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FACULTY OF APPLIED SCIENCE, SCHOOL OF ENGINEERING

Analysis of Sustainable Textile Supply Chain

Introduction

Textile recycling is a form of recycling that focuses on collecting no longer wanted fabric, yarn or fiber and reprocessing them into useful products such as new clothes, fillings for pillows, furniture linings and much more. This helps reduce waste and demand for newly produced textile materials which are desirable as both consume energy which contribute to carbon emissions. Producing new textile material also uses farming space for plant-based materials and oil for petroleum-based fabrics which leads to clearing of forests for farming and oil extraction which damage habitats around oil fields.

Supply chain

The supply chain of recycled textiles involve 5 components in a structure shown in figure 1:

1. Collection centers collect unwanted textiles from potential donors.
2. Recycling facilities sort textiles collected by collection centers based on whether they could be used for new products. They also process usable textiles into raw material form.
3. Textile manufacturers use recycled raw material-form fabrics, yarns and fiber from recycling facilities to produce their products.
4. Retail distributors take products from textile producers and sell them to customers in the market.
5. Disposal sites take textiles deemed unusable from recycling facilities to be treated as waste.

The supply chain uses the push supply chain strategy which means supply chain components are required to fulfill the known demand from the market.

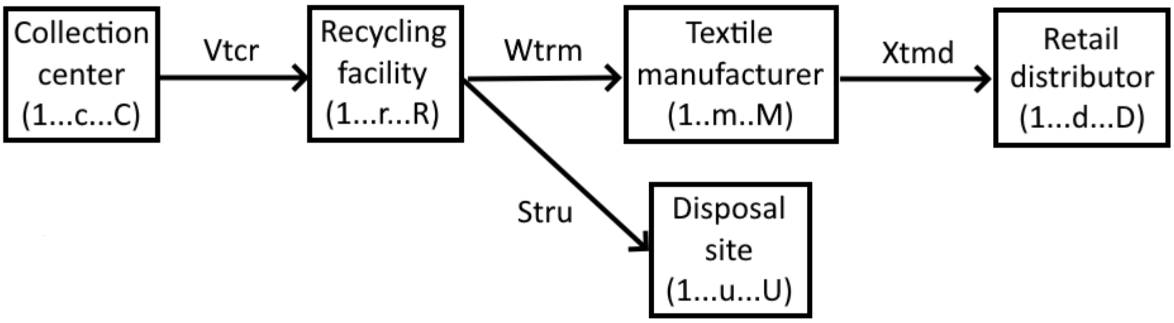

Figure 1: The recycled textile open-loop supply chain

Optimization model design

For our CPLEX analysis we have created a list of potential options to be part of our supply chain members. Factors that affect how well they suit our supply chain both positively and negatively are recorded and are considered by the CPLEX model. The data involved is listed below in Table 1-16. The aim for the analysis is to determine the optimal locations and capacities for textile collection centers, recycling facilities, textile manufacturers, disposal sites and retailers to balance economic efficiency and environmental impact in the form of carbon emissions.

Data

Supply Chain Component	Quantity
Collection center	4
Recycling facilty	3
Textile manufacturer	3
Disposal site	2
Retail distributor	5

Table 1: Quantity of supply chain component options

Supply Chain Component	Setup cost ($)
Collection center	5,000
Recycling facilty	20,000
Textile manufacturer	25,000
Disposal site	N/A
Retail distributor	N/A

Table 2: Setup cost of supply chain component options

Collection center options	Collection cost ($/kg)
#1	40
#2	55
#3	60
#4	75

Table 3: Collection cost of collection center options

Recycling facility options	Sorting cost ($/kg)
#1	35
#2	50
#3	50

Table 4: Sorting cost of recycling facility options

Recycling facility options	Processing cost ($/kg)
#1	90
#2	100
#3	110

Table 5: Processing cost of recycling facility options

Textile manufacturer options	Manufacturing cost ($/kg)
#1	240
#2	250
#3	280

Table 6: Manufacturing cost of textile manufacturer options

Disposal site options	Disposal cost ($/kg)
#1	10
#2	15

Table 7: Disposal cost of disposal site options

	Recycling facility options			
Collection center options		#1	#2	#3
	#1	3	5	15
	#2	4	2	17
	#3	7	6	7
	#4	10	12	4

