ABSTRACT

A supply management system that includes a set of green criteria, relevant supply cost drivers and indirect factor is proposed. The set of green criteria, the cost drivers, and the indirect factors form the Green Supply Management (GSM) practices. Supply cost drivers include quality, supplier’s production system, and quoted cost. Indirect factors include supplier/purchaser relationship; spent energy, harmful emission generation, and other green and sustainability practices of suppliers and buying company. This research integrates GSM practices in supply chain planning model to improve its green image and overall cost performances. A numerical example illustrates usefulness of the approach.

KEYWORDS: green and sustainability criteria, supply cost drivers, supplier quality and reliability, supplier/purchaser relationship, supply chain planning model.

INTRODUCTION

For manufacturing based businesses supply management covers a significant part of their overall expenses. About 59% of the firm’s revenue of the US manufacturing sector are made up by materials cost (Tate et al, 2012). In addition to cost, manufacturing and transportation of supply items involve considerable amount of spent energy, environmental wastes, and harmful emissions. Green practices in supply management do not only address these environmental concerns but contribute in minimizing costs of supply items and improve overall supply chain (SC) performances in terms of improving customer satisfaction, market growth, and quality image of the Firm in the market places. Today it is recognized that the environmental performances and businesses performances of a firm are interlinked (Holos et.al, 2012). Quality and brand image for the product of a company have been found to be influenced by the green supply management (GSM) practices (Lintukangas et al. 2015, Cooling 2007). Since several firms in today’s business outsource their components and materials, majority of their operations are performed by suppliers. According to Tate et al. (2011) a firm’s aggregate environmental impact depends on the environmental impacts of its supply network. As such SC should integrate GSM practices to improve their economic and environmental sustainability.

Collaboration and partnering with suppliers to improve supply quality; incorporation of lean systems to reduce inventory obsolescence of supply items; reduction of scrap, fuel, lubricant, cutting fluid, and other process wastes using appropriate quality raw materials and inputs are also included Green supply practices (EPA, 2000). By incorporating collaboration and partnering GSM in effect is contributing to the overall product quality through use of high quality inputs by utilizing supplier’s expertise and capability to provide such inputs. It is apparent that the combined effect of superior quality product and environmental practices by the supplier and the
firm will improve perceived quality and image of the business (Narasimhan and Schoenherr, 2012). To address environmental requirements purchasing of supply items should be directed to reduction of resource use, reuse of product, and recycling (Zsidisin and Siferd, 2001). According to EPA requirements (EPA 2005) companies reporting “scope three” emission needed to include energy used in extraction, production, and transportation of supplied components and services. U.S. EPA also initiated mandatory greenhouse gas (GHG) emissions reporting (Federal Register 2009). Based on these requirements SCs must have a plan to engage suppliers in GHG requirements, which intern will make them environmentally conscious suppliers. As discussed before, the buying firm will have several benefits when suppliers adopt environmental practices. These benefits include improved process efficiencies, reduced costs, cycle time, and better quality inputs (Tate et al. 2011). It is evident that integration of GSM will facilitate SC in addressing environmental concerns in the major part of their business process and they will also benefit in terms of economic performance by minimizing cost. Such integration of GSM will further contribute in obtaining better quality customer returns for remanufactured product and reduce overall waste from returns. There is minimum number research in the literature that includes a comprehensive SC planning model to integrate GSM and other green practices through reverse SC process to improve overall SC performances. This research is intended to contribute in this area.

This research integrates GSM practices in overall SC planning model for improving overall SC costs for operations, spent energy and penalty cost for harmful emissions. The paper is organized in the following way: Section 2 reviews select relevant literature, Section 3 includes problem statement and mathematical models, and section 4 illustrates application of the model in a numerical example, Section 5 concludes.

LITERATURE REVIEW

This literature review covers select well cited recent literature in supply management that includes some considerations of green practices in procurement policies, in procured items, and/or selecting/enlisting suppliers.

In a global economy when supply management plays a significant role in the overall business performances SC needs to analyze the ways to obtain supplies that will make them competitive at the same time environmentally responsible. Taking a resources based view GSM may be defined as the process incorporated in the corporate and plant level of a SC to improve environmental performance of a supplier base (Gavronski, et al., 2011). In these perspectives GSM consists of partnering with suppliers, supporting them in pursuing environmentally sustainable practices. Such approaches of developing GSM have been found to be successful option in several cases. Lee (2010) described examples of steps taken by Textile Manufacturing Company Esquels to successfully obtain organic cotton from Chinese supplier, and taking similar approaches Nike could establish sustainable practices for their 150 contract manufacturers in China. Lee also mentioned several similar successful examples in his state of the art research. In each of these cases the organization could improve their sustainability image and improve their overall SC performances. Recent SC literature shows that an increasing number of organization have been giving importance to the suppliers that pursue environment friendly practices for the supply items (Genovese et al. 2013).

GSM have been explained in the literature as greening the purchasing process for purchased items and suppliers by including collaborative effort between buyer and supplier for recycling, reduction of packaging waste, joint development of environment friendly product/ processes and such other environmental consideration (Bowen et al., 2001). In addition to collaborative effort between purchaser and supplier Bowen et al. also emphasized importance of liaison between purchasing and other functions of purchasing company in this GSM process. Such liaison is
considered important to have socially responsible buying. Bowen et al.’s green purchasing is supporting the features of environmental purchase in Zsidiisin and and Siford, (2001). Purchasing policy that takes environmental requirements into considerations is considered as a part of corporate social responsibility (CSR) (Carter and Jennings, 2004). GSM also contributes in CSR by pursuing people oriented culture to establish collaboration with suppliers and liaison of other SC functions with suppliers. GSM practices may be extended to include environmental collaborative activities for joint planning of sessions for knowledge sharing, greener product development, process modification, and reducing waste in the logistics process (Vachon and Klassen, 2006). As is apparent, integration of such GSM practices will contribute in furthering overall SC performance.

Institutional pressures and government regulations to adopt sustainable practices are often enablers in developing GSM practices, especially for globally located suppliers (Sancha et al. 2015). To continue their businesses such suppliers need to comply with sustainability requirements specified by global businesses.

