipped by supplier *s* to plant *f* in time period *t*
$X2_{pft}$	Quantity of product *p* produced at plant *f* in time period *t*
$X3_{pfdt}$	Quantity of product *p* from plant *f* to distribution centre *c* in time period *t*
IN_{pdt}	Inventory level of product *p* at DC d in time period *t*
a_{fp}	$\begin{cases} 1 & if\ plant\ f\ is\ open \\ 0 & otherwise \end{cases}$
e_{sf}	$\begin{cases} 1 & if\ supplier\ s\ serves\ plant\ f \\ 0 & otherwise \end{cases}$
b_{dp}	$\begin{cases} 1 & if\ DC\ d\ is\ open \\ 0 & otherwise \end{cases}$
g_{dc}	$\begin{cases} 1 & if\ DC\ d\ serves\ customer\ c \\ 0 & otherwise \end{cases}$

The mathematical model is as follows:

Minimize;

$$Z_1 = \sum_f \sum_p \sum_t KF_{fpt}\, a_{fp} + \sum_r \sum_s \sum_f \sum_t TP_{sft}\, X1_{rsft} + \sum_r \sum_s \sum_f \sum_t KR_{rsft}\, X1_{rsft} + \sum_p \sum_f \sum_t KP_{pft}\, X2_{pft} + \sum_d \sum_p \sum_t KD_{dpt}\, b_{dp} + \sum_p \sum_f \sum_d \sum_t KT_{pfdt}\, X3_{pfdt} + \sum_p \sum_f \sum_d \sum_c \sum_t UK_{pdt}\, g_{dc}\, (X3_{pfdt} - DE_{pct} + \sum_p \sum_d \sum_t UK_{pdt}\, IN_{pdt} + \sum_p \sum_c \sum_d \sum_t TY_{pdct}\, DE_{pct} \quad (1)$$

Minimize;

$$Z_2 = \sum_r \sum_s \sum_f \sum_t CO2_{sft}\, X1_{rsft} + \sum_p \sum_f \sum_d \sum_t CO22_{fdt} X2_{pft} + \sum_p \sum_f \sum_d \sum_c \sum_t CO23_{dct} X3_{pfdt} + \sum_p \sum_f \sum_t (EG_{pft} + EP_{ft} + WG_{pft}) X2_{pft} \quad (2)$$

Minimize;

$$Z_3 = \sum_p \sum_f \sum_t R_{pft}\, a_{fp} \quad (3i)$$

$where;\ R_{pft}\ is\ the\ incidence\ rate\ for\ each\ product\ p\ in\ plant\ f.Given\ by$

$$R_{pf} = \frac{INJ*200{,}000}{HRS} \quad (3ii)$$

The 200,000 hours in the formula represents the equivalent of 100 employees working 40 hours per week, and 50 weeks per year.

subject to:

$\sum_f X2_{pft} \le L_{fpt}$ $\quad \forall p \in P, \forall t \in T$ (4)
$\sum_d X3_{pfdt} \ge DE_{pct}$ $\quad \forall p \in P, \forall f \in F, \forall t \in T$ (5)
$\sum_f X1_{rsft} \le BS_{rst}$ $\quad \forall r \in R, \forall s \in S, \forall t \in T$ (6)
$\sum_f X2_{pft} - \sum_d X3_{pfdt} = 0$ $\quad \forall p \in P, \forall t \in T$ (7)
$\sum_p X2_{pft} \le \sum_s X1_{rsft}$ $\quad \forall f \in F, \forall r \in R, \forall t \in T$ M (8)
$\sum_d X3_{pfdt} \le \sum_d J_{pdt}$ $\quad \forall p \in P, \forall f \in F, \forall t \in T$ (9)
$\sum_d X3_{pfdt} \ge \sum_d IN_{pdt}$ $\quad \forall p \in P, \forall f \in F, \forall t \in T$ (10)
$\sum_d b_{dp} = 1$ $\quad \forall p \in P$ (11)
$\sum_f a_{fp} = 1$ $\quad \forall p \in P$ (12)
$a_{fp} = \{0, 1\}$ $\quad \forall f \in F, \forall p \in P$ (13)
$b_{dp} = \{0, 1\}$ $\quad \forall d \in D, \forall p \in P$ (14)
$e_{sf} = \{0, 1\}$ $\quad \forall s \in S, \forall f \in F$ (15)
$g_{dc} = \{0, 1\}$ $\quad \forall d \in D, \forall c \in C$ (16)
$X2_{pft} \ge 0$ $\quad \forall p \in P, \forall f \in F, \forall t \in T$ (17)
$X1_{rsft} \ge 0$ $\quad \forall r \in R, \forall s \in S, \forall f \in F, \forall t \in T$ (18)
$X3_{pfdt} \ge 0$ $\quad \forall p \in P, \forall f \in F\ \forall d \in D, \forall t \in T$ (19)
$IN_{pdt} \ge 0$ $\quad \forall p \in P, \forall f \in F\ \forall d \in D, \forall t \in T$ (20)