Table 8: Distance in km between collection center and recycling facility options

	Textile manufacturer options			
Recycling facility options		#1	#2	#3
	#1	2	3	4
	#2	3	2	3
	#3	4	2	1

Table 9: Distance in km between recycling facility and textile manufacturer options

	Disposal site options		
Recycling facility options		#1	#2
	#1	12	14
	#2	15	14
	#3	13	11

Table 10: Distance in km between recycling facility and disposal site options

	Retail distributor					
Textile manufacturer options		#1	#2	#3	#4	#5
	#1	120	80	47	35	23
	#2	130	65	41	42	35
	#3	80	60	25	41	66

Table 11: Distance in km between textile manufacturer options and retail distributors

Retail distributor	Demand (arbitrary units of product)
#1	10,000
#2	7,000
#3	5,000
#4	3,000
#5	2,000

Table 12: Demand of retail distributors

Collection center options	Collection capacity (kg)
#1	18,000
#2	10,500
#3	13,000
#4	20,000

Table 13: Collection capacity of collection center options

Recycling facility options	Recycling capacity (kg)
#1	11,000
#2	13,000
#3	17,000

Table 14: Collection capacity of recycling facility options

Textile manufacturer options	Manufacturing capacity (kg)
#1	12,000
#2	16,500
#3	19,000

Table 15: Collection capacity of textile manufacturer options

Transportation cost ($/km)	2
Disposal rate of collected textiles	10%
Truck capacity (kg)	1000
Truck carbon emissions (kg/km)	0.35
Monetary cost of carbon emissions ($/kg)	10,000
Weight of first objective	0.75
Weight of second objective	0.25

Table 16: Independent variables relevant to the analysis

Model

Sets:

- T: Types of textiles (1 ... t ... T).

- C: Collection centers (1 ... c ... C).

- R: Recycling facilities (1 ... r ... R).

- U: Disposal sites (1 … u … U).

- M: Textile manufacturers (1 ... m ... M).

- D: Retail distributors (1 ... d ... D).

Parameters:

- FC_c: Setup cost of collection center c.

- FC_r: Setup cost of recycling facility r.

- FC_m: Setup cost of textile manufacturer m.

- PC_{tc}: Collection cost of textile t at center c.

- PCA_{tr}: Sorting cost of collected textile t at facility r.

- PCB_{tr}: Processing cost of recyclable textile t at facility r.

- PC_{tm}: Manufacturing cost of recycled textile t at manufacturer m.

- PC_{tu}: Disposal cost of textile t at site u.

- E_{cr}: Distance between collection center *c* and recycling facility *r*.

- E_{rm}: Distance between recycling facility *r* and manufacturer *m*.

- E_{ru}: Distance between recycling facility *r* and disposal site *u*.

- E_{md}: Distance between manufacturer *m* and distributor *d*.

- D_{td}: Demand for textile *t* at distributor *d*.

- CC_{tc}: Maximum collected amount of textile *t* at center *c*.

- CC_{tr}: Recycling capacity for textile *t* at facility *r*.

- CC_{tm}: Manufacturing capacity for textile *t* at manufacturer *m*.

- N_t: transportation cost per km associated with textile *t*

- e_t: Disposal rate of textile *t*.

- g_t: Truck capacity for textile t.

- *h*: Truck carbon emissions per km.

- *CE*: Carbon emissions' monetary value per kg of emission.

- *WE1*: Weight of the first objective.

- *WE2*: Weight of the first objective.

Decision Variables:

- V_{tcr}: Amount of textile *t* transported from collection center *c* to recycling facility *r*.

- W_{trm} : Amount of textile *t* transported from recycling facility *r* to manufacturer *m*.

- S_{tru} : Amount of textile *t* transported from recycling facility *r* to disposal site *u*.

- X_{tmd}: Amount of textile *t* transported from manufacturer *m* to distributor *d*.

- Y_c: Binary variable; 1 if collection center *c* is utilized, 0 otherwise.

