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A goal programming model for paper recycling system☆

Rupesh Kumar Pati[a], Prem Vrat[b], Pradeep Kumar[c,*]

[a]PPEG, SHAR Centre, Indian Space Research Organisation, Sriharikota, Nellore, Andhra Pradesh-524124, India
[b]Indian Institute of Technology Roorkee, Roorkee, Uttaranchal- 247667, India
[c]Mechanical and Industrial Engineering Department, Indian Institute of Technology Roorkee, Roorkee, Uttaranchal-247667, India

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Abstract

The conflict between economic optimization and environmental protection has received wide attention in recent research programs for waste management system planning. This has also resulted in a set of new waste management goals in reverse logistics system planning. The purpose of this analysis is to formulate a mixed integer goal programming (MIGP) model to assist in proper management of the paper recycling logistics system. The model studies the inter-relationship between multiple objectives (with changing priorities) of a recycled paper distribution network. The objectives considered are reduction in reverse logistics cost; product quality improvement through increased segregation at the source; and environmental benefits through increased wastepaper recovery. The proposed model also assists in determining the facility location, route and flow of different varieties of recyclable wastepaper in the multi-item, multi-echelon and multi-facility decision making framework. The use of the model has been illustrated through a problem of paper recycling in India.

Keywords: Environmental studies; Mixed integer goal programming; Multicriteria; Reverse logistics; Paper recycling

1. Introduction

Sustainable development is emerging as a dominant paradigm that is likely to play an important role in the design of any societal and economical policies. According to Petek et al. [1], there are three main requirements for sustainable development: resource conservation, environmental protection, and social as well as economic development. Reverse logistics concept of a supply chain provides the best strategy to reduce and reutilize waste.

In the past, various deterministic mathematical programming models have been used for planning waste management systems. The spectrum of these techniques includes linear programming (LP) [2,3], Mixed integer programming (MIP) [4,5]. Chang et al. [6,7] and Chang and Wang [8,9] combined the effects of the environmental impacts, such as air pollution, noise control and traffic congestion, as a set of risk constraint in an economic-oriented locational model for the solid waste management systems.

Goal programming (GP), proposed by Charnes et al. [10], is most widely used approach within the multi-criteria decision-making (MCDM). It attempts to combine the logic of optimization in mathematical programming with the

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* Corresponding author. Tel.: +91 1332 285602; fax: +91 1332 285665, +91 1332 273560.

E-mail addresses: rupesh_pati@rediffmail.com (R.K. Pati), director@iitr.ernet.in (P. Vrat), kumarfme@iitr.ernet.in (P. Kumar).

decision maker's desire to satisfy several goals. Carlson [11] and Chang [12] used weighted non-linear goal programming to discuss the economic impacts of material recycling on energy recovery facilities. Perlack and Willis [13] further presented the analysis of multi-objective decision making in waste disposal planning. Chang and Wang [14,15] applied the compromise programming and goal programming techniques to ease the potential conflict among land filling, incineration, and recycling in a growing metropolitan region. Short-term planning of vehicle routing and scheduling problems would be a valuable subsequent analysis after the completion of long-term regional planning for solid waste management [16,17].

2. Background information of Indian paper industry

The paper industry is one of the key industrial sectors in India. However, the domestic per capita consumption of paper and board in the country is very low at 6 kilograms (kg) compared to South Asian and world average of 11 and 53 kg, respectively [18]. The pulp and paper industry in India has a tremendous growth potential, which is currently estimated at 8% per annum. But with the existing resources, Nagwekar [18] have projected a shortage of about 0.7 million tonnes per annum by 2010.

At present several problems impede the future growth prospects of Indian paper industry [19]. These are: (i) increase in literacy rates, rapidly growing urbanization and increasing economic growth put tremendous pressure on the limited resources available, (ii) lack of raw material viz. wood; as forest cover is not an abundant resource in India. In 1993 only 19.5% of the total land surface was covered with forest. This forest cover is decreasing rapidly at an annual rate of 0.6%, (iii) low productivity of Indian forests, i.e. Indian forests grow at maximum rate of 0.5 m^3 per hectare as compared to 2.5 m^3 per hectare in Europe and USA, (iv) energy consumption is relatively higher than the international standard, due to interruptions in production, poor quality of fuel and equipment and relatively low rate of utilization of wastepaper in the production.

The study on physical composition municipal solid waste collected in some of the Indian cities by Kumar et al. [20] reveals that the proportion of plastic and paper in waste generated are very significant and needs immediate attention in order to reduce environmental pollutants. Recycling provides a better option to reduce paper and plastics wastes. However, the inherent complexity of various priorities in wastepaper recycling system like waste composition (or segregation at source), waste recovery quantity and the total relevant reverse logistics cost may cause additional difficulties in decision making. While the task of manufacturing recycled paper at a lower reverse logistics costs may be an important objective, trade-offs among quality of recycled paper, wastepaper recovery as a social responsibility and other factors may need to be incorporated in an optimization process. GP was found to be an efficient tool for such an analysis compared to other mathematical programming techniques. A mixed integer goal programming (MIGP) model has been proposed for a reverse distribution network facility location problem. The model can be used in the analysis of tradeoff between the achievements of goals in different combinatorial strategies.