Equations (1) to (3) are the objective functions, the first, minimizing the total costs in the supply chain, the second is the environmental objective that minimizes CO_2 emissions from delivery trucks/vehicles and use of electricity for production, and wastes generated. The third objective represents the social aspect of the supply chain, minimizing the incidence rates due to illnesses/injuries. Equations (4) through (20) represent the constraints.

Equation (4) ensures production is not beyond the plant capacity.

Equation (5) makes products available to meet demand from customer zone.

Equation (6) constrains suppliers to supply raw materials within their capacity.

Equation (7) ensures that quantity of products shipped to DCs equals what is available at the plant.

Equation (8) ensures production requirements for each product is met by raw materials.

Equation (9) ensures the amount of products shipped is within the DC capacities while Equation (10) makes sure products are available above inventory level.

Equations (11) and (12) ensures that each DC serves exactly one customer zone, and each plant produces one product type at every time period.

Equations (13) to Equation (16) are restrictions for binary variables, while Equations (17) to Equation (20) enforce the decision variables to be nonnegative.

2.4 Solution Methods

The solution to the multi-objective optimization problem formulated is implemented using the weighted sum method. The general form of the weighted sum model is presented (Chen and Andresen, 2014) as:

$$minimize\ \varphi = \sum_{i=1}^{K} w_i\, f_i(x)$$

$$\sum_{i=1}^{K} w_i = 1 \qquad with \quad w_i \geq 0 \quad \forall i \tag{21}$$

$where\ f_1, \dots, f_K$ are the objective functions, w_i are weights assigned

Applying this to our model, we have

$$minimize\ \varphi = w_1 Z_1 + w_2 Z_2 + w_3 Z_3 \tag{22}$$

$$\sum_{i=1}^{3} w_i = 1 \qquad with \quad w_i \geq 0 \quad \forall i$$

2.5 Weight Selection

Weights can be assigned by decision makers based on their judgment on the importance of one objective over the other. However, a more systematic approach called the Analytic Hierarchy Process (AHP) is preferred. The AHP provides us with a means of breaking down a problem into hierarchy ofsub-problems, which can be understood and evaluated easily. These evaluations are converted into numerical values and each alternative is then numerically ranked (Buhshan and Rai, 2004; Badea *et al*., 2014). We assume that the economic model is slightly more important than the environmental factor and moderately important than the social factor. Standing on the assumption above, the different weights for the objectives are derived by calculating the eigenvector of the evaluation matrix (Seker *et al*., 2013). The solution is implemented using the Cplex solver developed by GAMS. It is a solver that combines the high level modelling capabilities of GAMS with the power of Cplex optimizers. They are developed to solve large, difficult problems quickly and with minimal user intervention. Cplex uses a branch and cut algorithm which solves a series of LP sub problems. The Branch and cut method is a very successful algorithm for obtaining optimality for a variety of Integer Programming Problems. The algorithm combines the advantages of a pure Branch and Bound Scheme and the Gomory Cutting Planes Scheme. It works by searching the solution space for the best solution. The use of bounds for the function to be optimized combined with the value of the current best solution enables the algorithm search parts of the solution space only implicitly.