Lean and green strategies are compatible to each other based on waste reduction as their common focus. By allowing flow of only the demanded production or inputs lean facilitates GSM practices by reducing amount of inputs to be ordered, packaged, and transported. The main contradiction of lean with GSC comes when lean advocates multiple trips with increased emission and waste of fuel energy to ensure customer demand satisfaction according to JIT (Mollenkopf et al. 2010, Hajmohammad et al. 2013). But such problem may be solved in select cases by taking collaborative effort to support suppliers to relocate near to buyer.

Above literature review provides importance to GSM practices in the perspectives of customer emphasis on such practices in addition to its contributions in improving environmental and economic sustainability of a business. Above findings and recommendations motivated us to extend GSM practices in improving overall SC performances. This research integrates GSM practices with the closed loop SC planning criteria to address environmental sustainability concerns related to harmful emissions and spent energy for SC operations to improve overall SC performances.

THE SUPPLY CHAIN PLANNING MODEL

This section includes Problem Statement and Mathematical Models for supply chain planning. Notations used in the model equations are included in the APPENDIX.

Problem Statement

A SC procures a set of components $i \in I$ from a sub-set of overall supply base called tier 1(t1) supplier $s \in S$ that are then used by a subset $s' \in S'$ called tier 2(t2) suppliers to make modules $m \in M$ and supply to SC plants. The modules are finally assembled in SC operated plants $j \in J$ to realize the product $p \in P$. The SC markets product through a set of retailers $r \in R$. Based on a market study they have been planning to include green practices in their business system. Since the SC assembles the product by procuring modules and then markets them through retail outlets, their business is supply management dependent. For the last two to three years the SC worked with their suppliers and conducted several experiments by partially implementing green practices in their supply management. As a part of green strategy they also plan to implement reverse SC practices and have developed a partnering based agreement to collect customer returns through retailers using an incentive scheme. Based on this agreement the SC plans to market their entire product (new, remanufactured, and second hand used product) through the retailers. To implement reverse SC, the business also worked and provided training to a set of recovery service provider (RSP) $v \in V$ to recover, upgrade, and repair the modules.
(as appropriate) to get planned quality level for reverse SC products. This study is to implement GSM and reverse SC practices in a SC operation and compare the outcome with the business performance of traditional supply management practices. Traditional or non-green supply management does not consider customer returns or reverse SC. After integrating GSM practices in SC planning that includes reverse SC practices may be called as green supply chain.

**Supply Management (SM) Model in Non-green Era**

First model is defined as non-green era model when SC planning does not include reverse SC and GSM in business operation.

**Objective function for Non-green Era Model**

\[
\text{maximize Profit} = \text{NGREV} \cdot \text{TC} 
\]

\[
\text{NGREV} = \sum_{re} \sum_{pe} \sum_{pj} VP_{pj} \sum_{y_{pj}} 
\]

\[
\text{TC} = \text{Assembling and supply management (SM) cost} (\text{ASMC}) + \text{Penalty cost for spent energy in SM activities} (\text{PES}) + \text{Penalty cost for generated harmful emission in Kgs of equivalent CO2} (\text{PHE}) 
\]

\[
\text{ASMC} = \sum_{re} \sum_{pe} \sum_{pj} \sum_{jc} x_{pj} \cdot AC_{pdj} + \sum_{re} \sum_{pe} \sum_{pj} u_{pj} \cdot FAS_{pj} + \sum_{re} \sum_{pe} \sum_{s} (z_{is} \cdot SPC_{is} + b_{is} \cdot SPC_{is}) + \\
\sum_{s} \sum_{m} (r_{ms} \cdot SVC_{ms} + c_{ms} \cdot FV_{ms}) + \sum_{re} \sum_{pe} \sum_{y_{pj}} y_{pj} \cdot DC_{pjr} 
\]

\[
\text{PES} = k' \left[ \sum_{re} \sum_{s} \sum_{v} z_{is} \cdot PJ_{is} + \sum_{v} \sum_{m} z_{ms} \cdot PM_{ms} + \sum_{re} \sum_{pe} \sum_{s} x_{pj} \cdot AJ_{pdj} + \\
\left\{ \sum_{re} (r_{ms} \cdot TRL_{ms}) \sum_{j} DT_{y,j} + \sum_{re} \sum_{pe} \sum_{y_{pj}} (y_{pj} \cdot TPR_{pj}) DS_{jr} + \\
\left\{ \sum_{re} \sum_{s} \sum_{v} \sum_{m} (z_{is} \cdot TRS_{is}) \sum_{j} SS_{s,j} \right\} SDE \right\} 
\]

\[
\text{PHE} = k'' \left( \sum_{re} \sum_{s} \sum_{m} z_{is} \cdot PE_{is} + \sum_{v} \sum_{m} r_{ms} \cdot ME_{ms} + \sum_{re} \sum_{pe} \sum_{s} x_{pj} \cdot AE_{pdj} + \\
\left\{ \sum_{re} (r_{ms} \cdot TRL_{ms}) \sum_{j} DT_{s,j} + \sum_{re} \sum_{pe} \sum_{y_{pj}} (y_{pj} \cdot TPR_{pj}) DS_{jr} + (z_{is} \cdot TRS_{is}) SS_{s,j} \right\} SHE \right) \}
\]