3. Formulation of MCDM model for paper recycling distribution network

The reverse distribution network for the wastepaper recycling is shown in Fig. 1. There are five entities in the network i.e. vendor–customer (initial source of wastepaper), dealer, godown owner, supplier and the manufacturer. Vendor–customer represents a bin or collection area where the end user of the finished paper/paper products can assemble the paper for recycling after its use. Dealer collects the wastepaper (which contains the mixture of relevant and non-relevant waste) from vendor–customers and supplies it to the godown owner stage, where the segregation for relevant wastepaper occurs. The supplier collects the relevant wastepaper for recycling from the godown owner and supplies it to the final customer of the reverse distribution network, i.e. the recycling plant/manufacturer. At each echelon of the network, numbers of sub-stages/sub-entities exist. The direction of the material flow in the entire network can be seen in Fig. 1.

Based on the requirements of the paper recycling distribution network, the goal programming model consists of three objectives/goals. These are explained below:

1. *Reverse logistics cost*: From the manufacturer's point of view, it is essential that there is no overrun of the logistics cost associated with recovery of recyclable wastepaper from various possible sources. Hence the objective is to

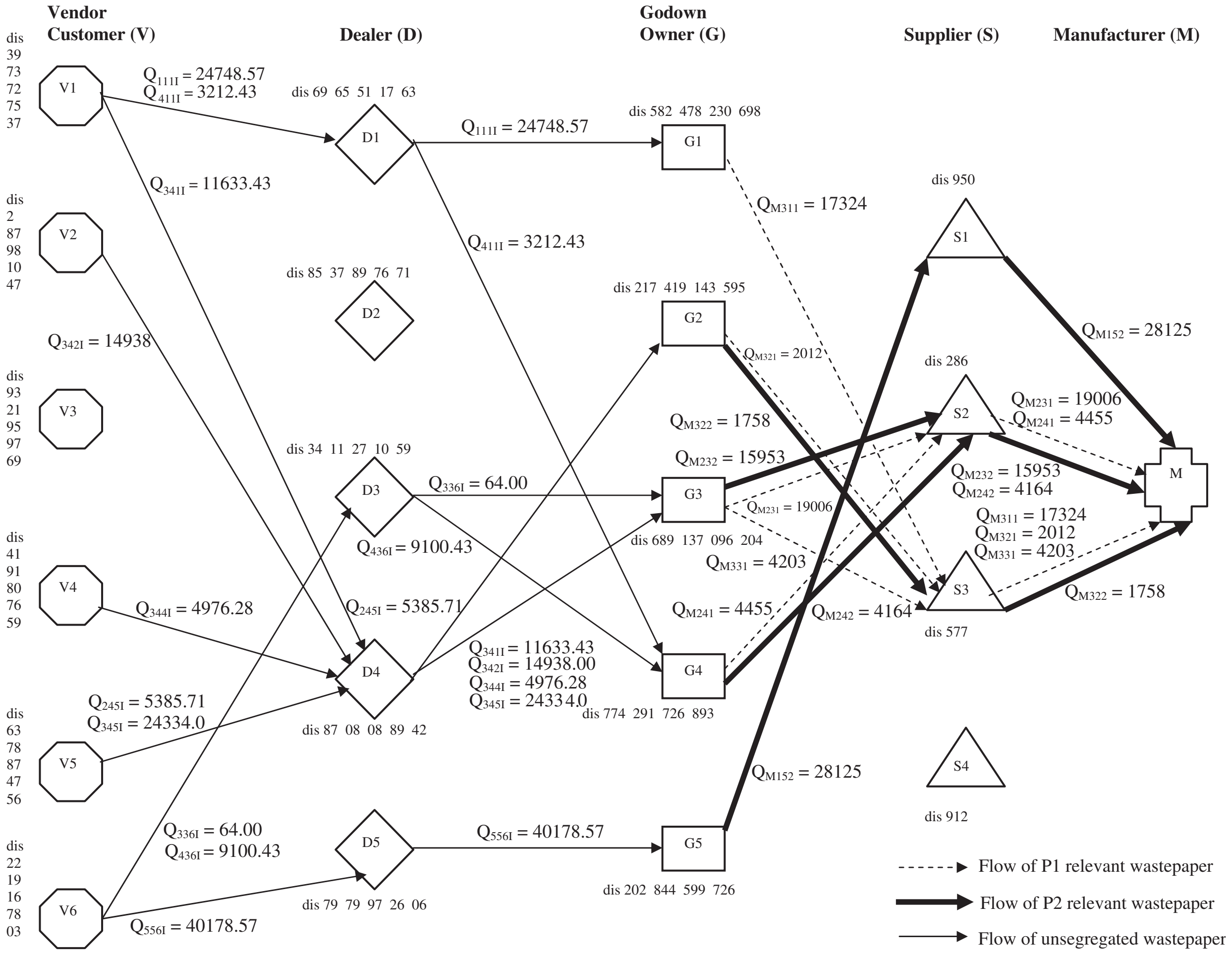

Fig. 1. Reverse logistics distribution network for paper recycling problem with 'CNW' priority structure * the distance (in kilometers) between the sub-entities of successive stages are given along with notation 'dis' and the quantities of material flow in the represented over the lines in tonnes.

minimize the reverse logistics cost i.e. $(RL)_c$. The corresponding goal is stated as: minimize the positive deviation from the planned budget allocated for reverse logistics activities (d_c^+) (Eq. (2)).