2.6 Data

The input data, output data and major simulations are presented in this section. To solve the model, data was collected from the case study and international sources online. Reasonable assumptions were also made based on the designed model. The fixed costs associated with opening the plants and distribution centres are presented in Table 2. This is estimated based on reasonable assumptions, taking into consideration, the unit production costs, capacity and technology available. Transportation costs between suppliers and plants, plants and distribution centres, and distribution centres to customer zones are given in Table 3. They are based on the distances between the respective nodes and also the weight of shipments. To estimate the effect of SC activities on the environment, GHG emission, in this case, CO_2 emission data is presented in Table 4. This is done by using weight-based truck emission factors for a freight truck (EPA, 2014) and an online calculator to get CO_2 emissions amounts based on the distances between nodes (km) and the weight or amount of shipments (kg or tons) (EDF, 2017).

Table 2. Production Costs, Fixed Costs for Plants and Distribution Centres

Fixed cost for plants ($x10^6$ Naira) and Distribution centres ($x10^3$ Naira)

Plant 1	10	Distribution Centre 1	1500
Plant 2	15	Distribution Centre 2	1200
Plant 3	10	Distribution Centre 3	1700
		Distribution Centre 4	1000

Unit production cost (Naira)

	Plant 1	Plant 2	Plant 3
Product 1	65, 000	-	-
Product 2	-	80, 000	-
Product 3	-	-	50, 000

Plant Capacity (units/period)

	Plant 1	Plant 2	Plant 3
Product 1	84, 000	-	-
Product 2	-	60, 000	-
Product 3	-	-	60, 000

Table 3. Cost of Transportation between Nodes (Naira/unit)

Cost of transportation in shipping raw materials

	Plant 1	Plant 2	Plant 3
Supplier 1	1, 200	1, 200	1, 000
Supplier 2	500	800	800
Supplier 3	1, 000	1, 200	1, 000
Supplier 4	1, 000	1, 200	1, 200

Cost of transportation in shipping products to DCs

	Distribution Centre 1	Distribution Centre 2	Distribution Centre 3	Distribution Centre 4
Plant 1	300	350	300	200
Plant 2	350	450	400	400
Plant 3	400	300	300	300

Transportation cost in shipping products to customer zones

	Customer Zone1	Customer Zone2	Customer Zone3	Customer Zone4
Distribution Centre 1	300	300	400	400
Distribution Centre 2	500	400	400	400
Distribution Centre 3	300	300	400	400
Distribution Centre 4	500	500	400	400

Table 4. *Carbon Dioxide Emissions from Trucks Shipping Raw Materials and Products (*Tonnes of Carbon Dioxide)

CO$_2$ Emissions from Trucks Shipping Raw Materials to Plants

	Plant 1	Plant 2	Plant 3
Supplier 1	3.649	3.464	3.464
Supplier 2	0.0830	0.0830	0.0830
Supplier 3	0.148	0.144	0.144
Supplier 4	0.0547	0.0556	0.0556

CO$_2$ emissions from trucks shipping products to DCs

	Distribution Centre 1	Distribution Centre 2	Distribution Centre 3	Distribution Centre4
Plant 1	0.0922	0.236	0.252	0.392
Plant 2	0.0976	0.250	0.267	0.415
Plant 3	0.104	0.278	0.296	0.461

CO$_2$ emissions from trucks shipping products to Customer zones

	Customer Zone1	Customer Zone2	Customer Zone3	Customer Zone4
Distribution Centre 1	0.0120	0.0130	0.0124	0.0230
Distribution Centre 2	0.0205	0.0220	0.0225	0.0230
Distribution Centre 3	0.0312	0.0350	0.0350	0.0360
Distribution Centre 4	0.0144	0.0132	0.0220	0.0340

RESULTS AND DISCUSSION

The weights computed to scale the objective functions as presented by Equation (22) is presented in Table 5.