- Z_r: Binary variable; 1 if recycling facility *r* is utilized, 0 otherwise.

- A_m: Binary variable; 1 if manufacturer *m* is utilized, 0 otherwise.

Objective Variables:

- *Z1*: Objective function for the first objective

- *Z2*: Objective function for the second objective

Objective function and constraints:

Objective Functions

Min

$$Z_1 = \sum_t \sum_c \sum_r V_{tcr}\left(PC_{tc} + E_{cr} \cdot N_t\right) + \sum_t \sum_r \sum_m W_{trm}\left(PCA_{tr} + PCB_{tr} + E_{rm} \cdot N_t\right) + \sum_t \sum_r \sum_u S_{tru}\left(PCA_{tr} + PC_{tu} + E_{ru} \cdot N_t\right) + \sum_t \sum_m \sum_d X_{tmd} \cdot \left(PC_{tm} + E_{md} \cdot N_t\right) + \sum_c FC_c \cdot Y_c + \sum_r FC_r \cdot Z_r + \sum_m FC_m \cdot A_m$$

Min

$$Z_2 = \sum_t \sum_c \sum_r V_{tcr} \cdot E_{cr} \cdot \frac{h}{g} + \sum_t \sum_r \sum_m W_{trm} \cdot E_{rm} \cdot \frac{h}{g} + \sum_t \sum_r \sum_u S_{tru} \cdot E_{ru} \cdot \frac{h}{g} + \sum_t \sum_m \sum_d X_{tmd} \cdot E_{md} \cdot \frac{h}{g}$$

Constraints

$$\sum_c V_{tcr} = \sum_m W_{trm} + \sum_u S_{tru} \qquad \forall t, r$$

$$\sum_r W_{trm} = \sum_d X_{tmd} \qquad \forall t, m$$

$$\sum_m X_{tmd} = D_{td} \qquad \forall t, d$$

$$e_t \sum_c V_{tcr} = \sum_u S_{tru} \qquad \forall t, r$$

$$\sum_r V_{tcr} \leq CC_{tc} \cdot Y_c \qquad \forall t, c$$

$$\sum_m W_{trm} + \sum_u S_{tru} \leq CC_{tr} \cdot Z_r \qquad \forall t, r$$

$$\sum_d X_{tmd} \leq CC_{tm} \cdot A_m \qquad \forall t, m$$

$$Y_c, Z_r, A_m \in \{0, 1\} \qquad V_{tcr}, W_{trm}, S_{tru}, X_{tmd} \geq 0$$

Figure 2: Objective functions and constraints of the model

Figure 2 shows the objective functions and constraints involved in the project. Objective function Z1 focuses on minimizing the cost of setting up and running the supply chain while objective function Z2 focuses on minimizing the carbon emissions from transportation using trucks.

The mathematical model involves 9 constraints. Constraints #1 and #2 ensures there is no loss of textiles in between supply chain components. Constraint #3 specifies that the amount of textiles received by retail distributors matches the market demand for the same distributor. Constraint #4 controls the amount of disposed textile to be a portion of all collected textiles based on the decided disposal rate. Constraint #5, #6 and #7 makes sure the collection centers, recycling facilities and textile manufacturers do not exceed their production capacities. Constraint #8 is a binary constraint. Constraint #9 ensures all decision variables that are not binary are non-negative.

Result analysis

IBM ILOG CPLEX 22.1.1 was used to solve this model which has 26 constraints, 42 non-zero variables, 10 binary variables and 232 non-zero coefficients.

Based on our data, the optimal supply network will run according to the diagram shown in figure 3 to minimize the total operating cost while fulfilling demands.