2. *Non-relevant wastepaper target*: The quality of the recycled paper can be improved to certain extent by the separation of the lower grade (non-relevant) of wastepaper at the source (i.e. vendor–customer stage). The objective may therefore be stated as, minimizing the quantity of non-relevant wastepaper in the reverse distribution network. The corresponding goal is stated as: minimize the positive deviation from the maximum limit of non-relevant wastepaper target (d_q^+) (Eq. (3)).
3. *Wastepaper recovery target:* The recycling of the paper consumes less energy; conserves the natural resources viz. wood pulp and decreases the environmental pollution. Hence, the objective of a recycled paper manufacturer should be to maximize the wastepaper collection at the source. In order to encourage the wastepaper recovery at the source, the goal may be stated as: minimize the negative deviation from the minimum desired waste collection (d_e^-) (Eq. (4)).

Therefore, the proposed MIGP model can be formulated as given in Eqs. (1)–(27). The notations used in the model are listed in Appendix A.

$$\text{Lexicographically minimize: } \{d_c^+, d_q^+, d_e^-\} \tag{1}$$

Subject to:

$$\left.(RL)_c + d_c^- - d_c^+ = T_{\text{RLC}}\right\} \begin{array}{l}\text{reverse logistics}\\ \text{cost constraint,}\end{array} \qquad (2)$$

$$\left.\sum_g \sum_d \sum_v Q_{gdvI} - \sum_s \sum_g \sum_p Q_{Msgp} + d_q^- - d_q^+ = W_A\right\} \begin{array}{l}\text{non relevant}\\ \text{wastepaper target,}\end{array} \qquad (3)$$

$$\left.\sum_g \sum_d \sum_v Q_{gdvI} + d_e^- - d_e^+ = C_T\right\} \begin{array}{l}\text{wastepaper}\\ \text{recovery target,}\end{array} \qquad (4)$$

$$\left.\sum_s \sum_g Q_{Msgp} \geqslant D_p \quad \forall s, g, p\right\} \begin{array}{l}\text{manufacturer' s demand}\\ \text{satisfaction for product`}p\text{',}\end{array} \qquad (5)$$

$$\left.\sum_d \sum_v Q_{gdvI} * (1-w) = \sum_s \sum_p Q_{Msgp} \quad \forall g\right\} \begin{array}{l}\text{godown owner' s demand}\\ \text{satisfaction for product`}p\text{',}\end{array} \qquad (6)$$

$$\left.\begin{array}{ll}\sum_g \sum_v Q_{gdvI} \leqslant T_{dI} * \alpha_d & \forall d\\ \sum_s Q_{Msgp} \leqslant T_{gp} * \gamma_g & \forall g, p\\ \sum_g Q_{Msgp} \leqslant T_{sp} * \phi_s & \forall s, p\end{array}\right\} \begin{array}{l}\text{annual throughput}\\ \text{constraint,}\end{array} \qquad (7,8,9)$$

$$\left.\sum_g \sum_d Q_{gdvI} \leqslant (SUP)_v * \pi_v \quad \forall v\right\} \begin{array}{l}\text{supply capacity constraint}\\ \text{of vendor customer,}\end{array} \qquad (10)$$

$$\left.\begin{array}{ll}Q_{Msgp} \leqslant B_{Msgp} * \psi_{psg} & \forall s, g, p\\ Q_{Msgp} \leqslant B_{Msgp} * \chi_{pMs} & \forall s, g, p\end{array}\right\} \begin{array}{l}\text{route capacity constraint}\\ \text{after segregation,}\end{array} \qquad (11,12)$$

$$\left.\begin{array}{ll}Q_{gdvI} \leqslant B_{gdvI} * \beta_{Idv} & \forall g, d, v\\ Q_{gdvI} \leqslant B_{gdvI} * \delta_{Igd} & \forall g, d, v\end{array}\right\} \begin{array}{l}\text{route capacity constraint}\\ \text{before segregation,}\end{array} \qquad (13,14)$$

$$\left.\begin{array}{l}\sum_d \alpha_d \leqslant O_d\\ \sum_g \gamma_g \leqslant O_g\end{array}\right\} \begin{array}{l}\text{limits on the number of}\\ \text{open dealers and godown}\\ \text{owners,}\end{array} \qquad (15,16)$$

$$\left.\begin{array}{l}\sum_s \phi_s \leqslant O_s\\ \sum_v \pi_v \leqslant O_v\end{array}\right\} \begin{array}{l}\text{limits on the number of}\\ \text{open suppliers and vendor}\\ \text{customers,}\end{array} \qquad (17,18)$$

$$\left.\begin{array}{l}\sum_d \sum_v \beta_{Idv} \leqslant O_{dv}\\ \sum_g \sum_d \delta_{Igd} \leqslant O_{gd}\end{array}\right\} \begin{array}{l}\text{limits on number}\\ \text{of open routes of}\\ \text{the system,}\end{array} \qquad (19,20)$$

$$\left.\begin{array}{ll}\sum_s \sum_g \psi_{psg} \leqslant O_{sgp} & \forall p \\ \sum_s \chi_{pMs} \leqslant O_{Msp} & \forall p\end{array}\right\} \begin{array}{l}\text{limits on number}\\ \text{of open routes of}\\ \text{the system,}\end{array} \tag{21,22}$$

$$\left.\begin{array}{l}\beta_{Idv} \in \{0,1\};\ \delta_{Igd} \in \{0,1\};\ \psi_{psg} \in \{0,1\};\ \chi_{pMs} \in \{0,1\}; \\ \alpha_d \in \{0,1\};\ \gamma_g \in \{0,1\};\ \phi_s \in \{0,1\};\ \pi_v \in \{0,1\}\end{array}\right\} \text{integrality constraint,} \tag{23}$$

$$\left.\begin{array}{ll}Q_{gdvI} \geqslant 0 & \forall g, d, v \\ Q_{Msgp} \geqslant 0 & \forall g, s, p \\ & d_c^+, d_c^-, d_q^+, d_q^-, d_e^+, d_e^- \geqslant 0\end{array}\right\} \text{non-negativityconstraint,} \tag{24,25}$$

$$\left. d_c^{+*}d_c^- = 0;\ d_q^{+*}d_q^- = 0;\ d_e^{+*}d_e^- = 0 \right\} \begin{array}{l}\text{complementary}\\ \text{constraints.}\end{array} \tag{27}$$