Objective function in equation (1) maximizes profit, which is computed by adjusting revenue computed in equation (2) with Total Cost (TC) described in in equation (3) in terms of its components. Revenue in equation (2) is generated by supplying product to retailer at market price. TC in equation (3) includes Assembling and SM cost (ASMC), penalty cost for the energy spent in SM activities (PES), and penalty cost for the generation of harmful emissions in SM (PHE). ASMC defined in equation (3.a) includes: 1) costs for assembling product; 2) fixed cost setting up the assembling plant; 3) cost for buying components from t1 suppliers; 4) fixed ordering costs for components; 5) scrap cost from the purchased components; 6) costs for
buying modules from t2 suppliers, 7) fixed ordering costs for modules; 8) cost involved due to
generated scrap from supplied modules, and 9) cost for distributing product from plants to
retailers. \textit{PES} defined in equation (3.b) first includes penalty a cost factor to transform energy
spent in SM activities into $ value. This penalty factor is equivalent to average cost per MJ\textit{s} of
energy used in US industries. \textit{PES} computes energy spent: 1) by t1 supplier for input
production, 2) by t2 supplier for assembling modules, 3) by SC plants for assembling product; 4)
to transport modules by t2 supplier; 5) distribute product from SC plants to retailer, and 5) to
transport components by t1 suppliers to SC plants. For computing energy from transportation,
distances in miles based on the number of trips are multiplied by standard per mile spent energy
by semi-trailer type trucks. \textit{PHE} in equation (3.c) uses penalty factor similar to carbon tax used
in Australia to transform harmful emission generated by production and SM activities into $ value. \textit{PHE}
includes harmful emission in Kgs of equivalent CO\textit{2} generated by: 1) t1 supplier to
manufacture components; 2) t2 supplier for assembling modules; 3) by SC plant to assemble
product; 4) to transport and modules from t2 suppliers to SC plants, 5) to distribute product from
plants to retailers, and 6) to transport components from t1 suppliers to plants. Similar to spent
energy from transportation, harmful emission is also estimated by multiplying distances in miles
from the trips by standard per mile harmful emission in equivalent Kgs of CO\textit{2} by semi-trailers.

\textbf{Constraints}

\begin{align*}
\sum_{d \in D} a_{pd} & \geq 1 & \forall p \\
\sum_{j \in J} y_{pjr} & = DR_{pr} & \forall p, r \\
\sum_{d \in D} x_{pdj} & = \sum_{r \in R} y_{pjr} & \forall p, j \\
\sum_{j \in J} x_{pdj} & \leq a_{dp}BN & \forall d, p \\
x_{pdj} & \leq u_{pj}CA_{pdj} & \forall p, d, j \\
\sum_{p \in P} \sum_{d \in D} \rho_{pmd} \sum_{j \in J} x_{pdj} & = TM_{m} & \forall m \\
TM_{m} & = \sum_{v \in V} t_{msv} & \forall m \\
t_{msv} & = c_{ms}CAM_{msv} & \forall s'' \in S'', m \\
\sum_{v \in V} \sum_{S'' \in S''} t_{msv}CN_{im} & = \sum_{s \in S''} z_{is} & \forall i 
\end{align*}
Constraint (4) ensures that a product may have more than one design. Constraint (5) balances product distributed from plants to the demand in the market. Constraint (6) balances production with the quantity distributed to market. It may be noted here that only new product is produced in non-green era. Constraint (7) assigns product to a plant based on the decided design. Constraint (8) limits production in a plant based on its capacity. Equation (9) computes number of modules needed for the required production quantity based on usage of modules for the decided designs for the product. Equation (10) assigns modules to t2 suppliers. Constraint (11) limits allocation of modules to tier 2 suppliers based on their capacity. Equation (12) computes inputs to assign to t1 suppliers based on usage of inputs in the modules. Constraint (13) limits the input to be assigned to t1 supplier based on its capacity.

**Supply Management (SM) Model in Green Era**

The second model in green era is the green supply chain (GSC) planning model that integrates GSM practices with GSC practices. We assume that GSC plans to market product with quality levels $q \in Q; q=1$ new, $q=2$ remanufactured equivalent to new quality in terms life and performance; and $q=3$ second hand product. GSC has modules with quality levels $l \in L; l=1$ new modules manufactured from new components by suppliers $s \in S; l=2$ and 3 are modules recovered by RSPs from customer returns. $l=2$ are good quality modules either obtained from good quality returns by just cleaning /minor steps, or upgraded to required quality level by applying appropriate quality enhancing procedure; $l=3$ modules are recovered second hand modules that are not suitable to be upgraded to required quality level for remanufactured product. $l=3$ quality modules are used for producing $q=3$ product. RSPs dismantle such inferior quality modules into components and apply applicable repair steps to make them usable. This plan for realizing and marketing $q=3$ product reduces waste and contributes to increased earning by SC. In the GSC model all the previous suppliers are in a single supply pool. They worked with SC to improve their production quality, get ISO 9000 certification, improve plant reliability, safety level, skill level of their employees, improve process capability of the production processes. Each of the suppliers has been affiliated to be the partner supplier of the SC. Supply from each supplier is quality ensured. In addition, the SC has been supporting suppliers to use energy efficient and low harmful emission generating type processes for producing components and assembling modules. The suppliers are now assigned modules by the SC and suppliers produce their own components to be used in modules. As such costs for each component are lower than previous cost because of savings in packing, packaging, transportations, ordering, and processing components and modules separately. In addition the SC is paying margin to suppliers on the modules only. The SC introduced reusable, and returnable metallic pallet boxes for the modules to reduce packing and packaging materials related costs and wastes. The metallic boxes have been developed jointly by SC and the supplier. The SC also uses same type of pallet boxes for transportation of recovered modules from RSPs to their assembly line. Suppliers and RSPs use one type of box for each type of module by attaching identification tags for module types in a box. The SC plants assemble modules to products. The suppliers and RSPs supply spent energy and harmful emission data to SC. The SC conducts audits to RSP and supplier facility in a set frequency to ensure that they are following EPA guide lines for other waste disposal.

**Objective Function for Green Era Model**

$$\text{maximize } \text{GSC Profit} = \text{GREV} - \text{GTC}$$ (14)
\[
GREV = \sum_{r e R} \sum_{q e Q} \sum_{p e P} V P Q_{pqr} \sum_{j e J} g y_{pqjr} + \sum_{c e C} \sum_{v e V} s_{mv} c S A L_{c}
\]  
(15)

\[GTC = \text{Cost of production and procurement (PCM) } + \text{Penalty cost for collecting customer returns (CCR) } + \text{Penalty cost for generating harmful missions by the GSC process (PGTJ) } + \text{Penalty cost for generating harmful missions by the GSC process (PGTE)}\]