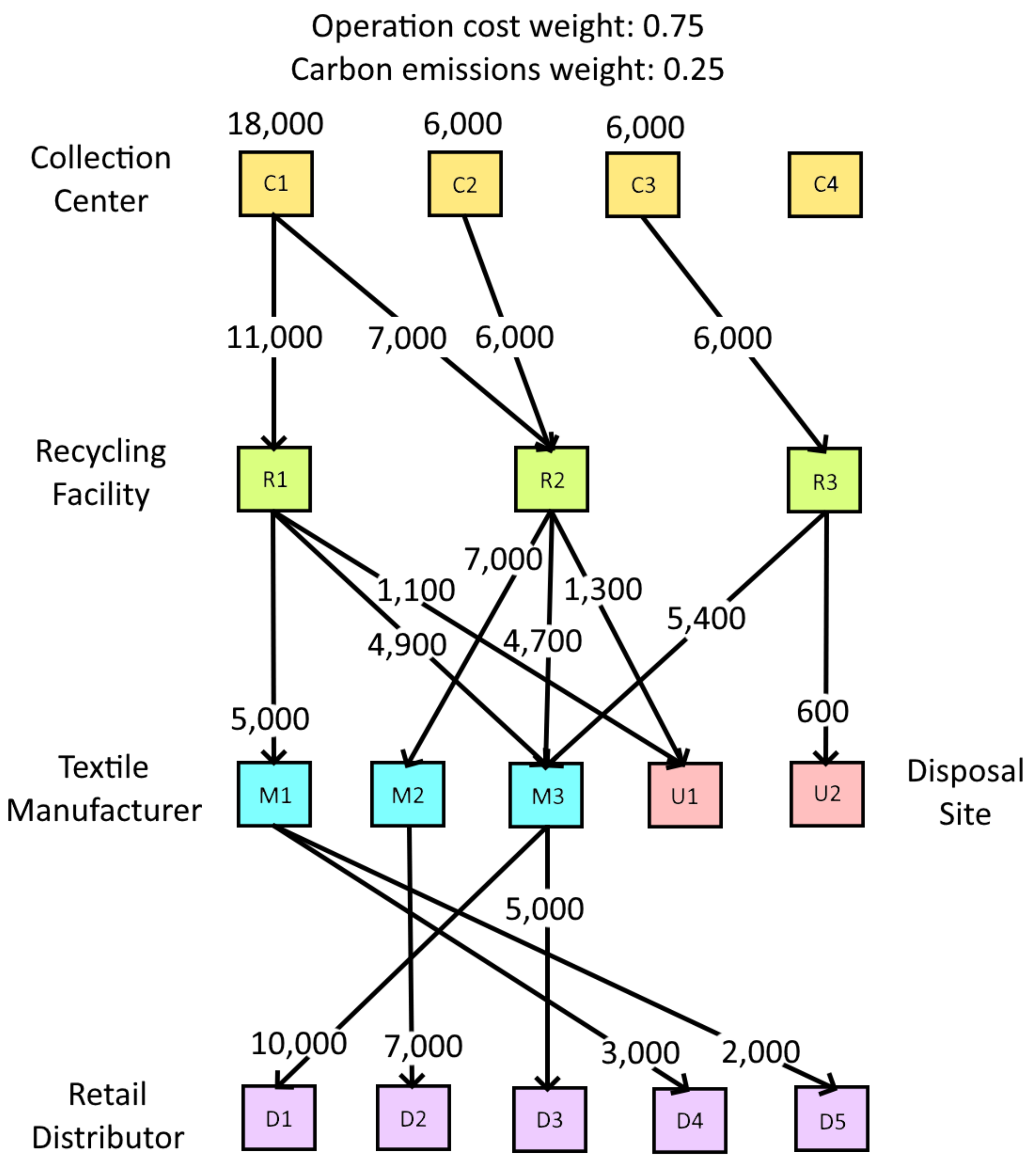

Figure 3: Optimal textile recycling supply network diagram

If we focus on reducing environmental pollution more by decreasing the weighting of Z1 and increasing that of Z2, we can see a shift in the collection centers chosen and flow of textiles in the diagram shown in figure 4 to reflect this change of focus.

