INL/XXX-XX-XXXXX

Comprehensive Manufacturing Assessment Tool (CMAT) User Manual

February 2022

Version 0.5

Md Mamunur Rahman
Sophie L. Williams
Ruby T. Nguyen
Damon S. Hartley
Idaho National Laboratory

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

INL/XXX-XX-XXXXX

Comprehensive Manufacturing Assessment Tool (CMAT) User Manual

Version 0.5

Md Mamunur Rahman
Sophie L. Williams
Ruby T. Nguyen
Damon S. Hartley

February 2022

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Page intentionally left blank

CONTENTS

FIGURES

TABLES

1. INTRODUCTION

1.1 Purpose

The Comprehensive Manufacturing Assessment Tool (CMAT) software provides the user with a fully customizable decision support framework that analyzes the optimal supply chain configurations for a given industrial e-waste recycling and refurbishment process. The software optimizes the logistics operations, helps to identify the best recycling process configuration, and generates valuable insights regarding the economic performance of different categories of e-waste. The ultimate purpose of the model is to provide insights on questions pertinent to the e-waste recycling industry including how to increase efficiency and reduce costs, energy consumption, and greenhouse gas emissions.

The software consists of three modules which operate from user-inputted process data (Figure 1):

1. Transportation Model—optimizes transportation routes for e-waste pick-up given vehicle information and collection locations.

2. Process Model—evaluates recycling process performance by simulating outputs, utilizations, and relevant costs of different workstations and machines.

3. Economic Model—provides overall economic analysis of a given e-waste recycling operation based on prices and operating costs.

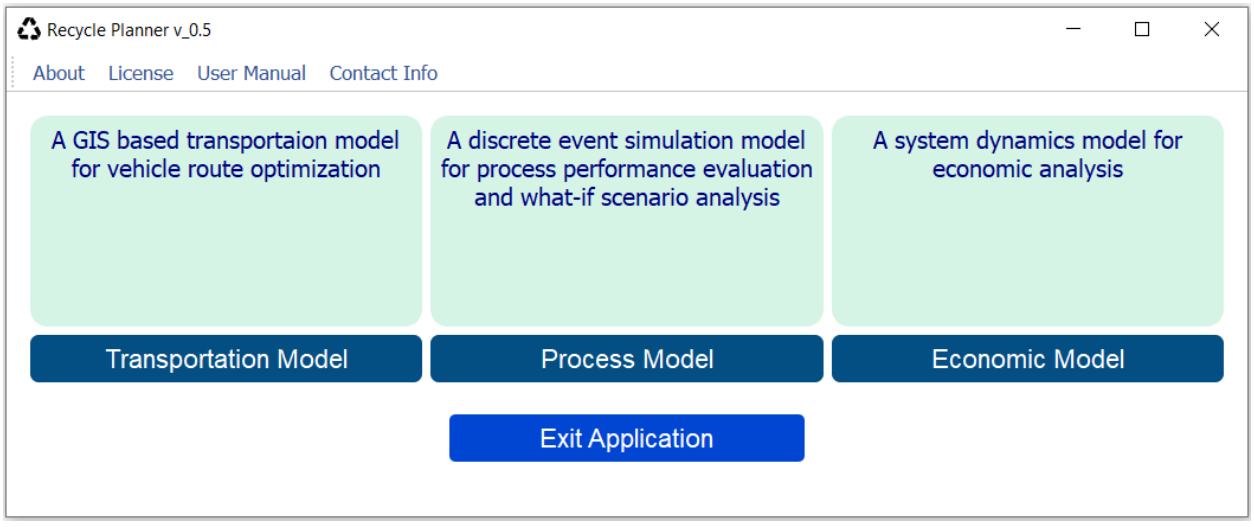

Figure 1. Main window displaying the three e-waste model options.

1.2 System Requirements

The CMAT software runs from an executable (.exe) file. The program will work on Windows and Mac computers.

2. TRANSPORTATION MODEL

When the user clicks on the left-most model, the main navigation: "Transportation Model", a window like Figure 2 will open. The window allows the user to choose between the Address Adder application and the Transportation model.