\[
PCM = \sum_{s e S} \sum_{m e M} g_{ms} G S V C_{ms} + \sum_{s e S} \sum_{m e M} g_{ms} G F S_{ms} + \sum_{s e S} \sum_{m e M} \left( \sum_{d e D} x_{pdg} G A C_{pdg} \right) + \sum_{r e R} \sum_{j e J} \sum_{p e P} \left( \sum_{q e Q} (g y_{pqjr} D C_{pj}) \right) + \sum_{m e M} \sum_{v e V} g r_{mv} C R V_{mv} + \sum_{v e V} v a_{c} F C V_{v} + \sum_{c e C} \sum_{v e V} s_{mv} R R_{vc} + \sum_{m e M} R e l_{m} F R C_{m}
\]

\[
CCR = \sum_{r e R} \sum_{p e P} e s_{pr} C L C_{pr} + \sum_{r e R} r c_{r} G F R_{r} + \sum_{p e P} e s_{pr} \sum_{v e V} T R V_{prv} + \sum_{j e J} \sum_{p e P} \sum_{q e Q} \sum_{s e S} \sum_{m e M} g r_{mv} R V J_{mv} + \sum_{j e J} \sum_{p e P} \sum_{q e Q} \sum_{s e S} \sum_{m e M} g y_{pqjr} T P R_{p} D S_{pr} + \sum_{j e J} \sum_{s e S} \sum_{m e M} D S M_{sj} + \sum_{v e V} e s_{pr} T R R_{p} D I S_{rv} + \sum_{m e M} s m_{mv} R C J_{mv}
\]

\[
PGTJ = k' \left[ \sum_{s e S} \sum_{i e I} g_{is} C J_{is} + \sum_{s e S} \sum_{m e M} g_{ms} M J_{ms} + \sum_{l e L} \sum_{v e V} \sum_{m e M} g r_{mv} R V J_{mv} \right] + \sum_{j e J} \sum_{p e P} \sum_{q e Q} \sum_{s e S} \sum_{m e M} g x_{pdq} A J_{pdq} + \sum_{r e R} \sum_{j e J} \sum_{p e P} \sum_{q e Q} g y_{pqjr} T P R_{p} D S_{pr} + \sum_{j e J} \sum_{s e S} \sum_{m e M} D S M_{sj} + \sum_{v e V} e s_{pr} T R R_{p} D I S_{rv} + \sum_{m e M} s m_{mv} R C J_{mv}
\]

\[
PGTE = k'' \left[ \sum_{s e S} \sum_{i e I} g_{is} C E_{is} + \sum_{s e S} \sum_{m e M} g_{ms} M E_{ms} + \sum_{l e L} \sum_{v e V} \sum_{m e M} g r_{mv} R V E_{mv} \right] + \sum_{j e J} \sum_{p e P} \sum_{q e Q} \sum_{s e S} \sum_{m e M} g x_{pdq} A E_{pdq} + \sum_{r e R} \sum_{j e J} \sum_{p e P} \sum_{q e Q} g y_{pqjr} T P R_{p} D S_{pr} + \sum_{j e J} \sum_{s e S} \sum_{m e M} D S M_{sj} + \sum_{v e V} e s_{pr} T R R_{p} D I S_{rv} + \sum_{m e M} s m_{mv} R C E_{mv} \right]
\]

Green era objective function defined in equation (14) maximizes \textit{GSC Profit} which is earned by adjusting total GSC cost \textit{GTC} defined in (16) from GSC revenue \textit{GREV} defined in equation (15). Revenue \textit{GREV} in (15) is earned by supplying product at different quality levels to retailer based on market price and selling of recovered materials from re-cycling if any. \textit{GTC} is defined
in terms of its components in equation (16). Production and procurement cost $PCM$ defined in equation (16.a) includes: 1) costs for purchasing new modules from suppliers; 2) fixed ordering costs for modules; 3) assembling cost for products; 4) setup cost for assembling; 5) costs for distributing product from plants to retailer; 6) procuring recovered modules supplied by RSPs; 7) fixed cost assigning recovery services to RSPs for recovered modules; 8) cost of recovering materials from recycling process, and 9) fixed cost for setting recycling process. Cost of collecting customer returns $CCR$ defined in equation (16.b) includes costs for collecting customer returns through retailers, fixed cost for contractual arrangement for collecting returns, and costs for transporting returns from retailer to RSPs. Penalty cost for spent energy in GSC processing, $PGTJ$ defined in equation (16.c) includes penalty cost factor ($k$) equivalent to average cost per MJ of energy use in US industries to transform it into $\$\$\$ value. $PGTJ$ computes penalty costs for the energy spent: 1) by suppliers for production of new components, and 2) modules, 3) by RSPs for recovery of modules, and 4) by SC plants for assembling products; 5) to distribute product from plants to retailers, 6) to transport customer returns from retailer to RSPs, 7) new modules from suppliers to SC plants, 8) recovered modules from RSP to plants, and 9) energy spent for recycling process in applicable recycling process. Penalty cost for generating harmful emission in GSC processes, $PGTE$ defined in equation (16.d) computes harmful emission in equivalent Kgs of CO$_2$ generated by GSC production and SM process. $PGTE$ also considers penalty cost factor equivalent to carbon tax used in Australia to transform emission amount into $\$\$\$ value. $PGTE$ computes harmful emission for manufacturing 1) components and 2) modules by suppliers; 3) recovering modules by RSP; 4) assembling products by SC plants; 5) distributing products from plants to retailers, 6) to transport new modules from suppliers to plants, 7) collected returns from retailers to RSP, 8) recovered modules from RSP to SC plants, and 9) harmful emission from recycling process if applied.