In the model, the structural constraints (5), (6) ensure that the demand for 'pth' variety of recyclable wastepaper and unsegregated wastepaper are satisfied at the manufacturer 'M' and godown owner 'g', respectively. At the godown owner stage the effect of proportion of non-relevant wastepaper (w) accompanying the unsegregated wastepaper has also been considered. The presence of non-relevant/undesired wastepaper adversely affects the quality of recycled paper. The limit on the annual throughput for dealer 'd', godown owner 'g' and supplier 's' are imposed by constraints (7)–(9). Restriction on the supply capacity for the source/vendor–customer 'v' is imposed by constraint (10). Supply capacity of source, largely depends on the population and recycling habit of members of the society residing in the area under consideration. Constraints (11)–(14) describe the route capacity limit on movement of wastepaper in a particular route from source (vendor–customer 'v') to godown owner 'g' as well as from godown owner 'g' to manufacturer 'M'. Route capacity depends on the mode of transportation, frequency of transportation and capacity at source/godown owner. Constraints (15)–(18), limit the number of dealers, godown owners, suppliers and vendor–customers that can remain open. Restrictions on the number of open routes between source-dealer, dealer-godown owner, godown owner-supplier and finally supplier-manufacturer are laid down by constraints (19)–(22), respectively. Set of integrality restrictions for decision variables $\beta_{Idv}, \delta_{Igd}, \psi_{psg}, \chi_{pMs}, \alpha_d, \gamma_g, \phi_s, \pi_v$ is imposed by constraint (23) while constraints (24)–(26) impose non-negativity restriction on the decision variables $\mathrm{Q}_{gdvI}, \mathrm{Q}_{Msgp}$ and the deviational variables $d_c^+, d_c^-, d_q^+, d_q^-, d_e^+, d_e^-$. Finally, the complementary constraints imposed by the deviational variables are shown in Eq. (27).

A sub-model to represent the total reverse logistics cost for paper recycling is required to support the effective operation of the above optimization model. The total reverse logistics cost comprises of all relevant logistics cost incurred for the collection and distribution of the wastepaper from source (vendor–customer) to the ultimate stage in reverse network i.e. recycling unit/manufacturer stage. It has been assumed in this formulation that the collection as well as ordering at various facilities follows the fixed period ordering/collection principle Appendix B describes the components of the reverse logistics cost. The expression for the total reverse logistics cost of paper recycling distribution network is given as

$$\begin{aligned}\text{Total reverse logistics costs} &= (RL)_c \\ &= \left\{\left[\sum_d \sum_v \frac{C_{Cdv}}{t_{dv}} * \beta_{Idv}\right] + \left[\sum_v F_v^c * \pi_v\right] + \left[\sum_g \sum_d \sum_v \frac{1}{2} * (\%S_d) * C_I * Q_{gdvI}\right]\right. \\ &\quad \left. + \left[\sum_g \sum_d \sum_v T_{gdvI} * l_{gdv} * Q_{gdvI}\right] + \left[\sum_d F_d^c * \alpha_d\right]\right\} + \left\{\left[\sum_g \sum_d \frac{C_{Ogd}}{t_{gd}} * \delta_{Igd}\right]\right.\end{aligned}$$

$$
\begin{aligned}
&+\left[\sum_{s}\sum_{g}\sum_{p} S_{gp} * Q_{Msgp}\right] + \left[\sum_{g}\sum_{d}\sum_{v} D_{g} * w * Q_{gdvI}\right] \\
&+\left[\sum_{s}\sum_{g}\sum_{p} \frac{1}{2} * (\%S_{pg}) * C_{p} * Q_{Msgp}\right] + \left[\sum_{g} F_{g}^{c} * \gamma_{g}\right]\Bigg\} \\
&+\Bigg\{\left[\sum_{s}\sum_{g}\sum_{p} \frac{C_{Osgp}}{t_{sgp}} * \psi_{psg}\right] + \left[\sum_{s} F_{s}^{c} * \phi_{s}\right] x + \left[\sum_{s}\sum_{g}\sum_{p} T_{Msgp} * l_{Msg} * Q_{Msgp}\right] \\
&+\left[\sum_{s}\sum_{g}\sum_{p} \frac{1}{2} * (\%S_{ps}) * C_{p} * Q_{Msgp}\right] + \left[\sum_{s}\sum_{p} \frac{C_{OMsp}}{t_{Msp}} * \chi_{pMs}\right]\Bigg\}. \qquad (28)
\end{aligned}
$$

GP has the ability to produce Pareto inefficient or dominated solution. In the case of integer GP an objective is Pareto inefficient if a different integer solution can be found that improves the objective without degrading the value of any other objective. If no such point exists, then that objective is termed as Pareto efficient. Tamiz et al. [21] proposed Pareto efficiency detection and restoration techniques for integer goal programming. Hence, after solving the above MIGP problem, the Pareto optimality/efficiency status of the solution is detected by constructing a new achievement function from the non-weighted deviational variables. The objective of the new achievement function is to maximize the sum of deviational variables which are not present in the achievement function of the MIGP problem i.e. maximize $\{d_c^-, d_q^-, d_e^+\}$, and subject to the same set of constraints i.e. constraints (2)–(27). The new solution is then compared with the initial optimal solution and the objective are then given the relevant Pareto status.

