LAMAR UNIVERSITY

SPRING 2023

PROJECT 2

CVEN 5301: Optimization for Engineers

A Report on Reproduction of Constrained Optimization portion of the paper "Linear Programming for Analysis of Material Recovery Facilities"

SUBMITTED BY

Jigarbhai Sonani (L2057804 8)
Kiran Khadka (L20564439)
Minhajul Abedin Tajik (L20521113)
Tauseef Munawar Ali (L20567221)

SUBMITTED TO

Dr. Elma Uddameri
Associate Professor
Department of Civil and Environmental Engineering

Date: April 12th, 2023

INTRODUCTION

Multi-objective decision making (MODM) is an essential technique used in optimization to address problems with multiple objectives, criteria or goals. It can be applied to a range of real-world scenarios that involve simultaneous consideration of multiple objectives, which are often conflicting or competing. Linear Integer Programming (LIP) is a commonly used approach in MODM. Our objective is to find a set of solutions that are not dominated by any other solutions in terms of all the objectives considered, referred to as –Pareto-optimal solutions. Linear integer programming allows us to model the integer decision variables and linear constraints, one common way of solving the MODM problems using linear-integer program is to use a scalarization approach, where multiple objectives are aggregated into a single objective function by assigning weights to each objective. The resulting single-objective problem can then be solved using linear integer programming. Another approach is to use the ε-constraint method, where one objective is considered as the primary objective and the other objectives are considered as constraints. The constraints are then relaxed one at a time, and the resulting solutions are evaluated to identify the Pareto-optimal solutions.

Importance of topic

Effective waste material management and sorting are important because they reduce the amount of waste that ends up in landfills or incinerators, conserve natural resources and reduce greenhouse gas emissions. This process requires careful planning and design so linear programming can be used to optimize the management of waste material recovery facilities. A linear programming model can identify the most efficient arrangement of equipment and resources that will maximize material recovery while minimizing costs. For example, they can determine the optimal placement of sorting equipment to minimize the distance that materials need to be transported within the facility, or they can identify the most effective balance between labor and automation to achieve the highest recovery rates at the lowest cost.

There are many applications of linear integer programming in wide ranging fields of civil engineering which are summarized as:

Irrigation scheduling: It is difficult to manage an irrigation system that supplies water to small farm outlets demanding water at varying time periods, LIP can also be used to model the irrigation schedule to optimize the allocation of water resources.

Channel design: It can be used for a stochastic design of an irrigation channel that delivers a certain amount of water to a crop field and the flow rate through the channel is uncertain due to variations in the water supply and demand.

Pipe Network Design: Water distribution networks are essential for providing clean water to communities but they face problem of avoiding leaks. Linear program models can be used for leak detection and localization in such networks that can help to reduce the water losses and enhance reliability of water supply.

Construction: Ready mixed concrete transportation is a crucial aspect of the construction industry, as it involves the delivery of concrete to construction sites in a timely and efficient manner. LIP technique is useful to solve the transportation problem by finding the most cost-effective route for concrete delivery taking into account the constraints of the vehicles and construction sites.

In this project, our goal is to reproduce the paper “Linear Programming For Analysis of Material Recovery Facilities” specifically the linear-integer portion of the paper. For that purpose, we will understand the decision variables and constraints associated with our problem of managing the waste material recovery facility. We will formulate a linear program and develop a R code based on it and compare our results to see if they match to those of the paper.

OBJECTIVES

- To reproduce the results of the paper “Linear Programming For Analysis of Material Recovery Facilities”
- To gain knowledge on how LIP can be used to allocate waste stream to different sorting process and allocate workers to these processes.

METHODOLOGY

Literature review

Identify decision variables and constraints

Formulate a linear integer program

Prepare a R code and run it

Compare results with the paper

Form conclusion

We studied research papers pertaining to the application of linear programming in material recovery facilities. Two research papers were referenced. The following diagram illustrates a flow diagram for a general Central Material Recovery Facility (CMRF).