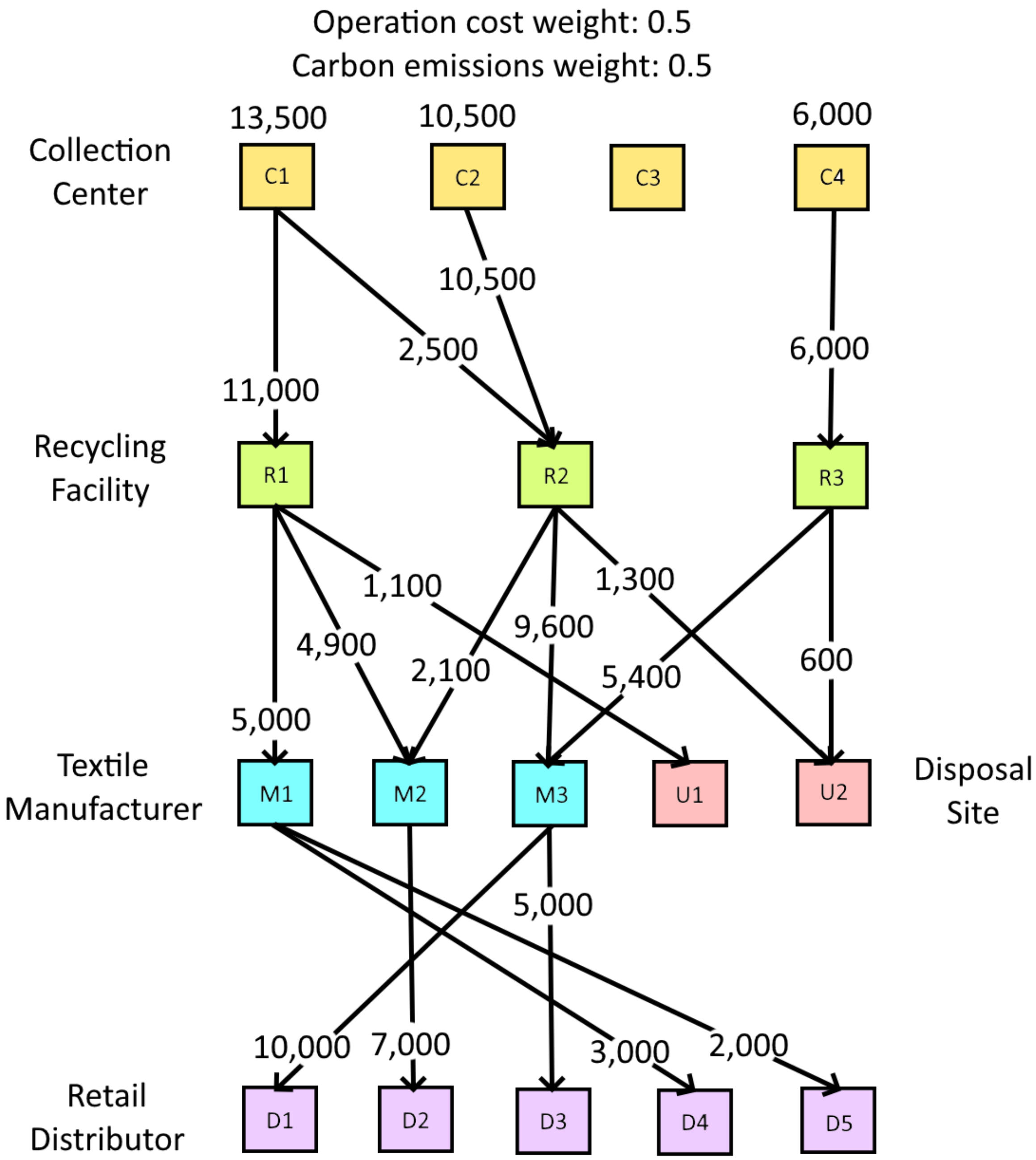

Figure 4: Optimal textile recycling supply network diagram with altered weighting

Conclusion

In conclusion, the objective of this study was to address the complexities inherent in a textile recycling supply chain network, with the primary focus of developing the most efficient solution utilizing IBM ILOG CPLEX 22.1.1. Furthermore, our focus extended to refining the spatial layouts and capacities of pivotal elements within the supply chain, spanning collection centers, recycling facilities, textile manufacturers, disposal sites, and retailers. To ensure feasibility and validity of the results, 9 constraints were used, including no loss of textiles between supply chain members, and the assurance that specific supply chain members do not exceed their production capacities.