Table 5. Weights for the Objective Functions using the AHP

Objective function	Sense of optimization (sign)	Weight
Economic (cost)	minimization (+)	w_1, 0.648
Environmental	minimization (+)	w_2, 0.230
Social (Incidence rate/Injuries)	minimization (+)	w_3, 0.122

Also, optimal values of quantity of products produced in different time periods and quantity of raw materials supplied to meet the Just-In-Time approach are shown in Table 6, while the optimal quantity of products shipped to distribution centres to meet demand from customer zones is given in Table 7. The optimal values of these decision variables optimized the model with the objective functions values given in Table 8.

Table 6. Optimal Solutions of Decision Variables in each Time Period

Optimal raw material (Raw) quantity supplied to plants in each time period, $X1_{rsft}$(Naira/Unit)

Supplier	1			2			3			4		
Plant	1	2	3	1	2	3	1	2	3	1	2	3
Raw1	1700	1800	1500	–	–	––	–	––	–	–		
Raw2	–	–	–	700	1100	1000	–	–	––	–	–	
Raw3	–	–	––	–	–	1200	1500	1200	–	–	–	
Raw4	–	–	––	–	–	-	–	–	−1200	1500	1400	
Period 2												
Raw1	1700	1800	1500	–	–	––	–	––	–	–		
Raw2	–	–	–	700	1100	1000	–	–	––	–	–	
Raw3	–	–	––	–	–	1200	1500	1200	–	–	–	
Raw4	–	–	––	–	––	–	–	1200	1500	1400		
Period 3												
Raw1	1500	1600	1500	–	–	–	–	–	––	–	–	
Raw2	–	–	–	750	1100	1000	–	–	––	–	–	
Raw3	–	–	––	–	–	1200	1600	1400	–	–	–	
Raw4	–	–	––	–	––	–	–	1200	1500	1400		
Period 4												
Raw1	1500	1500	1700	–	–	–	–	–	––	–	–	
Raw2	–	–	–	700	1200	1000	–	–	––	–	–	
Raw3	–	–	––	–	−1200	1500	1200	–	–	–		
Raw4	–	–	––	–	––	–	–	1200	1500	1500		

Optimal quantity of products produced at plants in each period ($X2_{pft}$)

Time Periods	1	2	3	4	1	2	3	4	1	2	3	4
Plants	1				2				3			
Prod1	4000	4000	3500	3500	–	–	––	–	–	––		
Prod2	–	–	––	5000	5000	4000	4000	–	–	––		
Prod3	–	–	––	–	–	––	3500	3500	3500	4000		

Table 7. Optimal Quantity of Products Shipped from Plants to DC in each Time Period ($X3_{pfdt}$)

	Time Period
	1 2 3 4
	Plant
	1 2 3 1 2 3 1 2 3 1 2 3
DC 1	860 -- 890 --740-- 900 --
DC 2	990-- 1000 -- 890 -- 850 --
DC 3	1140 -- 1020 -- 890 -- 750 --
DC 4	1010 -- 1090 -- 980 --1020--
	Product 2
DC 1	− 1400 --1140-- 1050 -- 980 −
DC 2	− 1200-- 1340 -- 1000 -- 1200 −
DC 3	− 1600-- 1280-- 850 -- 1000 −
DC 4	− 800-- 1240-- 1100 -- 820 −
	Product 3
DC 1	-- 820--820 -- 850 -- 1000
DC 2	-- 780-- 900-- 900 -- 1100
DC 3	-- 700-- 850-- 900-- 1000
DC 4	-- 700-- 930-- 850 -- 900