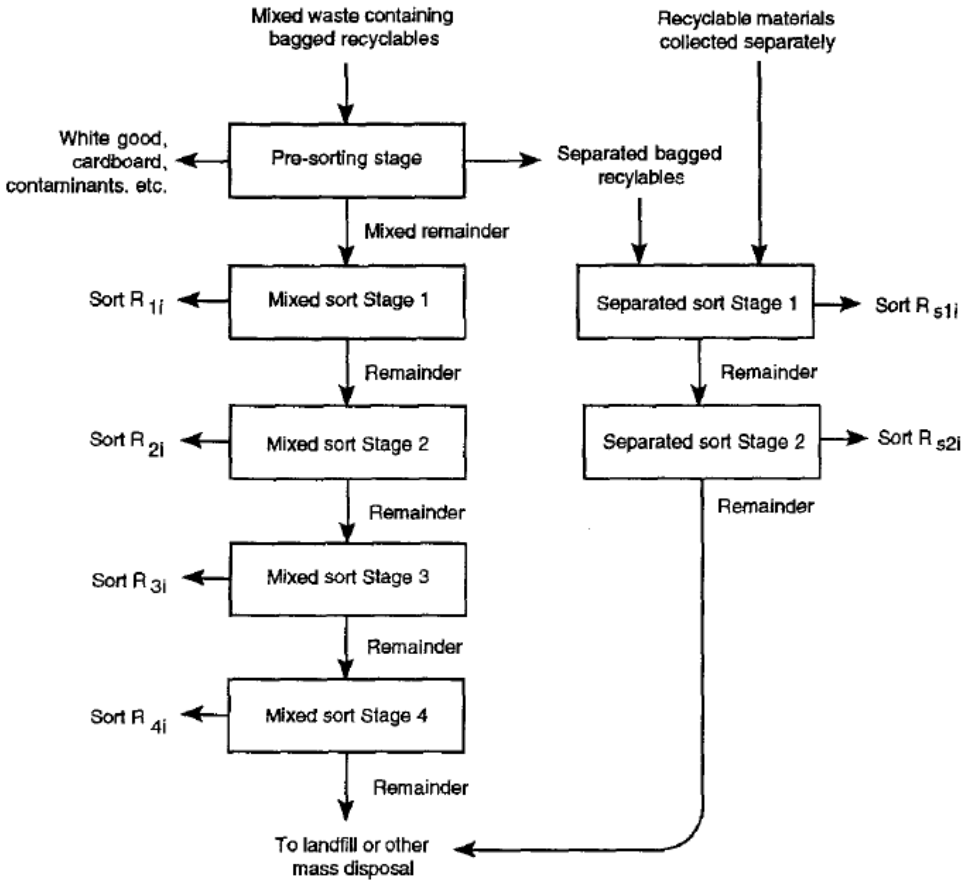

FIG. 1. Schematic Flow Diagram for General CMRF

1083

J. Environ. Eng., 1994, 120(5): 1082-1094

The CMRF accepts two kinds of wastes, mixed wastes and source separated wastes which are sorted separately. During initial presorting stage of mixed wastages, the bagged recyclables are removed and sent to a separate sorting train for separated wastes. During that time, large items not suitable for conveyor belt movement are removed. At the end of this stage, large plastic bags are emptied either manually or mechanically such that the process does not unduly mix the waste materials. Then the remaining mixed wastes are sent to a series of sorting stages as shown in the figure. Similarly the source separated wastes also undergo sorting stages and the remainder from both are disposed to landfill or other mass disposal site.

LINEAR PRGRAM FORMULATION

The following equations are taken from our research paper.

Objective Function:

$$\text{Minimize: } T_C = C_F + \sum_{i=1}^{n} \left(\sum_{k=1}^{N_k} P_L L_{ki} + \sum_{k=1}^{N_{ks}} P_{Ls} L_{ski} - P_{mi} R_{Tmi} - P_{si} R_{Tsi} \right) + P_{LF} D_T$$

Constraints:

Waste quantity remaining for landfill disposal

$$D_T = \sum_{i=1}^{n} \left(g_i + \sum_{j=1}^{N_b} b_{ji} + \sum_{j=1}^{N_s} s_{ji} \right) - \sum_{i=1}^{n} \left(\sum_{k=1}^{N_k} R_{ki} + \sum_{k=1}^{N_{ks}} R_{ski} \right)$$