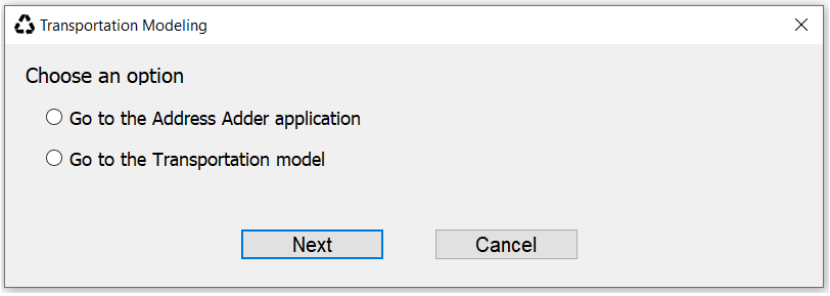

Figure 2. Transportation Modeling option window.

2.1 Address Adder Application

2.1.1 For the first time use of this application, the user will create the following three files using this Address Adder application.

- ActiveAccounts.csv.
- ActiveAccounts_unique.csv.
- ActiveAccounts_OD.csv.

2.1.2 Select the option "Go to the Address Adder application," to open the Address Adder option window as shown in Figure 3.

2.1.3 Click Next and follow the steps to prepare the three "csv" files:

2.1.3.1 Click on "File > Edit Config file," a new window will open (see Figure 4).

2.1.3.2 Enter your Google API key and complete the fields for your Home or Depot location.

2.1.3.3 IF the “Working Directory” field does not show the preferred path,
THEN click the “Browse” button and locate the right path as the working directory.

2.1.3.4 Click the “Ok” button.

2.1.3.5 Select “File > New” and type the file name “ActiveAccounts” in the “File Name” field.

2.1.3.6 Click the “Save” button.

NOTE: *A window like Figure 3 will open and the “File Being Edited” field will show the “ActiveAccounts.csv” file name path.*

2.1.3.7 Click the “Save” button. This will create the three files “ActiveAccounts.csv”, “ActiveAccounts_unique.csv”, and “ActiveAccounts_OD.csv” in the selected working directory.

2.1.3.8 In the AddressAdder window (see Figure 3), fill out the required fields for a new account.

2.1.3.9 Click the “Save” button. It will add the new account and automatically update the three “csv” files. The new account refers to a customer from where a recycling company wants to collect e-waste.

2.1.4 Repeat Steps 2.1.3.8 and 2.1.3.9 to add more accounts.

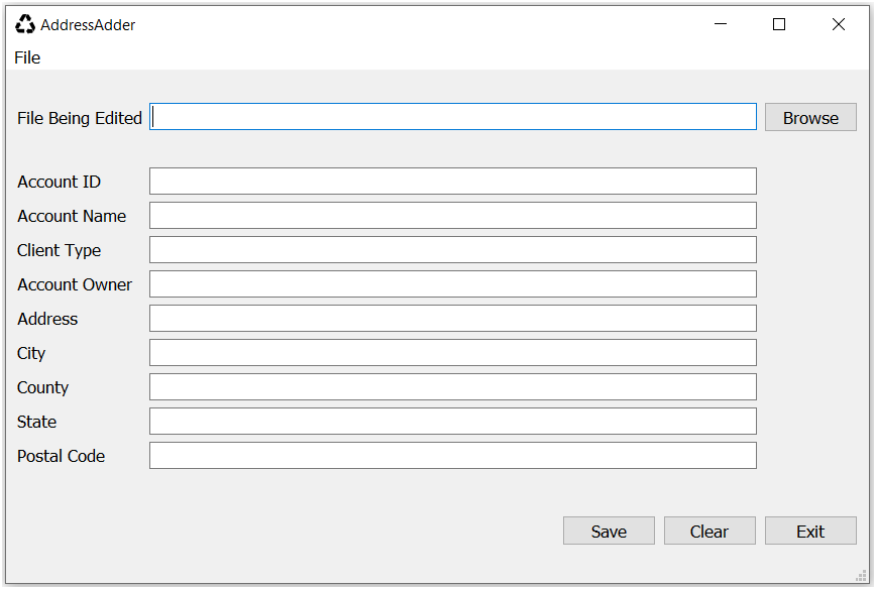

Figure 3. AddressAdder window.