Table 8. Objective Function Values

Objective function	Value	Unit
Total cost, Z_1	232,615,300	Naira
CO_2 emission, Z_2	22.343	Tonnes of CO_2
Incidence rate, Z_3	5.68	−

The results obtained by running the numerical data through the model explain its effectiveness and feasibility. Using the preliminary analysis, the fixed demand quantities for each of the customer zones lead to the amount of raw materials (Table 6) supplied to each plant to meet these demands, considering the processes and the capacities of the production units. The conflicting characteristic of the multi-objective model comes into play also. The objective function value when the cost minimization model was run alone gave ₦221,462,800, but when run with the conflicting environmental and social models, the optimal solution was ₦232,615,300. This is acceptable for reasons that a considerable price has to be paid to operate a green and sustainable SCN in which the environment is not polluted. The emissions from supply trucks and production plants from the entire supply chain as shown by the optimal value of the second objective gives 22.343 tonnes of CO_2, with the transportation activities resulting in 7.47 tonnes of CO_2 emissions. This is equivalent to 1.44E-04 tonnes of CO_2 per km (estimated total distance travelled in the SCN is 52, 000 km). Converting this further, we got 144 grams of CO_2 per km and by international standard; the accepted CO_2 emission for 2017 is pegged at 175g of CO_2 per km (ICCT, 2014). This result shows that the activities of the supply chain do not violate international environmental regulations as regards CO_2 emissions from trucks involved. Besides, the sensitivity of the solution can be analysed by varying these parameters in the model in order to evaluate their effects on the optimal solution. The ranges within which the solutions are acceptable were calculated by the optimizer and are presented for selected model parameters. The effect of changes in demand on the objective function cost is shown in Fig. 4. It can be seen that changes in demand is most sensitive to the cost function as supply chain costs increases are highly proportional to demand rates from the customer zones.

The allowable variations in the costs of shipping raw materials to plants and products to customer zones are shown in Fig. 5. Expectedly, each increase in transportation cost leads to a corresponding increase in the total cost of the supply chain. This can be explained in terms of the costs incurred as a result of increases in logistics management charges, and the additional costs incurred in managing a sustainable supply chain. The supply chain trucks used for supplies must emit only minimal amounts of CO_2 as approved by international bodies, and this can be achieved by investing in clean trucks, which is reflected in the final costs of the supply chain. In Fig. 6, the unit holding cost makes the economic objective function to increase slightly with each increase in its value. This is due to the fact that cost is incurred in holding up products in distribution centres and warehouses. Also, at an increasing capacity, production costs tend to reduce slightly as a result of bulk purchases, mass production, and constant modes of production processes, hence the effect on the total cost of the supply chain. The weights on the objective functions largely affect the resulting values. Different weights were calculated as a result of altering the preferences of the decision makers and are plotted in Fig. 7. It can be seen that for every weight combination, an increase in the weight of an objective function leads to a corresponding increase in that objective function value.