Constraints

$$
\sum_{j=J} g_{y_{pqjr}} = DR_{pqr} \quad \forall p, q, r
$$

(17)

$$
\sum_{d=\Delta} g_{x_{pqd}} = \sum_{e=\Delta} g_{y_{pqjr}} \quad \forall p, q, j
$$

(18)

$$
\sum_{j=\Delta} g_{x_{pdaj}} \leq a_{pd}BN_{1} \quad \forall p, d
$$

(19)

$$
\sum_{j=\Delta} g_{x_{pdaj}} \leq gu_{pj}CAP_{pdaj} \quad \forall p, d, q, j
$$

(20)

$$
\sum_{d=\Delta} g_{x_{pdaj}f_{pd}} = \sum_{l=L} g_{m_{ml}} \quad \forall m
$$

(21)

$$
\sum_{l=L} g_{m_{ml}} - \sum_{v=V} g_{r_{mvl}} = \sum_{v=S} g_{n_{ms}} \quad \forall m
$$

(22)

$$
 gn_{ms} \leq g_{s_{ms}}GC_{sv} \quad \forall m, s
$$

(23)
\[
\sum_{ms} gn_{ms} CN_{im} = g_{is} \quad \forall i, s \tag{24}
\]
\[
g_{is} \leq e_{is} GCA_{is} \quad \forall i, s \tag{25}
\]
\[
DRQ_{pqr} \leq rc_{pr} BN3 \quad \forall p, q, r \tag{26}
\]
\[
es_{pr} = rc_{pr} \sum_{re} RE_{ri} PR_{r} \sum_{qrQ} DR_{pqr} \quad \forall p, r \tag{27}
\]
\[
\sum_{re} es_{pr} = \sum_{ve} alv_{pv} \quad \forall p \tag{28}
\]
\[
alv_{pv} \leq va_{v} CV_{pv} \quad \forall p, v \tag{29}
\]
\[
\sum_{p\in P} alv_{pv} \sum_{d\in D} \rho_{pdm} = mxgr_{mv} \quad \forall m, v \tag{30}
\]
\[
\sum_{m\in M} \left( \sum_{v\in [2, 3]} gr_{mv1} - mxgr_{mv} \right) \leq (1 - aux_{v})M \quad \forall v \tag{31.a}
\]
\[
ex_{mv} \leq aux_{v} M \quad \forall m, v \tag{31.b}
\]
\[
ex_{mv} RCL_{m} = rcm_{mv} \quad \forall m, v \tag{32.a}
\]
\[
sm_{vc} \leq \sum_{m\in M} rcm_{vm} PR_{mc} \quad \forall v, c \tag{32.b}
\]
\[
a_{pd} \in \{0, 1\} \forall p, d; b_{is} \in \{0, 1\} \forall i, s; c_{ms} \in \{0, 1\} \forall m, s; rc_{pr} \in \{0, 1\} \forall p, r; aux_{v}, va_{v} \in \{0, 1\} \forall v \tag{33}
\]

Constraint (4) is applicable in GSC model as well. Equation (17) balances distribution of product at the green era with the market demand for different quality level products. Equation (18) balances distribution of product with the production quantity. Constraint (19) assigns production at different quality levels to plants based on the decided design in constraint (4). Constraint (20) limits assembling of products in SC plant based on its capacity. Equation (21) computes modules at different quality levels to fulfill requirements of products at different quality levels. Equation (22) balances total modules needed for production with new modules to be procured from suppliers, and recovered modules at two quality levels. Constraint (23) limits assignment of modules based on the capacity of the suppliers. Constraint (24) computes components to be manufactured by suppliers to produce modules assigned to them. Constraint (25) limits manufacturing of components by suppliers based on their capacity. Constraint (26) considers demand of products from retailer only when SC has a contractual arrangement with the retailer. Equation (27) computes estimated amount of returns collected through retailers out of demand in an incentive based scenario analysis. In this collection process quality level of products are not considered. The collection inspectors considered them equivalent product based on physical
Das & Rahman  
Green supply management in supply chain planning

evidence only. Constraint (28) allocates customer returned product to RSP. Constraint (29) limits allocation of returns to RSP based on the capacity. Equation (30) computes maximum obtainable modules by the RSP from dismantled returns irrespective of their quality. Constraint (31.a) and (31.b) decides if excess amount of modules are recovered. Based on the past experiments by SC, if excess amounts of are there they will not be suitable for using them as l=2 or 3 level modules. If there are shortage the SC will limit marketing of q=3 level products but will compensate requirements of l=2 level modules by new modules. In the case excess usable modules are there, constraint (32.a) segregates recyclable non-usable-module based on their inspection experience and the remaining non usable modules are dumped following EPA guidelines. Constraint (32.b) estimates saleable possible materials to be obtained from recycling. Constraint (33) imposes integrality

NUMERICAL EXAMPLE

We assume an example SC that markets 7 products through 12 retailers to illustrate applicability of the model and research approach. Input data are assumed based on the operations data ranges from practically operating welding equipment manufacturing businesses. Each product is made up of 3 to 4 modules out of a total 12 based on two designs. Each module is formed by 3 to 5 components out of total 20 components. The SC procures the modules from 7 t2 suppliers and assembles them to market directly to retailers. t2 suppliers realize modules based on the designs and components from SC. The components are supplied by 10 tier 1 suppliers. During last two to three years SC went for limited scale reverse SC practices. This year they are implementing select green supply management (GSM) practices and implementing planned reverse SC process. The SC worked with t1 and t2 suppliers, organized several training sessions, and developed partnering based collaborative agreement to obtain ensured quality supplies and implement select green practices. Based on the current GSM practices the SC has a pool of 17 suppliers for obtaining quality ensured modules. The suppliers manufacture components and assemble modules following designs and manufacturing process established jointly over the past years for improved sustainability (economic and environmental). The suppliers share spent energy, waste information, and harmful emission data with SC as a part of agreement. The SC plans to market new (Quality level 1: QL1), remanufactured (QL2), and second hand (QL3) product. QL 1 products are made up of new modules (Module quality 1 or MQ1) procured from suppliers; QL2 and QL3 products are made of recovered modules (of quality MQ2 and MQ3) by 6 recovery service providers (RSPs) affiliated with SC. Recovered modules used for QL2 product (MQ2) go through a rigorous quality enhancement procedure by the RSPs to make them suitable for such product. RSPs have been provided trainings on recovery and quality enhancement procedure; waste disposal, and possible recycling process for select applicable unusable modules. The retailers collect customer returns and markets QL2 and QL3 products in addition to QL1 product based agreement mentioned before. For comparison and analysis, a forward SC planning by considering entire demand to be fulfilled with only new product is also prepared.