Moreover, the sensitivity analysis reveals the adaptability of the supply chain to varying environmental priorities. By adjusting the weights assigned to the two objectives, the model can respond to a shift in focus towards environmental sustainability. This is demonstrated by the altered supply network configuration when environmental concerns take precedence, resulting in a redistribution of collection centers and textile flow.

In essence, the findings underscore the importance of adopting a holistic approach to textile recycling supply chain management. The proposed model provides a robust framework for decision-makers to optimize operations, considering both economic and environmental factors. As the textile industry continues to grapple with sustainability challenges, the insights from this study offer actionable strategies to foster a circular economy, reduce waste, and mitigate the ecological footprint of textile production and disposal.

Appendix

```
//Sets
range T = 1..1; // Types of textile
range C = 1..4; // Collection center
range R = 1..3; // Recycling facility
range M = 1..3; // Textile manufacturer
range U = 1..2; // Disposal site
range D = 1..5; // Retail distributor

//Parameters
float FCc[C] = [5000, 5000, 5000, 5000];
float FCr[R] = [20000, 20000, 20000];
float FCm[M] = [25000, 25000, 25000];
float PCtc[T][C] = [[40, 55, 60, 75]];
float PCAtr[T][R] = [[35, 50, 50]];
float PCBtr[T][R] = [[90, 100, 110]];
float PCtm[T][M] = [[240, 250, 280]];
float PCtu[T][U] = [[10, 15]];
float Ecr[C][R] = [[3, 5, 15], [4, 2, 17], [7, 6, 7], [10, 12, 4]];
float Erm[R][M] = [[2, 3, 4], [3, 2, 3], [4, 2, 1]];
float Eru[R][U] = [[12, 14], [15, 14], [13, 11]];
float Emd[M][D] = [[120, 80, 47, 35, 23], [130, 65, 41, 42, 35], [80, 60, 25, 41, 66]];
float Dtd[T][D] = [[10000, 7000, 5000, 3000, 2000]];
float CCtc[T][C] = [[18000, 10500, 13000, 20000]];
float CCtr[T][R] = [[11000, 13000, 17000]];
float CCtm[T][M] = [[12000, 16500, 19000]];
float Nt[T] = [2];
float et[T] = [0.1];
float gt[T] = [1000];
float h = 0.35;
float CE = 10000;
float WE1 = 0.75;
float WE2 = 0.25;

//Decision variables
// Boolean
dvar boolean Y[C];
dvar boolean Z[R];
dvar boolean A[M];
// Positive
dvar int+ V[T][C][R];
dvar int+ W[T][R][M];
dvar int+ S[T][R][U];
dvar int+ X[T][M][D];

//Objectives
dvar float+ Z1;
dvar float+ Z2;

//Model
minimize (WE1*Z1)+(WE2*Z2);

subject to {
  Z1 == sum(T in T, C in C, R in R)(V[T][C][R]*(PCtc[T][C]+Ecr[C][R]*Nt[T]))
        +sum(T in T, R in R, M in M)(W[T][R][M]*(PCAtr[T][R]+PCBtr[T][R]+Erm[R][M]*Nt[T]))
        +sum(T in T, R in R, U in U)(S[T][R][U]*(PCAtr[T][R]+PCtu[T][U]+Eru[R][U]*Nt[T]))
        +sum(T in T, M in M, D in D)(X[T][M][D]*(PCtm[T][M]+Emd[M][D]*Nt[T]))
        +sum(C in C)(FCc[C]*Y[C])+sum(R in R)(FCr[R]*Z[R])+sum(M in M)(FCm[M]*A[M]);
  Z2 == CE*(sum(T in T, C in C, R in R)(V[T][C][R]*Ecr[C][R]*h/gt[T])
        +sum(T in T, R in R, M in M)(W[T][R][M]*Erm[R][M]*h/gt[T])
        +sum(T in T, R in R, U in U)(S[T][R][U]*Eru[R][U]*h/gt[T])
        +sum(T in T, M in M, D in D)(X[T][M][D]*Emd[M][D]*h/gt[T]));

  forall(T in T, R in R){sum(C in C)V[T][C][R] == sum(M in M)W[T][R][M]+sum(U in U)S[T][R][U];}
  forall(T in T, M in M){sum(R in R)W[T][R][M] == sum(D in D)X[T][M][D];}
  forall(T in T, D in D){sum(M in M)X[T][M][D] == Dtd[T][D];}
  forall(T in T, R in R){(sum(C in C)V[T][C][R]*et[T]) == (sum(U in U)S[T][R][U]);}
  forall(T in T, C in C){sum(R in R)V[T][C][R] <= CCtc[T][C]*Y[C];}
  forall(T in T, R in R){sum(M in M)W[T][R][M]+sum(U in U)S[T][R][U] <= CCtr[T][R]*Z[R];}
  forall(T in T, M in M){sum(D in D)X[T][M][D] <= CCtm[T][M]*A[M];}
}
```