4. Implementation of model and solution procedure

Using the three objectives of the MIGP model, a set of six priority structures can be constructed. Hence, following priority structures are considered for the purpose of this study: CNW, CWN, WCN, WNC, NWC, and NCW. Where, the position of the characters (C, W, N) in the sequence indicates the priority assigned to reverse logistics cost, waste recovery and non-relevant waste goals, respectively. The analysis of the priority structures will assist policy makers to understand the effect of target values of individual goals on the system behavior and also guide the managers in deciding the best priority structure for their reverse distribution network under the given condition. The priority structure mentioned appears to capture the interrelationship among the goals of various actors involved in the paper recycling system.

The model developed in this paper has been illustrated through a 'real world' problem. The cost data were approximated from a survey conducted by authors on paper recycling units in India, which has a considerable number of small and large-scale paper recycling plants. It is assumed that the manufacturer has demands for two varieties of wastepaper (relevant) from the reverse logistics network for recycling. Annual demands for the two varieties $P1$, $P2$ are 50 000 tonnes (T) and 47 000 tonnes (T), respectively. It is estimated that a sum of Indian rupees (INR) one thousand (10^3) millions is the total reverse logistics cost (T_{RLC}) available for varieties $P1$ and $P2$. The minimum desired annual target waste recovery/collection (C_T) at the source is 150 000 tonnes (T), whereas, the maximum limit of non-relevant wastepaper in reverse network is 15 000 tonnes (T). The model assumes that the degree of segregation at the source is 70% i.e. percentage of non-relevant waste reaching godown owner stage is 30% ($w = 30\%$). The number of available sub-entities for the source/vendor–customer, dealer, godown owner and supplier are six ($V1, V2 \ldots V6$), five ($D1, D2 \ldots D5$), five ($G1, G2 \ldots G5$) and four ($S1, S2 \ldots S4$), respectively. Other parameters required for solving the problem were generated from the random number table to capture the wide range of problem structure. To solve the optimization problem LINDO-32 (version 6.1) software has been used. The solution procedure entails the partitioning of the objective function according to the priority levels and the sequential solution of the resultant mixed integer linear programming models. The solution obtained at each priority levels is used as a constraint at the lower level. The example discussed here is intended to serve as an illustration for applicability of the model to a practical sized problem.

The results of the MIGP reverse logistics problem formulated with priority structure 'CNW' and solved by LINDO-32 (version 6.1) are depicted in Fig. 1. The sub-entities that should be opened or closed for 'CNW' priority structure are represented in Fig. 1 along with the associated path and quantity of flow for different varieties of papers. For the given problem with 'CNW' priority, vendor–customer $V3$, dealer $D2$ and supplier $S4$ are not essential for wastepaper distri-

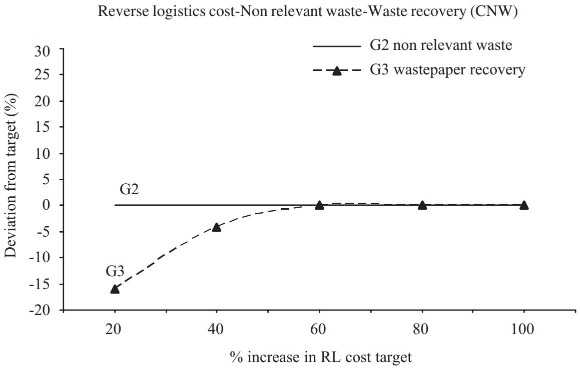

Fig. 2. Effect of target reverse logistics cost (T_{RLC}) with priority structure 'CNW'.

bution; hence these sub-entities should be closed. The solid lines represent the flow of unsegregated wastepaper between the vendor–customer (V) and godown–owner (G) stage. The dotted lines and bold solid lines respectively denotes the flow of segregated $P1$ and $P2$ relevant wastepaper from the godown–owner (G) stage to the manufacturer stage for recycling. The quantities of the flow of wastepaper between the entities are represented over the above mentioned lines in Fig. 1. In order to check the Pareto efficiency of the solutions generated by the MIGP model, Pareto detection techniques was applied on the model with 'CNW' priority structure by using LINDO-32 (version 6.1) As no other integer points could be found in the feasible dominating area i.e. the pareto state of the three objectives was found to be efficient, and hence the optimum MIGP point/solution is classified as Pareto efficient. Similarly, the reverse logistics network design with other priority structures has been carried out using the proposed MIGP model and the objectives are found to be Pareto efficient.

5. Results and discussions

Application of the proposed MIGP model to analyze the inter-relationships among the various goals of paper recycling system resulted in the following observations.

5.1. Resource requirements

It is observed that for the priority structure 'CNW', where segregation at source (non-relevant wastepaper target) is given a higher priority compared to the wastepaper recovery, achievement of latter goal is improved for reverse logistics cost levels greater than the target value. With a minimum of 60% increase in reverse logistics cost target (T_{RLC}) all the desired goals can be achieved (Fig. 2). Increase in T_{RLC} improves the recovery of wastepaper from the source due to availability of additional resources for collection/recovery.