<table>
<thead>
<tr>
<th>PRODUCT QUALITY LEVEL</th>
<th>DEMAND FOR DIFFERENT QUALITY LEVEL PRODUCTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>QL1</td>
<td>1 2 3 4 5 6 7</td>
</tr>
<tr>
<td>1</td>
<td>7,329 12,829 7,755 7,524 11,159 8,233 12,861</td>
</tr>
<tr>
<td>2</td>
<td>3,288 6,127 3,528 3,291 4,995 3,975 5,677</td>
</tr>
<tr>
<td>3</td>
<td>364 681 391 366 553 442 632</td>
</tr>
<tr>
<td>TOTAL</td>
<td>10,981 19,637 11,674 11,181 16,707 12,650 19,170</td>
</tr>
</tbody>
</table>
Table 1 presents assumed average market demand for products. For an example, total demand from all retailers for new (QL1), remanufactured (QL2), and secondhand hand (QL3) product 1 are 7,329, 3,288, and 364, respectively (Table 1). Table 2 presents formation of modules by components and requirements of modules by a typical product. Based on Table 2 module 1 is formed by components 1, 5, 9, and 10; and product 1 needs modules 1, 3, and 11 according to Design 1 and modules 2, 5, 6 and 8 following Design 2, for example.

Table 2: Data on formation of typical modules and products

<table>
<thead>
<tr>
<th>COMPONENTS</th>
<th>MODULE 1</th>
<th>MODULE 2</th>
<th>MODULE 3</th>
<th>Module 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product 1</td>
<td>1,3,10</td>
<td>2,5,6,8</td>
<td>2,3,10</td>
<td>1,4,5,9</td>
</tr>
</tbody>
</table>

Typical cost of modules in Non-GSM era and breakups for the costs are shown in Table 3. For example total cost of module 1 has been $47.17 out of which $43.04 paid to t1 supplier as procurement cost of components 1, 5, 9 and 10 needed for making module 1 and $4.66 paid to t2 supplier for supplying the module. $4.66 in fact includes costs for manufacturing, transportation and margin for t2 supplier for supplying one unit of module 1. It may be mentioned here that in Non-GSM era each module is new (MQ1 level quality) made with new components.

Table 3: Typical cost of modules including cost breakups in non-GSM era

<table>
<thead>
<tr>
<th>MODULE 1</th>
<th>MODULE 2</th>
<th>MODULE 3</th>
<th>1 TOTAL COST OF MODULES</th>
</tr>
</thead>
<tbody>
<tr>
<td>$47.7</td>
<td>$40.54</td>
<td>$44.2</td>
<td>$43.04</td>
</tr>
<tr>
<td>$40.35</td>
<td>$37.08</td>
<td>$3.46</td>
<td>$3.85</td>
</tr>
</tbody>
</table>

Table 4 presents typical procurement and recovery cost of modules after implementing GSM. For example based on Table 4 typical procurement cost of new (MQ1 quality) modules 1, 2, and 3 are {$46.36, $38.9, and $39.13 } in GSM era compared to procurement cost of same modules in Non-GSM era, as shown in Table 3 ($47.7,$40.54, and $44.2), for example. Also cost of recovered MQ2 level modules 1, 2, and 3 are, which are almost same as new (used for remanufactured product) are ($4.94, $4.05, and $4.29). These costs are much lower than new ones. The SC has the option of procuring these recovered modules at a lower cost also when they use MQ3 quality level modules for their QL 3 level products, for example (Table 4).
Table 5 presents typical model outputs for MQ1 module requirements in non-green era. Since total market demand for product in non-green era is met by new product, MQ1 modules shown in Table 5 are the total module requirements. For an example, the model procured 20,545 units of modules 1 to fulfill production requirements to comply with the market demand for product (Table 5). Table 5 also presents Model decisions on the requirements of modules at different quality levels in Green era based on the same gross product requirements of Non-green era. This consideration may be considered logical based on the fact that overall market demand may not change for the initial years of applying GSM and other green practices. But, based on the procurement cost of MQ1 and recovery cost of MQ2, and MQ3 modules in addition to generation of harmful emissions and spent energy in realizing the modules, the model changed the design to optimize cost. For an example, the model decided to procure module 1 of quality level MQ1: 11, 472; MQ2: 4,930 and MQ3: 678 units to fulfill market demand for QL1, QL2, and QL3 products that will use module 1 with optimum cost (Table 5). The model similarly decided about other modules of different quality level to full market requirements. From customer returns the model recovered MQ2 and MQ3 quality modules through RSPs as also shown in Table 5. Based on the Table 5 the recovered MQ2 and MQ3 quality modules are higher in number in most cases and lower in two cases compared to the requirements for module types as shown in the Table. The SC managers should study such outcomes carefully and plan to establish and improve demand for their remanufactured and secondhand product in the market to utilize customer returns or they need to plan lower quantity of collections in a similar example situation. Such decisions are needed to be based on feedback from the market. Due to shortage of recovered modules in the example case for Modules 3 and 11 (see in Table 5), approximately 2% of QL 2 and 3 products could not be supplied to market in green era Model. In addition, we may observe the inventories of recovered modules that are not necessary for meeting customer demand are also generated. But contributions of GSM and other green practices, including recovery, reuse, limited recycling, and marketing of product in more than one quality levels could make overall performance of the SC superb, based on the discussion of model result on profit, revenue and cost to follow.

<table>
<thead>
<tr>
<th>MODULE REQUIREMENTS IN NON-GREEN ERA</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODULE</td>
<td>20,545</td>
<td>26,553</td>
<td>37,761</td>
<td>3,835</td>
<td>36,574</td>
<td>43,261</td>
<td>47,680</td>
<td>43,222</td>
</tr>
<tr>
<td>QUALITY LEVELS</td>
<td>11472</td>
<td>21062</td>
<td>37556</td>
<td>14525</td>
<td>10234</td>
<td>32221</td>
<td>30102</td>
<td>27401</td>
</tr>
<tr>
<td>MQ2</td>
<td>4930</td>
<td>10102</td>
<td>18445</td>
<td>7319</td>
<td>2106</td>
<td>15097</td>
<td>15329</td>
<td>12321</td>
</tr>
<tr>
<td>MQ3</td>
<td>678</td>
<td>1123</td>
<td>1916</td>
<td>946</td>
<td>360</td>
<td>1676</td>
<td>1442</td>
<td>1237</td>
</tr>
</tbody>
</table>