Total diversions from entering mixed and separated streams respectively

$$R_{Tmi} = \sum_{k=1}^{N_k} R_{ki}, \forall\ i$$

$$R_{Tsi} = \sum_{k=1}^{N_{ks}} R_{ski}, \forall\ i$$

Mass conservation between sorting stages for each component for mixed-sorting and separated waste sorting

$$M_{1,i} = g_i, \forall\ i$$

$$M_{k+1,i} = M_{k,i} - R_{k,i}; \forall\ i, k$$

$$M_{s1i} = \sum_{j=1}^{N_b} b_{ji} + \sum_{j=1}^{N_s} s_{ji}, \forall\ i$$

$$M_{sk+1,i} = M_{sk,i} - R_{sk,i}; \forall\ i, k$$

Removal efficiencies at each sorting stage for each component, for both mixed-waste sorting and source separated waste sorting

$$R_{ki} - a_{ki} M_{ki} \leq 0\ ;\ \forall\ i,k$$

$$R_{ski} - a_{ski} M_{ski} \leq 0\ ;\ \forall\ i,k$$

Labor efficiency at different sorting stages for different components, for both mixed-waste sorting and separated-wasted sorting

$$L_{ki} = d_{ki} R_{ki} \geq 0\ ;\ \forall\ i,k$$

$$L_{ski} = d_{ski} R_{ski} \geq 0\ ;\ \forall\ i,k$$

Definition of total waste diversion (by weight)

$$D_I + D_T = \sum_{i=1}^{n} \left(g_i + \sum_{j=1}^{N_b} b_{ji} + \sum_{j=1}^{N_s} s_{ji} \right)$$

A waste diversion target (by weight)

$$\frac{D_I}{\sum_{i=1}^{n} \left(g_i + \sum_{j=1}^{N_b} b_{ji} + \sum_{j=1}^{N_s} s_{ji} \right)} \geq T$$

Nomenclature of the terms used in the above equations are:

a_{ki} = removal efficiency of component i from mixed waste at the kth sort (tons of i removed per ton of i in mixed waste)

a_{ski} = removal efficiency of component i from source-separated waste at the kth sort (ton of i removed per ton of i in waste being sorted)

b_{ji} = constant quantity of waste com- ponent i entering the CMRF as bagged waste in bag j (t/day)

C_F = fixed cost of the CMRF, including additional costs for separate collection

D_1 = total waste diversion from the entire waste stream (t/day)

D_T = daily quantity disposed of to a landfill or other sink (t/day)

d_{ki}= amount of labor days needed to remove a ton of material i from the kth sort stage of mixed waste (labor days/t of i removed)

d_{ski} = amount of labor days needed to remove a ton of material i from the kth sort stage of source-separated waste (labor day/t of i removed)

g_i = constant quantity of waste component i entering the CMRF as mixed waste (t/day)

L_{ki} = quantity of labor used to sort out mixed waste component i in the kth mixed waste sort stage (labor day/day)

L_{ski} = quantity of labor used to sort out separated waste com- ponent i in the kth source-separated waste sort stage (labor day/day)

M_{ki} = amount of component i in mixed waste entering the kth sort stage

M_{ski} = amount of component i in source-separated waste entering the kth sort stage

n = number of waste components in the chosen waste characterization system

N_b = number of bags in the bag-collection system

N_k = number of mixed-waste sorting stages in series

N_{ks} = number of source-separated- waste sorting stages in series

N_s = number of bins separately collected

P_{mi} = unit price received from recovered material i from mixed waste (dollars/t)

P_{si} = unit price received from recovered material i from source- separated waste (dollars/t)

P_L = total cost of a day's labor for sorting mixed wastes (dollars/worker day)

P_{Ls} = total cost of a day's labor for sorting source-separated wastes (dollars/worker day)

P_{LF} = unit cost of landfill disposal (dollars/t)

R_{ki} = quantity of waste component i removed from the mixed waste stream at the kth sorting stage (t/day)

R_{ski} = quantity of waste component i removed from the source-separated waste stream at the kth sorting stage (t/day)

R_{tmi} = total quantity of waste i recycled from the entering mixed waste stream (t/day)