Figure A1: CPLEX Code

Solution with objective 13,718,825

Name	Value
Data (29)	
C	1..4
CCtc	[[18000 10500 13000 20000]]
CCtm	[[12000 16500 19000]]
CCtr	[[11000 13000 17000]]
CE	10000
D	1..5
Dtd	[[10000 7000 5000 3000 2000]]
Ecr	[[3 5 15] [4 2 17] [7 6 7] [10 12 4]]
Emd	[[120 80 47 35 23] [130 65 41 42 35] [80 60 25 41 66]]
Erm	[[2 3 4] [3 2 3] [4 2 1]]
Eru	[[12 14] [15 14] [13 11]]
et	[0.1]
FCc	[5000 5000 5000 5000]
FCm	[25000 25000 25000]
FCr	[20000 20000 20000]
gt	[1000]
h	0.35
M	1..3
Nt	[2]
PCAtr	[[35 50 50]]
PCBtr	[[90 100 110]]
PCtc	[[40 55 60 75]]
PCtm	[[240 250 280]]
PCtu	[[10 15]]
R	1..3
T	1
U	1..2
WE1	0.75
WE2	0.25
Decision variables (9)	
A	[1 1 1]
S	[[[1100 0] [1300 0] [0 600]]]
V	[[[11000 7000 0] [0 6000 0] [0 0 6000] [0 0 0]]]
W	[[[5000 0 4900] [0 7000 4700] [0 0 5400]]]
X	[[[0 0 0 3000 2000] [0 7000 0 0 0] [10000 0 5000 0 0]]]
Y	[1 1 1 0]
Z	[1 1 1]
Z1	1.6244e+7
Z2	6.1439e+6

Figure A2: Results of optimization problem with default weightings

Solution with objective 11,185,650

Name	Value
Data (29)	
C	1..4
CCtc	[[18000 10500 13000 20000]]
CCtm	[[12000 16500 19000]]
CCtr	[[11000 13000 17000]]
CE	10000
D	1..5
Dtd	[[10000 7000 5000 3000 2000]]
Ecr	[[3 5 15] [4 2 17] [7 6 7] [10 12 4]]
Emd	[[120 80 47 35 23] [130 65 41 42 35] [80 60 25 41 66]]
Erm	[[2 3 4] [3 2 3] [4 2 1]]
Eru	[[12 14] [15 14] [13 11]]
et	[0.1]
FCc	[5000 5000 5000 5000]
FCm	[25000 25000 25000]
FCr	[20000 20000 20000]
gt	[1000]
h	0.35
M	1..3
Nt	[2]
PCAtr	[[35 50 50]]
PCBtr	[[90 100 110]]
PCtc	[[40 55 60 75]]
PCtm	[[240 250 280]]
PCtu	[[10 15]]
R	1..3
T	1
U	1..2
WE1	0.5
WE2	0.5
Decision variables (9)	
A	[1 1 1]
S	[[[1100 0] [0 1300] [0 600]]]
V	[[[11000 2500 0] [0 10500 0] [0 0 0] [0 0 6000]]]
W	[[[5000 4900 0] [0 2100 9600] [0 0 5400]]]
X	[[[0 0 0 3000 2000] [0 7000 0 0 0] [10000 0 5000 0 0]]]
Y	[1 1 0 1]
Z	[1 1 1]
Z1	1.6342e+7
Z2	6.0291e+6

Figure A3: Results of optimization problem with changed weightings