Table 5: Typical model results on managing Modules needed for products

| MODULE REQUIREMENTS AT QUALITY LEVELS IN GREEN ERA |
|---------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| MQ1                              | 11472 | 21062 | 37556 | 14525 | 10234 | 32221 | 30102 | 27401 |
| MQ2                              | 4930 | 10102 | 18445 | 7319 | 2106 | 15097 | 15329 | 12321 |
| MQ3                              | 678 | 1123 | 1916 | 946 | 360 | 1676 | 1442 | 1237 |

| MQ2 AND MQ3 QUALITY LEVEL MODULES RECOVERED |
|---------------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| MQ2                                         | 13805 | 12758 | 15328 | 16215 | 11504 | 15203 | 14428 | 15224 |
| MQ3                                         | 1534 | 1418 | 1703 | 1802 | 1278 | 1689 | 1603 | 1692 |

Table 6 presents the model result for SC planning at non-green era before adopting GSM and other green practices and results for green era after employing such practices. Profit in green era soared to $4.8M compared to $.67M in green era. As may be observed in Table 6 that this could be achieved even if the revenue earning have been lower by $(22.83-18.59)= $4.29M from non-green era. The revenue is lower than non-green era because a considerable
percentage (almost 50%) of product of the overall demand is sold at quality level QL2 and QL3. QL2 and QL3 products are sold at lower price than QL1 or new product.

<table>
<thead>
<tr>
<th>MODELS AT ERA</th>
<th>FIGURES IN MILLION $</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PROFIT</td>
</tr>
<tr>
<td>NON GREEN</td>
<td>0.67</td>
</tr>
<tr>
<td>GREEN</td>
<td>4.8</td>
</tr>
</tbody>
</table>

The main differences in the profit is made by improving SM cost ($9.02M compared to $9.85M), savings in penalty from spent energy ($2M compared to $9.5M ) and emission($0.24 M compared to $0.61M). Almost 50% of the components were not needed to be produced and 50% of the modules only involved recovery operation with much lower spent energy and emission than production. Green era model spent extra ($0.75M) for collecting customer returns. The model result provides several useful managerial thinking and decision challenges. Although in USA penalty for emission is not there, energy penalty considered here is basically the cost of spent energy. As such savings from energy penalty is in effect savings in energy cost at average USA per KWH energy rate for industry. The remaining amount of Total Cost not shown in Table 6 is the final production cost that involved assembling of modules for both eras. They should necessarily be almost same. This is because, assembling of modules (new or recovered) are needed to be done to realize the product at quality levels.

Based on the above analysis on model result it is clear that the model and the overall approach will facilitate SC managers to plan their GSM and reverse SC process to improve overall business sustainability in terms of profit and environmental requirements. We believe above analysis include several managerial implications.

**CONCLUSION**

The proposed model will facilitate SC managers to plan and integrate their GSM process with overall SC planning to improve their profit and environmental performances. By including reverse SC and other GSM practices, the business will establish their image in the market. Marketing new and remanufactured products including offering of secondhand product will provide options to the customers for selecting products at different quality levels with price differences. It will not only increase revenue, it will also increase customer base or market share in real sense. GSM practices will make the business sustainable and create prospects for their continuous future market growth. In addition to the discussed managerial implications in applying proposed business and green performance improvement steps, the research and the model includes state of the art options to include and exclude business and green practices based on unique business of a company. Such options will provide what-if analysis based decision scopes to the businesses in general.
APPENDIX

Notations

Note on green or non-green era is included where necessary.

- \( p \in P \): product, \( p \in P^{\text{nw}} \) for green era; \( p' \in P \) customer returned product;
- \( p \in P^{m} \): remanufactured product; \( p^* \in P^{\text{sc}} \) second hand product; \( P^{m} \cup P^{\text{nw}} \cup P^{\text{sc}} \): customer returns do not have a quality level.
- \( v \in V \): recovery service provider (RSP)
- \( d \in D \): design
- \( DR_{pr} \): demand for product \( p \) from retailer \( r \)
- \( AC_{pdj} \): assembly cost of product \( p \) of design \( d \) in plant \( j \)
- \( GAC_{pdqj} \): assembly cost of product \( p \) of design \( d \) at quality level \( q \) in plant \( j \)
- \( FAS_{pj} \): fixed assembly set up cost for product \( p \) in plant \( j \)
- \( u_{pj} \): 1 if product \( p \) is assigned to plant \( j \), 0 otherwise
- \( y_{pj} \): product \( p \) supplied from plant \( j \) to retailer \( r \)
- \( x_{pdj} \): realization of product \( p \) of design \( d \) in SC plant \( j \) in non-green era
- \( g_{x_{pdj}} \): realization of product \( p \) of design \( d \) at quality level \( q \) in SC plant \( j \) in green era
- \( gu_{pj} \): 1 if product \( p \) is assigned to plant \( j \), 0 otherwise
- \( DC_{pj} \): cost for distributing product from plant \( j \) to \( r \)
- \( gy_{x_{pdqj}} \): product \( p \) of quality level \( q \) supplied from plant \( j \) to retailer \( r \)
- \( p_{\text{mpd}} \): usage of module \( m \) by product \( p \) of design \( d \)
- \( CN_{mi} \): component \( i \) usage for module \( m \)
- \( tmd_{m} \): total number of modules \( m \) needed to fulfill production requirements in non-green SC
- \( a_{d_{p}} \): 1, if design \( d \) is selected for product \( p \); 0 otherwise
- \( tz_{ms}^" \): modules manufactured by t2 supplier \( s" \) \( \in S; s' \in S' \); \( S' \subseteq S \)
- \( c_{ms}^" \): 1, if module \( m \) is assigned to t2 supplier \( s" \); 0 otherwise
- \( CM_{ms}^" \): capacity of t2 supplier \( s" \) for producing module \( m \);
- \( b_{is}^" \): 1, if component \( i \) is assigned to t1 supplier \( s' \); 0 otherwise; \( s' \in S; s' \in S; S' \subseteq S \)
- \( PJ_{is}^" \): MJ's of energy for producing input \( i \) by the process followed by t1 supplier \( s' \)
- \( PE_{is}^" \): harmful emission in Kgs of equivalent CO\(_2\) for producing input \( i \) by t1 supplier \( s' \)
- \( PM_{ms}^" \): energy in MJ's for producing module \( m \) by the process followed by t2 supplier \( s" \)
- \( EM_{ms}^" \): harmful emission in Kgs of equivalent CO\(_2\) for producing module \( m \) by the process followed by t2 supplier \( s" \)
- \( AJ_{pdj} \): spent energy for assembling product \( p \) of design \( d \) in plant \( j \)
- \( AE_{pdj} \): generation of harmful emission for assembling product \( p \) of design \( d \) in plant \( j \)
- \( DS_{jr} \): distance between plant \( j \) and retailer \( r \)
- \( DT_{s'j} \): transportation distance for supplying module from t2 supplier \( v \) to SC plant \( j \)
- \( TRL_{m} \): amount of module \( m \) for one truck load
- \( TPR_{p} \): amount of module \( p \) for one truck load
- \( SDE \): standard MJ for per mile truck transportation
- \( SHE \): standard harmful emission in equivalent Kgs of CO\(_2\) for per mile truck transportation
- \( SP_{C_{is}}^" \): cost of purchasing component \( i \) (in standardized packaging) from t1 supplier \( s' \)
- \( FS_{is}^" \): fixed cost for ordering input \( i \) to t1 supplier \( s' \)
- \( SVC_{ms}^" \): assembling cost of module \( m \) (including standard packaging) by t2 supplier \( s" \)
- \( FV_{ms}^" \): fixed ordering cost for module \( m \) to t2 supplier \( s" \)
- \( TRC_{is_{j}} \): transportation cost to supply component \( i \) from \( s' \) to SC plant \( j \)
- \( CJ_{is} \): spent energy in KJ for producing input \( i \) by the process followed by supplier \( s \)
MJ_{ms} : spent energy in KJ for producing module \( m \) using the process followed by supplier \( s \)