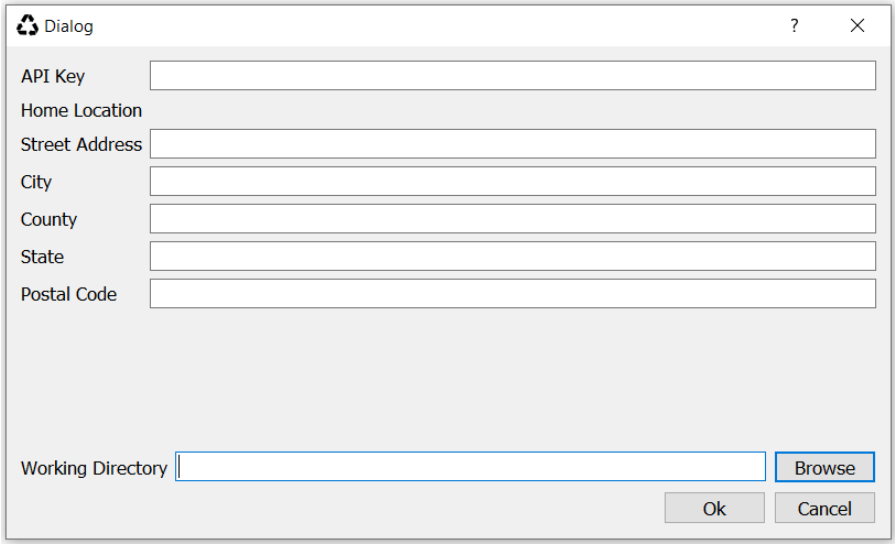

Figure 4. Home or depot location configuration window.

If the user is not going to use the application for the first time in a computer and only wants to add a new account, then follow the below steps:

2.1.5 Open the AddressAdder application.

2.1.6 Go to “File > Edit Config file” and make sure all the fields are displaying correct information.

2.1.7 Click “Ok” to go back to the AddressAdder main window.

2.1.8 Click the “Browse” button and choose the “ActiveAccounts.csv” file.

2.1.9 Fill out all the required fields for a new account.

2.1.10 Click the “Save” button. This will automatically update the three “csv” files for the new account.

2.1.11 Repeat Steps 2.1.9 and 2.1.10 to add more accounts.

2.2 Transportation Model

If a user chooses the second option from the option window, as shown in Figure 2, and clicks the “Next” button, then a new window like Figure 5 will appear.

Figure 5. Transportation Model window view.

Following are more detailed descriptions of the labeled features for the Transportation Model window view, including information that the user is expected to input. Each number in the descriptions below corresponds with the numbers shown in Figure 5.

2.2.1 Inputs

1. Average Weight Per Pallet (lbs)
   The user inputs the average weight per pallet of e-waste in this field.

2. Target Collection Points Data
   The Transportation Model derives its inputs from an Excel file named "TEMPLATE_transportation_model.xlsm". When using the transportation model, the completed Excel file must be uploaded under the "Target Collection Points Data (excel file)" section using the browse button. This file contains three spreadsheets of data necessary for the model to run: e-waste collection addresses, a vehicle list, and active account names (see Figure 6). Below are descriptions of each.

   A. Collection Addresses spreadsheet
      In this spreadsheet, the user selects the desired account names in which e-waste will be picked up. Each cell in the spreadsheet list contains a drop-down menu of all account names that are available in the Unique Accounts spreadsheet tab. The account names are associated with an address and latitude/longitude in the "ActiveAccounts_Unique.csv" file.
      Next to each account name, the user enters the number of pallets that will be collected at that account's address. The first entry "Company-XYZ" (see Figure 6) represents the home or depot location from where the vehicles start and finish their trips. Therefore, the number of pallets to be collected from this location is zero.

(A)

	Account Name	Amount (pallets)
2	Company-XYZ	0
3	Account 1	3
4	Account 2	5
5	Account 3	4
6	Account 4	4
7	Account 5	3
8	Account 6	3
9	Account 7	3
10	Account 8	4
11	Account 9	3

(C)

	A
1	Account Name
2	Account 1
3	Account 2
4	Account 3
5	Account 4
6	Account 5
7	Account 6
8	Account 7
9	Account 8

(B)

	A	B	C	D	E	F	G	H
1	Name	Capacity (pallets)	Vehicle Weight (lbs)	Engine Size (Liter)	Engine Efficiency	Idle Engine RPM	Max Engine RPM	Frontal Area (square meter)
2	vehicle_1	20	14000	10	20%	500	2100	5
3	vehicle_2	50	15500	10	50%	500	2100	5
4	vehicle_3	35	19000	10	40%	500	2100	5

Figure 6. Spreadsheet tabs in "TEMPLATE_transportation_model.xlsx" Excel file: (A) Collection Addresses spreadsheet; (B) Vehicle List spreadsheet; (C) Unique Accounts spreadsheet.