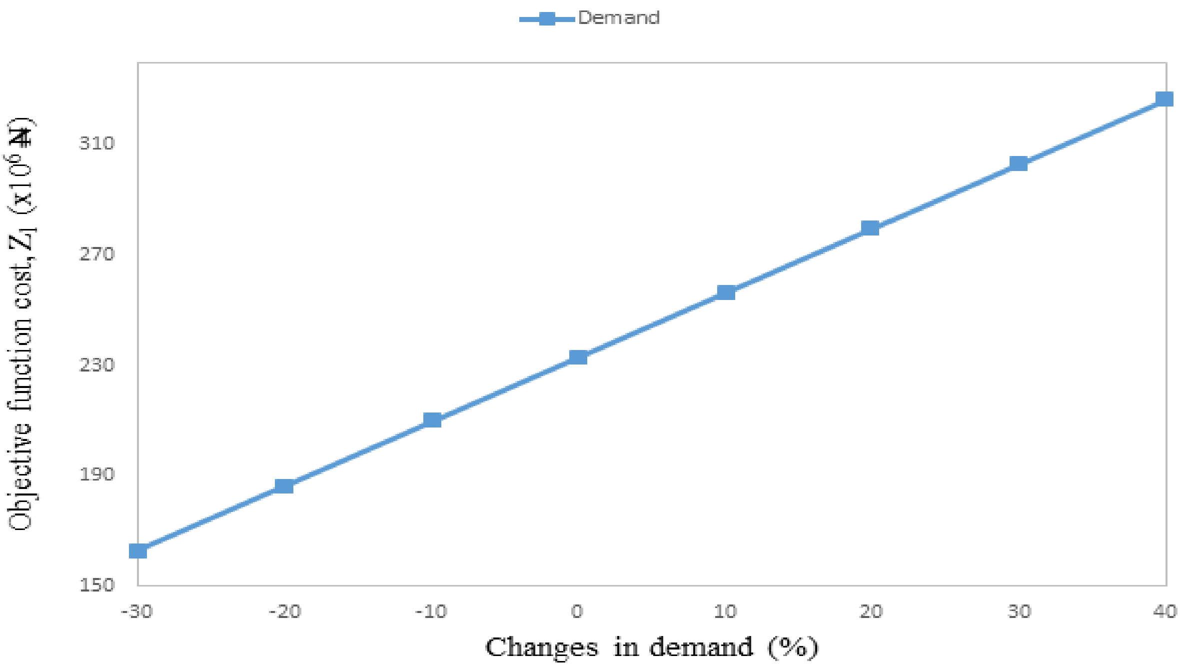

Fig. 4**:** Sensitivity of Demand Parameter on the Total Cost

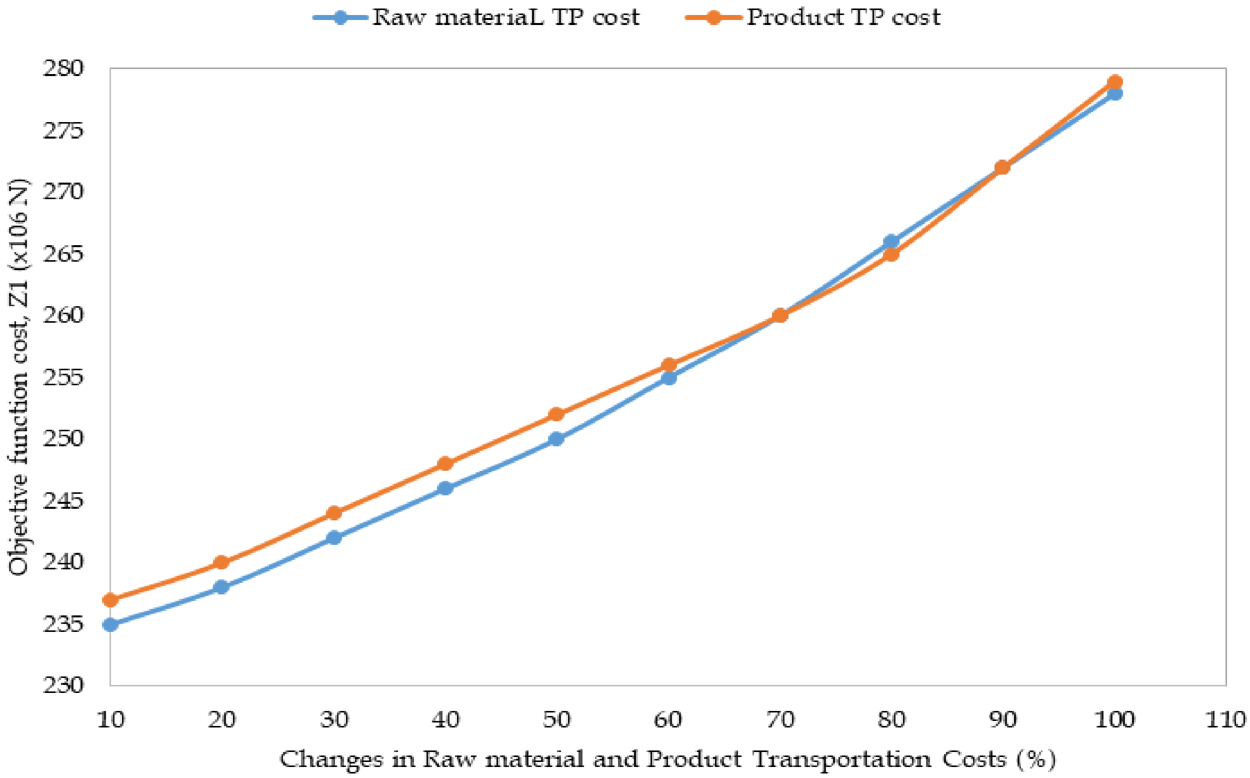

Fig. 5**:** Sensitivities of Raw Material and Transportation Costs on Total Cost

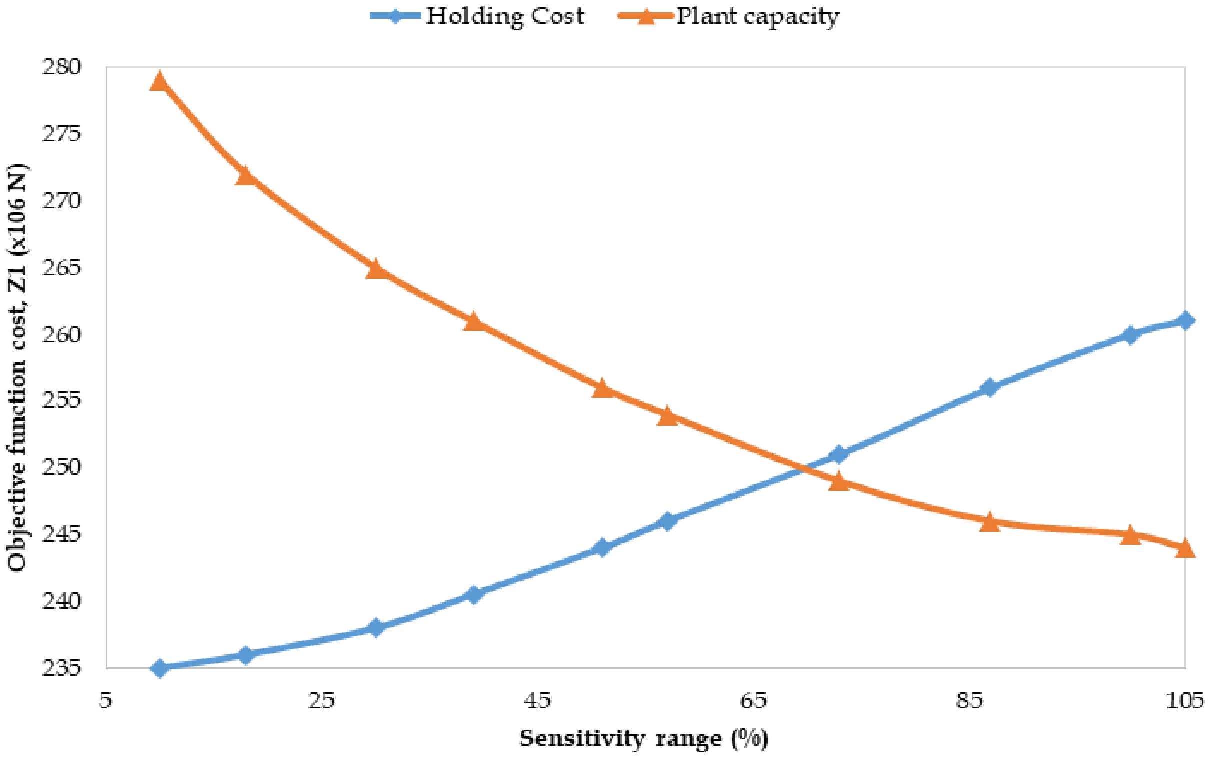

Fig. 6**:** Sensitivities of Holding Cost and Plant Capacity on Total Cost

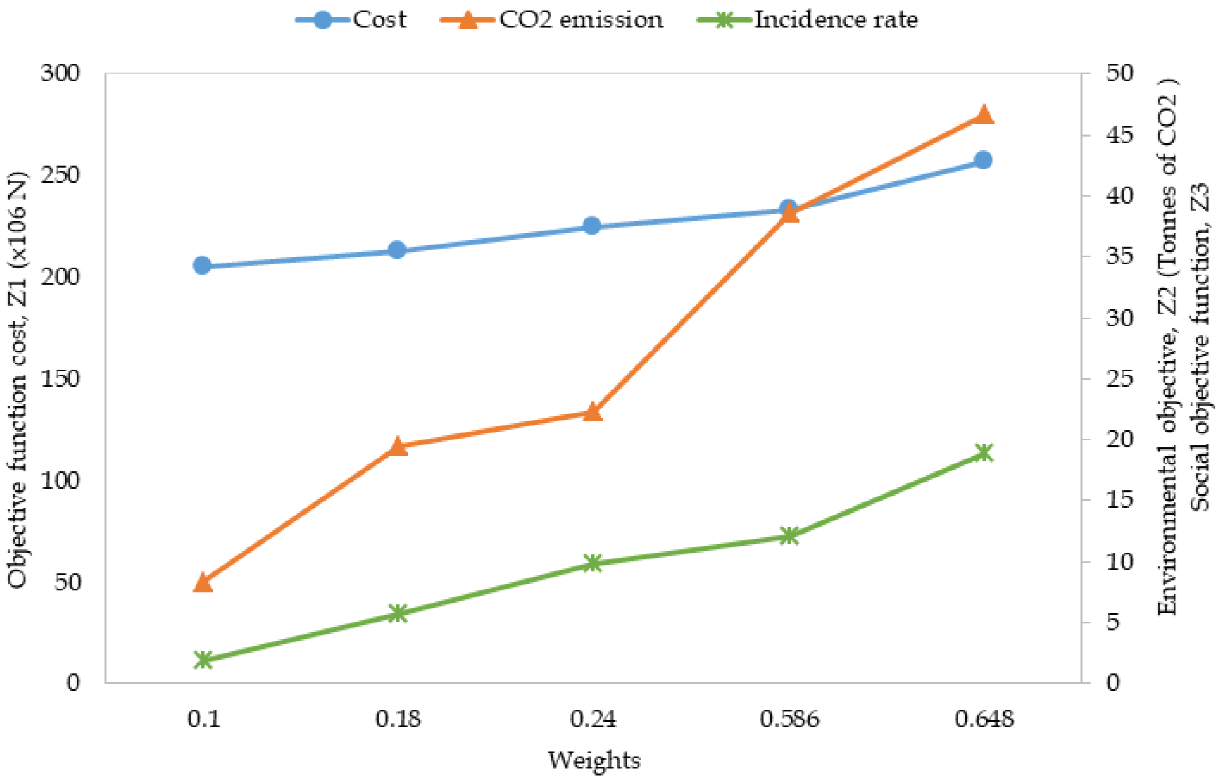

Fig. 7**:** Effect of Weight Selection on the Objective Function Values

CONCLUSION

Supply chain management describes the links from raw material to end-product delivery stages. In this research work, the effectiveness of multi-objective optimization model for SCM was successfully demonstrated. Three objectives were formulated, the first one minimized the entire cost through the chain, the second ensured the 'greenness' factor by minimizing CO_2 emissions from trucks and plants and the third, a social objective metric, ensured safety operations by minimizing accident/incidence rates. The outcome of the results revealed a successful supply chain management which minimized the total costs, CO2 emissions and incidence rates, thereby solving the conflicting problems created by the objective functions.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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