RVJ_{mvl} : spent energy in KJ for recovering module \( m \) at quality level \( l \) by RSP \( v \)

RCJ_{vc} : spent energy in KJ for obtaining recycled materials \( c \) through RSP \( v \)

DSM_{sj} : travelling distance between supplier \( s \) and plant \( j \)

CE_{is} : harmful emission in Kgs of equivalent CO\(_2\) for producing input \( i \) using the process followed by supplier \( s \)

SS_{sj} : distance between t1 supplier \( s' \) and SC plant \( j \)

ME_{ms} : harmful emission in Kgs of equivalent CO\(_2\) for producing module \( m \) by the process followed by supplier \( s \)

RVE_{mvl} : harmful emission in Kgs of equivalent CO\(_2\) for recovering module \( m \) at quality level \( l \) by RSP \( v \)

RCE_{vc} : harmful emission in Kgs of equivalent CO\(_2\) for obtaining recycled materials \( c \) through RSP \( v \)

e_{x_{mv}} : unusable modules \( m \) generated from recovery process at RSP’s place

gm_{ml} : module \( m \) at quality level \( l \)

gm_{m} : module \( m \) recovered by RSP \( v \) at quality level \( l \)

gs_{ms} : new module \( m \) assigned to supplier \( s \)

GSVC_{ms} : cost of module \( m \) by green supplier \( s \). It includes realization cost of components needed for the module without any packaging plus assembling cost of the module without packaging), \( GSVC_{ms} \leq SVC_{ms} + SPC_{is} + TRC_{is}'s \)

GCA_{is} : capacity of supplier \( s \) for manufacturing components \( c \)

gs_{ms} : 1, module \( m \) assigned to supplier \( s \); 0 otherwise

gz_{is} : component \( i \) manufactured/used by supplier \( s \)

e_{io} : 1, if component \( i \) is processed following process plan \( o \), 0 otherwise

rcm_{vm} : module \( m \) to be recycled by \( v \)

sm_{vc} : extracted saleable material \( c \) obtained from recycling by RSP \( v \)

RR_{vc} : cost of saleable material \( c \) obtained from recycling process by RSP \( v \)

PR_{mc} : maximum obtainable saleable material \( c \) from module \( m \)

M_{gs} : manufacturing capacity of supplier \( s \) for component \( i \) under process plan \( o \)

RE_{pt} : proportion of the possible returns for product \( p \) that customer may return at scenario \( t \) for an incentive

PR_{t} : probability of scenario \( t \) for the incentive

CLC_{pr} : collection cost of returns for product \( p \) by retailer \( r \). It includes personnel and management costs for collecting, keeping in storage, accounting, sorting, converting to equivalent product, incentive cost per equivalent product; and services charge to retailer.

Incentive cost is paid to retailer based on a detailed agreement such that retailer implies implement incentive plan effectively to motivate customer returns.

es_{pr} : estimated customer returns for product \( p \) to retailer \( r \)

dr_{pqr} : average demand for product \( p \) for quality level \( q \) from retailer \( r \)

dv_{pqv} : estimated demand for product \( p \) for second hand quality \( q \) from RSP \( v \)

al_{ipv} : allocated customer returned product \( p \) to RSP \( v \)

PS : possible return % assumed or considered by management to allocate return management resources. If estimated life of product is three years, PS for end of use returns may be U(25,40) percentage of product demand. This is because some customer return earlier than 3 years and some return after 3 years.

rc_{r} : 1; if SC has a contract with retailer \( r \) to collect returns; 0 otherwise

va_{rv} : 1; if RSP \( v \) is assigned recovery work, 0 otherwise.

GFS_{ms} : fixed set up cost for green supplier \( s \) to realize \( m \)
Das & Rahman  Green supply management in supply chain planning

$GTR_{msj}$: transportation cost for module $m$ from supplier $s$ to SC plant $j$

$GFR_{r}$: fixed cost for contractual arrangement to collect returns through retailer $r$

$FCV_v$: fixed cost for RSP $v$ to set up recovery process (considered same for each product).

$FRC_m$: fixed cost for arrangement for sorting module $m$ for recycling and installation of recycling process.

$CRV_{mvl}$: recovery cost of module $m$ at quality level $l$ by RSP $v$

$TVL_{muj}$: transportation cost module for $m$ from RSP $v$ to SC plant $j$

$TRV_{rvp}$: transportation cost for customer returned

REFERENCES