B. Vehicle List spreadsheet

The user enters the list of vehicles in the "Vehicle List" spreadsheet tab. The vehicle capacity (number of pallets), vehicle weight (lbs), engine size (liters), engine efficiency (%), idle engine resolution per minute (RPM), max engine RPM, and vehicle frontal area (square meters) is entered for each vehicle in the list.

For a heavy-duty truck, the typical values of some of the above parameters are: engine size: 13 to 16 liters, engine efficiency: 35 to 40%, idle engine RPM: 600 to 900, max engine RPM: 2000 to 2400, and vehicle frontal area: 5 to 6 square meters. These parameters are utilized for the calculation of fuel consumption and corresponding CO_2 emissions.

C. Unique Accounts spreadsheet

This spreadsheet is hidden on purpose so the user does not make any modifications here. This spreadsheet is linked up with the "ActiveAccounts_Unique.csv" file and updates automatically if the user makes any changes to the "ActiveAccounts_Unique.csv" file. The purpose of this spreadsheet is to populate the drop-down options in the "Collection Addresses" tab.

3. Active Accounts Unique Addresses Data (csv file)
The "ActiveAccounts_Unique.csv" file is generated using the "Address Adder" application discussed in Section 2.1. The file contains information on the different accounts for e-waste pick-up including account IDs and addresses. Once the application is used to generate this file, the user uploads it to the Active Accounts Unique Addresses Data (csv file) section in the Transportation Model.

4. Active Accounts OD Matrix Data (csv file)
The "ActiveAccounts_OD.csv" file is generated using the "Address Adder" application discussed in Section 2.1. OD stands for "Origin Destination." This file contains information on the travel times and distances between the collection addresses for active accounts. Once the application is used to generate this file, the user uploads it to the Active Accounts OD Matrix Data (csv file) section in the Transportation Model.

5. Objective to Minimize
The user has two choices for the objective to minimize in the Transportation Model, each of which will run a different simulation (as described further in Section 2.2.2, Outputs). Choosing "Travel Time" will minimize the total time traveled by each vehicle. On the other hand, choosing "Travel Distance" will minimize the total distance traveled by each vehicle.

2.2.2 Outputs

A. Using Travel Time Option
Choosing the travel time minimization option for the transportation model will run a simulation in a new window which minimizes the total time traveled by collection vehicles. Once the simulation finishes, the user clicks "Show Simulation Results." A list of routes using the vehicles supplied in the "Vehicle List" Excel spreadsheet and accounts supplied in the "Collection Addresses" spreadsheet will be displayed. For each vehicle, the vehicle name, list of accounts included in the route, time traveled by the vehicle, number of pallets collected, fuel burnt, and CO_2 emissions released by the vehicle's operation are displayed (see Figure 7).