R_{Tsi} = total quantity of waste i recycled from the entering source-separated waste stream (t/day)

s_{ji} = constant quantity of waste component i entering the **CMRF** as separately collected binned waste in bin j (t/day)

T = waste diversion target (proportion di- verted), by mass

T_c = total daily cost of landfill operations

For our formulation, we have simplified the objective function in terms of R_{ki} and R_{ski} which is presented below:

$$T_c = \sum_{i=1}^{n}(\sum_{k=1}^{Nk} P_L\, d_{ki}\, R_{ki}) + \sum_{i=1}^{n}(\sum_{k=1}^{Nks} P_{Ls}\, d_{ski}\, R_{ski}) - \sum_{i=1}^{n}(P_{mi}\sum_{k=1}^{Nk} R_{ki}) - \sum_{i=1}^{n}(P_{si}\sum_{k=1}^{Nsk} R_{ski})$$

$$+ P_{LF}(1000) - P_{LF}(\sum_{i=1}^{n}(\sum_{k=1}^{N} R_{ki} + \sum_{k=1}^{Nsk} R_{ski}))$$

Since the term P_{LF} (1000) is a constant term, we rearrange the equation to convert in the form of constraints only:

$$T_c - P_{LF}(1000) = \sum_{i=1}^{n}(\sum_{k=1}^{Nk} P_L\, d_{ki}\, R_{ki}) + \sum_{i=1}^{n}(\sum_{k=1}^{Nks} P_{Ls}\, d_{ski}\, R_{ski}) - \sum_{i=1}^{n}(P_{mi}\sum_{k=1}^{Nk} R_{ki}) - \sum_{i=1}^{n}(P_{si}\sum_{k=1}^{Nsk} R_{ski})$$

$$P_{LF}(\sum_{i=1}^{n}(\sum_{k=1}^{N} R_{ki} + \sum_{k=1}^{Nsk} R_{ski}))$$

Note: To get the final value of Tc, after we get our results in R, we add P_{LF} (1000) to get the actual Tc where P_{LF} varies from 0 to 100 in interval of 20. (0, 20, 40, 60, 80, 100)

R CODE

```
library(lpSolve)
path <-'C:/Users/Family/OneDrive/Desktop/Semester1/Optimization for engineers/files/R-Notebooks/TOPSIS'
setwd(path)
getwd()
model <- read.csv('Project2.csv',skip=1, header= FALSE)

#bind constraints into a matrix
mat <- cbind(model[2:98,1:48])

#set up our binary program
obj <- c(model[1,1:48])
con <- as.matrix(mat)
dir <- c(model[2:98,50])
rhs <-c(model[2:98,49])
zz <-lp(direction="min",obj, con, dir, rhs, all.bin = FALSE)

print(zz)
zz$solution

#This will save the Rki/Rski values in a separate .csv file

write.csv(zz$solution, file = "LP_solution6.csv", row.names = FALSE)
```

RESULTS AND DISCUSSION

	Landfill disposal price in dollars per ton					
	0	20	40	60	80	100
Total system price (Dollars/Day)	-9239.51	5044.39	15191.33	24653.22	31244.11	36678.2
Result from paper	-9200	5000	15100	24600	31100	36600

Our main objective is to reproduce the linear integer portion of the paper and analyze the result. The values of the total system price obtained from our linear-integer model are summarized and compared with the result with the paper in the table above. We can see that our results closely match with the paper.

Component	Number	Stage 1					
Disposal Cost (Plf)		0	20	40	60	80	100
Paper	1	0	0	150	150	150	150
Cardboard	2	0	0	40	40	40	40
Plastics	3	0	0	0	0	0	48
Aluminium	4	2.4	2.4	2.4	2.4	2.4	2.4
Ferrous	5	16	16	16	16	16	16
Glass	6	0	0	0	35	35	35
Garden Wastes	7	0	0	0	0	80	80
Other	8	0	0	0	0	0	0