On the other hand, if the reverse logistics cost is increased by 50% for the priority structure 'CWN' all the goals can be achieved. Prior to 50% increase in T_{RLC}, substantial deviation form non-relevant wastepaper target is observed (Fig. 3). This decreases the quality of recycled paper. Increase in T_{RLC} facilitates increased segregation at the source and hence the amount of non-relevant wastepaper decreases to an acceptable quantity. The comparison of the two priority structures (CNW and CWN) confirms that an increase in target reverse logistics cost (minimum 60%) is necessary for fulfilling the decision maker's desire to satisfy the three stated goals irrespective of the priority of non-relevant and wastepaper recovery goals. This will indirectly benefit the environment as well as improve the quality of wastepaper reaching the recycling unit.

5.2. Impact of wastepaper recovery at source

The sensitivity analysis with the priority structure 'WCN' reveals the effect of change in wastepaper recovery target on the reverse logistics cost as well as non-relevant wastepaper goals. With the increase in wastepaper recovery target

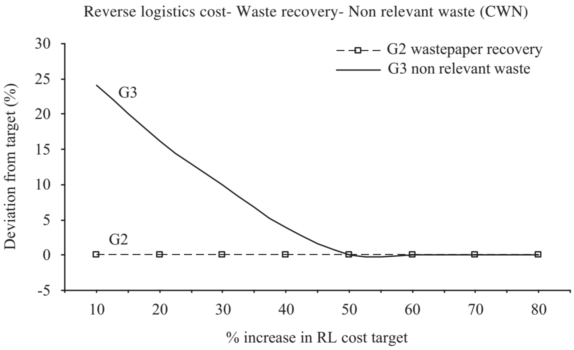

Fig. 3. Effect of target reverse logistics cost (T_{RLC}) with priority structure 'CWN'.

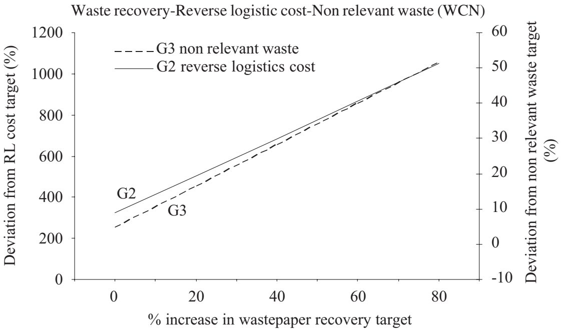

Fig. 4. Effect of wastepaper recovery target (C_T) with priority structure 'WCN'.

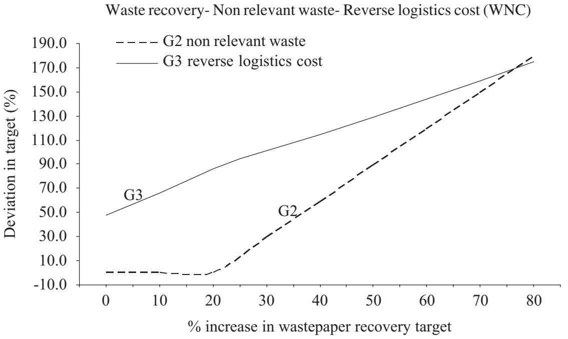

Fig. 5. Effect of wastepaper recovery target (C_T) with priority structure 'WNC'.

(C_{T}), steep increase in T_{RLC} and W_{A} was observed. Both the goals were overachieved (Fig. 4). The increase in the reverse logistics cost could be attributed to the increase in collection, transportation, inventory, segregation and the disposal costs.

In contrast, 'WNC' priority structure (Fig. 5) with non-relevant wastepaper goal given higher priority compared to the reverse logistics cost goal, overachievement of the prior goal is observed after 20% increase in the wastepaper recovery target. The reverse logistics cost goal is always overachieved with the increase in waste recovery due to increase in collection, transportation, inventory, segregation and the disposal costs. In both the cases the overachievement of the non-relevant wastepaper goal is attributed to the increased quantity of non-relevant wastepaper accompanying the wastepaper recovered at the source. The implication of the analysis for wastepaper recovery at the source signifies that a recycling unit with prime concern for social and environmental benefit approach has to invest an increased amount in reverse logistics activities—may be as a premium for their social concern.

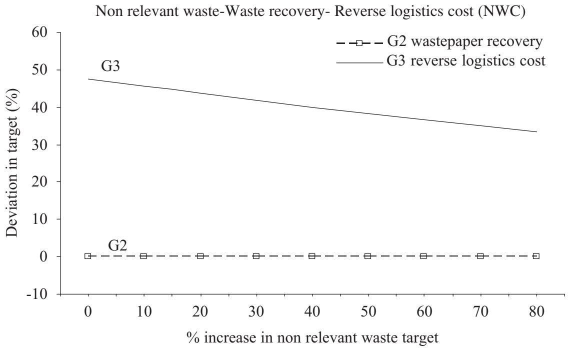

Fig. 6. Effect of decreased segregation (increased non-relevant waste target) with priority structure ‘NWC’.

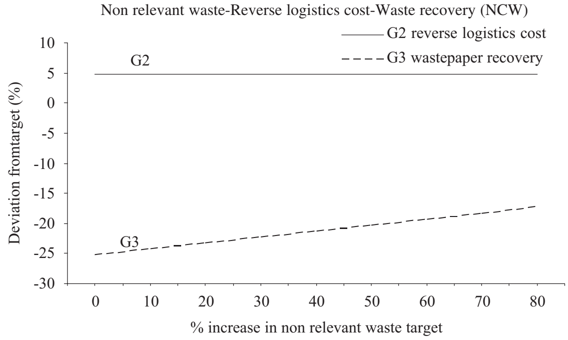

Fig. 7. Effect of decreased segregation (increased non-relevant waste target) with priority structure ‘NCW’.