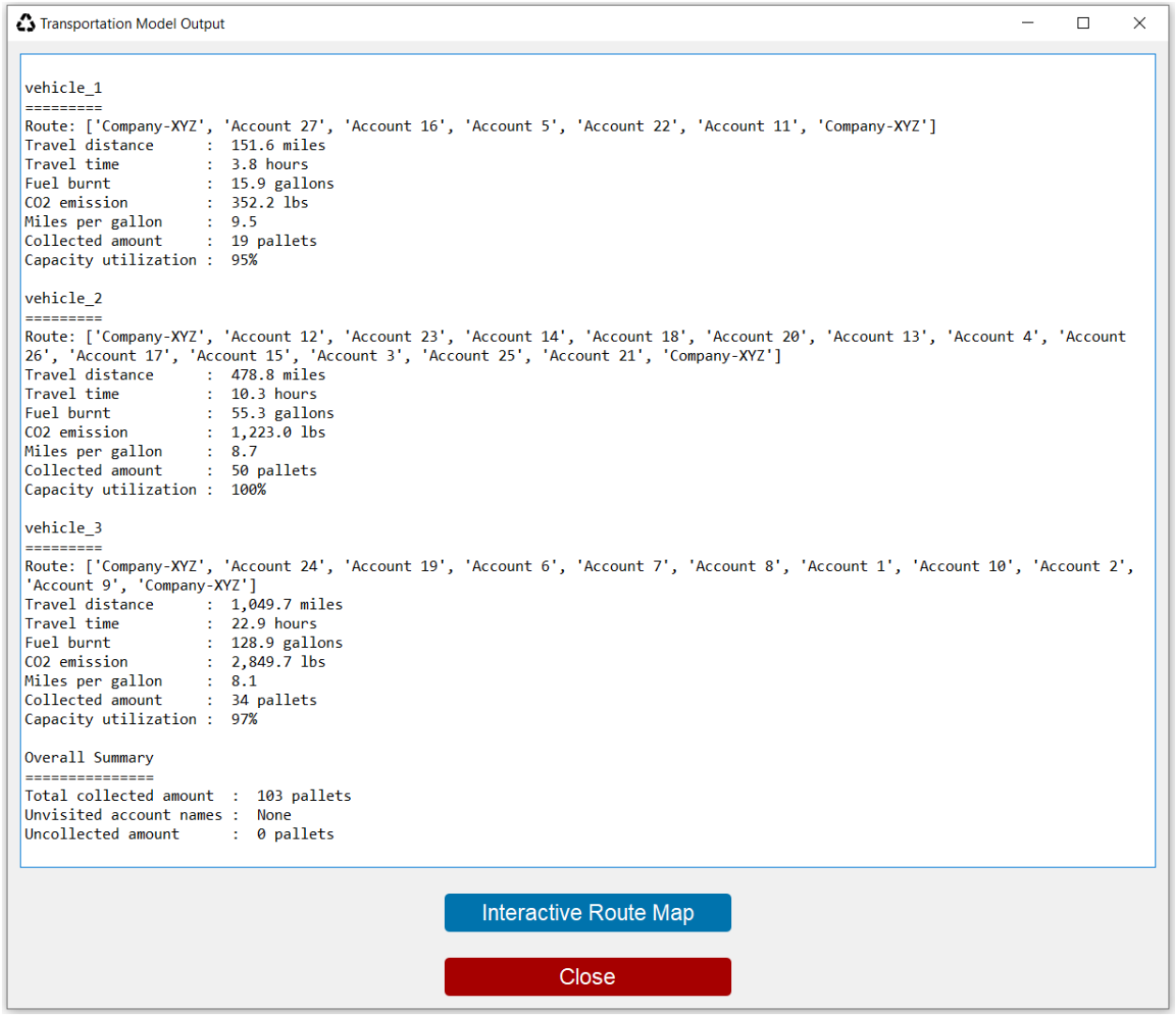

Figure 7. Transportation Model sample output for travel time option.

B. Using Travel Distance Option

Choosing the travel distance minimization option for the Transportation Model will run a simulation in a new window. This minimizes the total distance traveled by collection vehicles. Once the simulation finishes, the user clicks “Show Simulation Results.” A list of routes using vehicles supplied in the “Vehicle List” Excel spreadsheet and accounts supplied in the “Collection Addresses” spreadsheet will be displayed. For each vehicle, the vehicle name, list of accounts included in the route, distance traveled by the vehicle, number of pallets collected, fuel burnt, and CO_2 emissions released by the vehicle’s operation are displayed (see Figure 8).