Component	Number	Stage 2					
PLF		0	20	40	60	80	100
Paper	1	0	0	35	35	35	35
Cardboard	2	0	0	7.5	7.5	7.5	7.5
Plastics	3	0	0	0	0	0	0
Aluminium	4	0.42	0.42	0.42	0.42	0.42	0.42
Ferrous	5	2.8	2.8	2.8	2.8	2.8	2.8
Glass	6	0	0	0	0	9	9
Garden Wastes	7	0	0	0	0	36	36
Other	8	0	0	0	0	0	0

Component	Number	Stage 3					
PLF		0	20	40	60	80	100
Paper	1	0	0	9	9	9	9
Cardboard	2	0	0	1.75	1.75	1.75	1.75
Plastics	3	0	0	0	0	0	0
Aluminium	4	0.108	0.108	0.108	0.108	0.108	0.108
Ferrous	5	0.72	0.72	0.72	0.72	0.72	0.72
Glass	6	0	0	0	0	3.3	3.3
Garden Wastes	7	0	0	0	0	16.8	16.8
Other	8	0	0	0	0	0	0

Component	Number	Stage 4					
PLF		0	20	40	60	80	100
Paper	1	0	0	3	3	3	3
Cardboard	2	0	0	0.4875	0.4875	0.4875	0.4875
Plastics	3	0	0	0	0	0	0
Aluminium	4	0.036	0.036	0.036	0.036	0.036	0.036
Ferrous	5	0	0	0.264	0.264	0.264	0.264
Glass	6	0	0	0	0	1.35	1.35
Garden Wastes	7	0	0	0	0	13.44	13.44
Other	8	0	0	0	0	0	0

Figure: Above Figure is for **Mixed Stage recover materials values R_{ki} (t/day)**

Component	Number	Stage 1					
PLF		0	20	40	60	80	100
Paper	1	120	120	120	120	120	120
Cardboard	2	21.25	21.25	21.25	21.25	21.25	21.25
Plastics	3	9.9	9.9	9.9	9.9	9.9	9.9
Aluminium	4	10.8	10.8	10.8	10.8	10.8	10.8
Ferrous	5	9.9	9.9	9.9	9.9	9.9	9.9
Glass	6	0	0	36	36	36	36
Garden Wastes	7	0	0	0.5	0.5	0.5	0.5
Other	8	0	0	0	0	0	0

Component	Number	Stage 2					
PLF		0	20	40	60	80	100
Paper	1	0	0	22.5	22.5	22.5	22.5
Cardboard	2	3	3	3	3	3	3
Plastics	3	0.88	0.88	0.88	0.88	0.88	0.88
Aluminium	4	0.96	0.96	0.96	0.96	0.96	0.96
Ferrous	5	0.88	0.88	0.88	0.88	0.88	0.88
Glass	6	0	0	3.2	3.2	3.2	3.2
Garden Wastes	7	0	0	0.15	0.15	0.15	0.15
Other	8	0	0	0	0	0	0

Figure: Above Figures are for Separated Stage recover materials values R_{ski} (t/day)

The tables listed above represent the amount of recovered material that can be achieved for different cost of landfill disposal (P_{LF}) that we found through our analysis.

Discussion:

After analysis of literature, we found some typos in equation of labor efficiency and removal efficiency of material equation. We can see that as PLF increase, the amount of recovered material increase.

MEMBER CONTRIBUTION

SN	Contribution	Team member
1	Literature review	Jigarbhai Sonani, Kiran Khadka, Minhajul Abedin Tajik, Tauseef Munawar Ali
2	Data analysis	Jigarbhai Sonani, Kiran Khadka, Minhajul Abedin Tajik, Tauseef Munawar Ali
3	Model formulation	Minhajul Abedin Tajik, Jigarbhai Sonani, Kiran Khadka
4	Report preparation	Jigarbhai Sonani, Kiran Khadka, Minhajul Abedin Tajik, Tauseef Munawar Ali

REFERENCES

Everett, J., & T.L, J. (1992). Optimal scheduling of consecutive landfill operations with recyling. *J. Environmental Engineering*.

Lund, J., & Englehardt, J. (1990). Economic analysis of recycling for small municipal waste collectors. *J. Resource Management and Technology*.

Lund, J., P. Anex, R., & A. Lawver, R. (1994). LINEAR PROGRAMMING FOR ANALYSIS OF MATERIAL RECOVERY FACILITIES.