5.3. *Effect of degree of segregation at the source*

Decrease in the degree of segregation at the source increases the proportion of non-relevant wastepaper reaching the godown owner stage. It is observed that for priority structure ‘NWC’ (giving wastepaper recovery a higher priority compared to reverse logistics cost) overachievement of the reverse logistics cost decreases with increase in the non-relevant wastepaper target value (Fig. 6). This decrease is due to the reduced cost of segregation at the source. On the other hand, improvement in wastepaper recovery goal with decrease in degree of segregation at the source is observed for the priority structure ‘NCW’ (Fig. 7). Thus, it is observed that source separation could provide good quality recyclables to the recycling industry but could also strongly effect the reverse logistics cost (for ‘NWC’) and waste recovery (for ‘NCW’) goals of the system.

6. Conclusion

Substantial quantities of wastes (recyclable and non-recyclable) are generated every day in the modern era leading to increase in environmental pollution level. Considerable effort should be directed towards decreasing the environmental load by recycling. But, multiple goals with appropriate priority structure must be taken into consideration when planning the recycling network system.

A mixed integer goal programming (MIGP) model proposed in this paper appears to capture the inter-relationships among the three most important goals identified in the context of paper recycling network system. The goals considered in the model have economical, social as well as quality implications on the paper recycling industry. The model can be used to address many of the problems and issues associated with the management of recycling distribution system such as the need to increase reverse logistics cost for achievement of good quality recyclables by better segregation at source and benefiting environment through increased wastepaper recovery. The proposed model also assists in determining the facility location, route and flow of different varieties of recyclable wastepaper in the multi-item, multi-echelon and multi-facility environment. The use of the model has been demonstrated, through a problem of paper recycling in India. The results obtained show that the model is a viable tool and can be used to assist in making appropriate decisions regarding the management of reverse distribution network for paper recycling system.

It is envisaged that the quantitative analysis presented in the paper can play a vital role in the decision making process of a manufacturing company for recycling paper. The selection of the priority structure of goals could now be justified quantitatively. Future studies on this topic can be undertaken by inclusion of non-linearities, stochasticity of parameters in the proposed linear model. The model can also be extended to other similar reverse logistics problem areas involving the environmental issues and conservation of natural resources such as recycling of plastic wastes.

Appendix A: Notations used in model formulation

Definition

I	set of varieties of wastepaper collected by dealer stage from the vendor–customer’s
P	set of varieties of wastepaper desired by manufacturer for paper production (p € I)
G	set of godown owners
V	set of vendor–customers or source of wastepaper
D	set of dealers
S	set of suppliers
C_{Cdv}	collection cost per trip for collecting unsegregated wastepaper from the source/vendor–customer ‘v’ by the dealer ‘d’
t_{dv}	cycle time for collection of unsegregated wastepaper by dealer ‘d’ from vendor–customer ‘v’
F_v^c	fixed operating cost of vendor–customer ‘v’
C_I	unit value of unsegregated wastepaper
$\%S_d$	annual inventory holding cost as percentage of unsegregated wastepaper cost at the dealer ‘d’
T_{gdvI}	unit transportation cost of unsegregated wastepaper from vendor–customer ‘v’ via dealer ‘d’ to godown owner ‘g’
l_{gdv}	total distance traveled by unsegregated wastepaper from vendor–customer ‘v’ via dealer ‘d’ to godown owner ‘g’
F_d^c	fixed operating cost of dealer ‘d’
C_{Ogd}	unit ordering cost at godown owner ‘g’ for ordering unsegregated wastepaper from dealer ‘d’
t_{gd}	cycle time for ordering the unsegregated wastepaper by godown owner ‘g’ from dealer ‘d’
S_{gp}	unit segregation cost of ‘pth’ variety of relevant wastepaper at godown owner ‘g’
D_g	unit disposal cost of non-relevant wastepaper at godown owner ‘g’
w	proportion of non-relevant wastepaper accompanying initial collection from source
$\%S_{pg}$	annual inventory holding cost as percentage of ‘pth’ wastepaper cost at the godown owner ‘g’
C_p	unit value of ‘pth’ variety of wastepaper after segregation
F_g^c	fixed operating cost of godown owner ‘g’
C_{Osgp}	unit ordering cost at supplier ‘s’ for ordering ‘pth’ variety of wastepaper from godown owner ‘g’
t_{sgp}	cycle time for ordering the ‘pth’ variety of wastepaper by supplier ‘s’ from godown owner ‘g’
F_s^c	fixed operating cost of supplier ‘s’
T_{Msgp}	unit transportation cost of ‘pth’ variety of wastepaper from a godown owner ‘g’ via a supplier ‘s’ to the manufacturer ‘M’
l_{Msg}	Total distance traveled by ‘pth’ variety of wastepaper from a godown owner ‘g’ via a supplier ‘s’ to the manufacturer ‘M’
$\%S_{ps}$	Annual inventory holding cost as percentage of ‘pth’ wastepaper cost at supplier ‘s’
C_{OMsp}	unit ordering cost at manufacturer ‘M’ for ordering ‘pth’ variety of wastepaper from supplier ‘s’
t_{Msp}	cycle time for ordering the ‘pth’ variety of wastepaper by manufacturer ‘M’ from supplier ‘s’
D_p	demand for the ‘pth’ variety of paper by the manufacturer
T_{dI}	annual throughput capacity at dealer ‘d’ for unsegregated wastepaper
T_{gp}	annual throughput capacity at godown owner ‘g’ for ‘pth’ variety of wastepaper