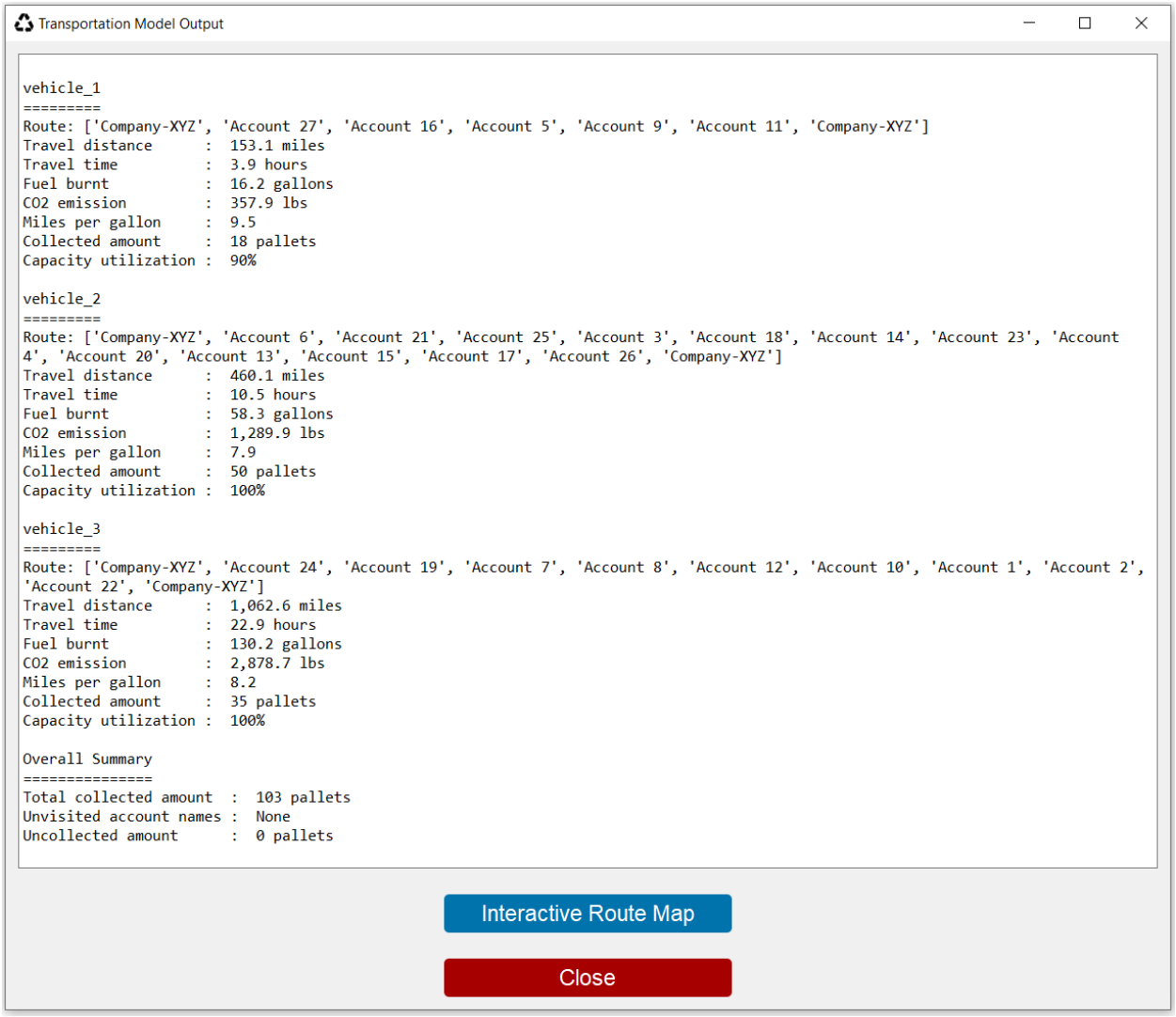

Figure 8. Transportation Model sample output for travel distance option.

2.2.3 Interactive Route Map

The travel time and travel distance minimization options allow the user to view an interactive route map with all pick-up locations and routes.

2.2.3.1 Click on the "Interactive Route Map" button after the simulation results are displayed to open a new window containing a map of the pick-up area.

2.2.3.2 Click on each location on the map to display the associated account number, account name, and address (see Figure 9).

2.2.3.3 To view routes individually, select the Layers button in the top right corner of the map and select the route(s) of interest (see Figure 10).

2.2.3.4 To zoom in and out, use the plus (+) and minus (–) buttons on the top left corner of the map or scroll in and out with the mouse.

2.2.3.5 The map can be easily navigated by clicking and dragging the map area using the left mouse button.

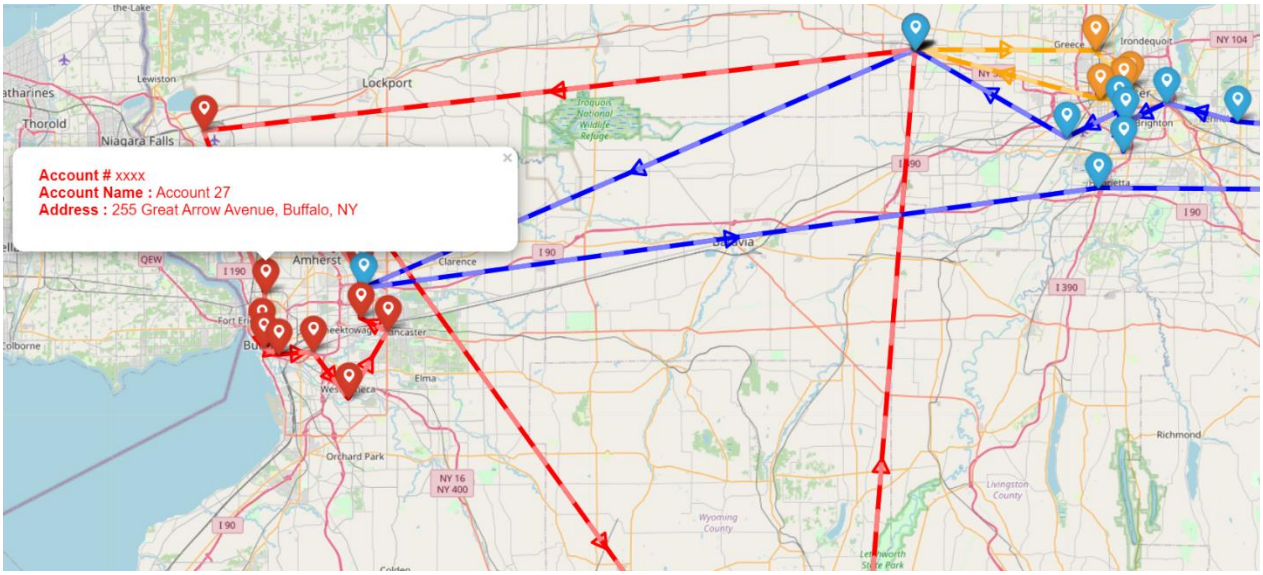

Figure 9. Information shown on the Transportation Model map when a location is selected.

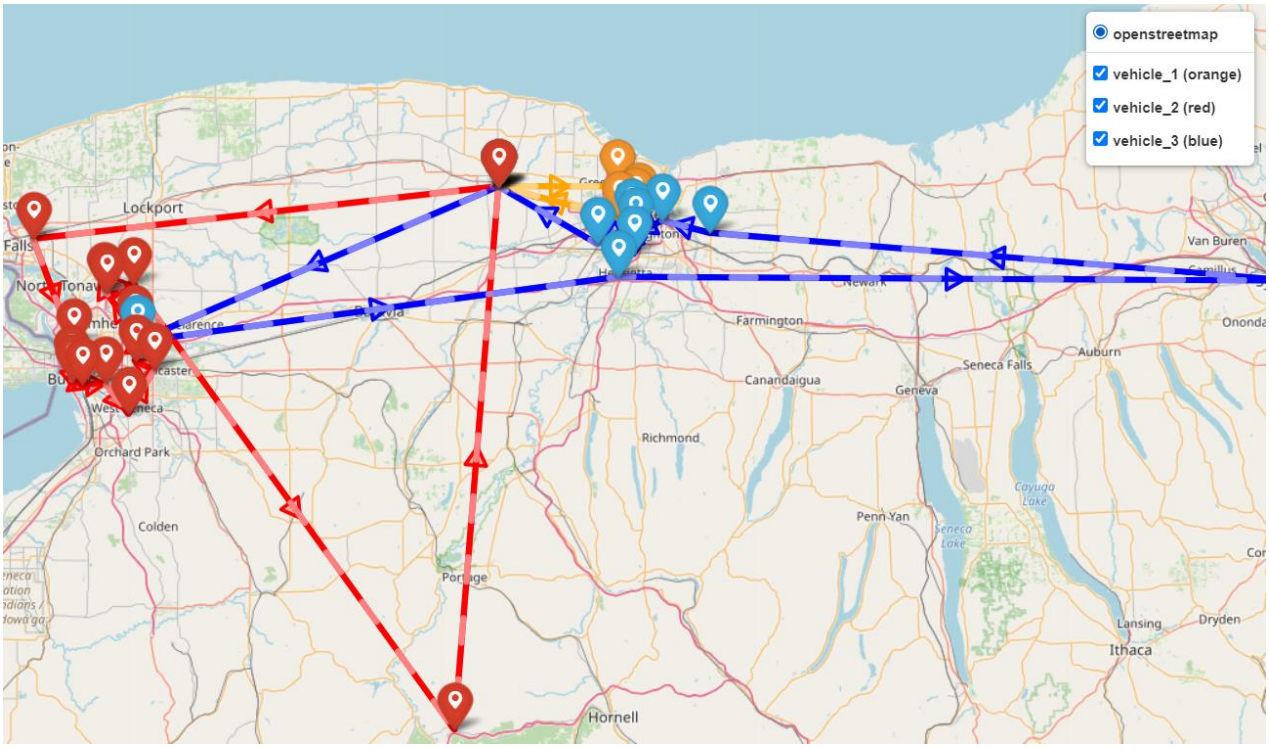

Figure 10. Transportation Model sample map showing optimal routes and collection locations with the Layers option selected.