T_{sp}	annual throughput capacity at supplier 's' for 'pth' variety of wastepaper
B_{Msgp}	route capacity limit of 'pth' wastepaper on route from godown owner 'g', supplier 's' and manufacturer 'M'
B_{gdvI}	route capacity limit of unsegregated wastepaper on route from vendor–customer 'v', dealer 'd' and godown owner 'g'
$(\mathrm{SUP})_v$	unsegregated wastepaper supply capacity at the source i.e. vendor–customer 'v'
O_d	maximum number of permissible dealers that can be operated/opened
O_g	maximum number of permissible godown owners that can be operated/opened
O_s	maximum number of permissible suppliers that can be operated/opened
O_v	maximum number of permissible vendor–customer/source or collection point that can be operated
O_{dv}	maximum number of allowed routes between the dealer stage and vendor–customer stage
O_{gd}	maximum number of allowed routes between the godown owner stage and dealer stage
O_{sgp}	maximum number of allowed routes between the supplier stage and godown owner stage for 'pth' variety of wastepaper
O_{Msp}	maximum number of allowed routes between the manufacturer stage and the supplier stage for 'pth' variety of wastepaper
T_{RLC}	total available budget for reverse logistics activities
W_A	maximum limit of non-relevant wastepaper permitted in reverse network
C_T	minimum desired limit of wastepaper collection at the source

Decision variables

Q_{gdvI}	quantity of unsegregated wastepaper (I) shipped from a source (vendor–customer 'v') via a dealer'd' to a godown owner 'g'.
Q_{Msgp}	quantity of 'p' varieties of relevant segregated wastepaper shipped from a godown owner 'g' via a supplier 's' to the manufacturer 'M'.
β_{Idv}	binary variable; equal to 1 if unsegregated wastepaper is collected by a dealer 'd' from a vendor–customer 'v', otherwise 0.
δ_{Igd}	binary variable; equal to 1 if order for unsegregated wastepaper is placed by a godown owner 'g' to a dealer 'd', otherwise 0.
ψ_{psg}	binary variable; equal to 1 if order for segregated/relevant 'pth' of wastepaper is placed by a supplier 's' to a godown owner 'g', otherwise 0.
χ_{pMs}	binary variable; equal to 1 if order for segregated/relevant 'pth' of wastepaper is placed by the manufacturer 'M' to a supplier's', otherwise 0.
α_d	binary variable; equal to 1 when a dealer'd' is open, otherwise 0.
γ_g	binary variable; equal to 1 when a godown owner 'g' is open, otherwise 0.
ϕ_s	binary variable; equal to 1 when a supplier's' is open, otherwise 0.
π_v	binary variable; equal to 1 when a source/vendor–customer 'v' is open, else 0.

Appendix B: Components of total reverse logistic cost $(RL)_c$

Component description	Mathematical formulation
1. Costs from vendor–customer to godown owner stage	
Wastepaper collection cost by dealer stage from source(V)	$\sum_d \sum_v \frac{C_{Cdv}}{t_{dv}} * \beta_{Idv}$
Fixed cost of operating the vendor–customer stage	$\sum_v F_v^c * \pi_v$
Inventory holding cost of unsegregated wastepaper at dealer stage	$\sum_g \sum_d \sum_v \frac{1}{2} * (\%S_d) * C_I * Q_{gdvI}$

Component description	Mathematical formulation
Transportation cost of unsegregated wastepaper from vendor–customer (source) to godown owner stage through dealer stage	$\sum_g \sum_d \sum_v T_{gdvI} * l_{gdv} * Q_{gdvI}$
Fixed cost of operating the dealer stage	$\sum_d F_d^c * \alpha_d$
2. Costs at godown owner stage	
Ordering cost at godown owner stage, for ordering unsegregated wastepaper from dealer stage	$\sum_g \sum_d \frac{C_{Ogd}}{t_{gd}} * \delta_{Igd}$
Segregation cost for relevant wastepaper at godown owner stage	$\sum_s \sum_g \sum_p S_{gp} * Q_{Msgp}$
Disposal cost of non-relevant wastepaper at godown owner stage	$\sum_g \sum_d \sum_v D_g * w * Q_{gdvI}$
Inventory holding cost of segregated wastepaper at godown owner stage	$\sum_s \sum_g \sum_p \frac{1}{2} * (\%S_{pg}) * C_p * Q_{Msgp}$
Fixed cost of operating the godown owner stage	$\sum_g F_g^c * \gamma_g$
3. Cost after godown owner stage to manufacturer stage	
Ordering cost at supplier stage, for ordering segregated wastepaper from godown owner stage	$\sum_s \sum_g \sum_p \frac{C_{Osgp}}{t_{sgp}} * \psi_{psg}$
Fixed cost of operating the supplier stage	$\sum_s F_s^c * \phi_s$
Transportation cost of segregated wastepaper from godown owner to manufacturer stage through supplier stage	$\sum_s \sum_g \sum_p T_{Msgp} * l_{Msg} * Q_{Msgp}$
Inventory carrying cost of segregated wastepaper at supplier stage	$\sum_s \sum_g \sum_p \frac{1}{2} * (\%S_{ps}) * C_p * Q_{Msgp}$
Ordering cost at manufacturer stage, for ordering segregated wastepaper from supplier stage	$\sum_s \sum_p \frac{C_{OMsp}}{t_{Msp}} * \chi_{pMs}$

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