3. PROCESS MODEL

3.1 Modularity

Because different e-waste recyclers have different process configurations, the process model is designed to be modular, meaning that the user may customize the order and layout of the workstations and storage areas. This step is only set up when running the model for the first time or when there is an update in the process layout.

A workstation is an operation in which some process is performed either manually or mechanically. A storage area is a place in which intermediate materials or finished products are held and can be considered as unit storage (countable items measured by number) or continuous storage (uncountable items measured by mass). This feature is accessible via the Excel file titled "TEMPLATE_process_model_data.xlsx".

The following tutorial creates a process with the configuration shown in Figure 11. The corresponding Excel tabs that need to be included in the TEMPLATE_process_model_data.xlsx file (see Figure 12) for this sample process are explained in the tutorial. Table 1 describes the meanings of different text colors in the Excel file.

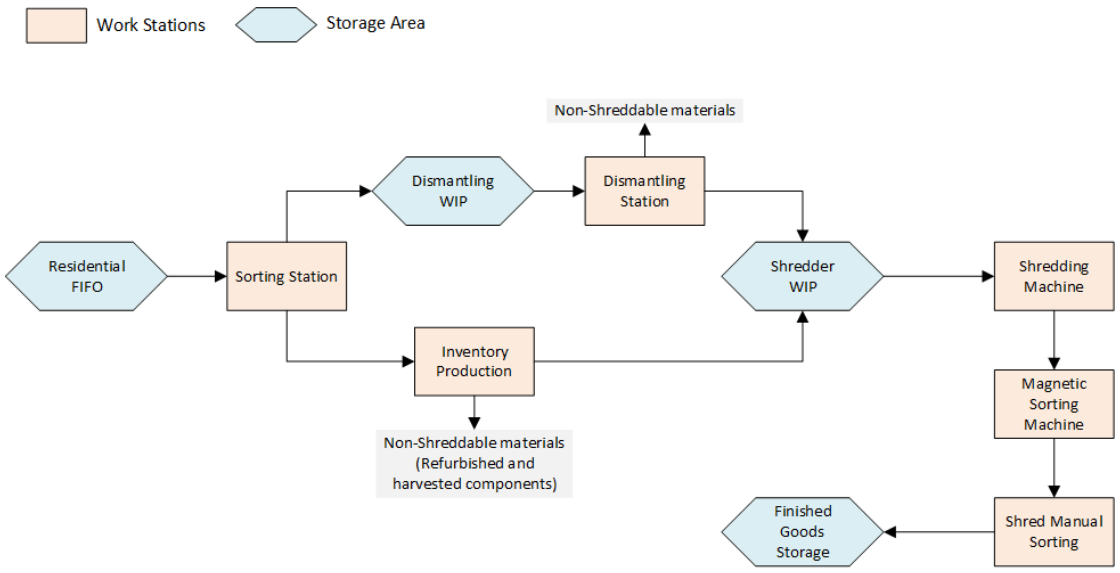

Figure 11. Sample process used to demonstrate process model modularity feature.

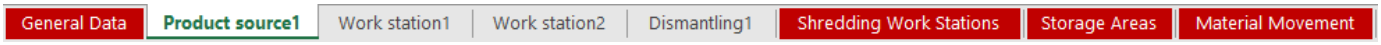

Figure 12. Corresponding spreadsheet tabs for the sample process. The tabs colored in red are permanent tabs that are added to the Excel file by default and should not be deleted. The other tabs are customized by the user based on the process configuration needed.

Table 1. Text color meanings in TEMPLATE_process_model_data.xlsx file.

Text Color	Meaning
Red	Do not change this cell.
Green	Manually input data in this cell.
Blue	Choose value using drop-down menu.

3.1.1 General Data

The first spreadsheet contained in the required Excel file is "General Data," which is a permanent tab. In this spreadsheet, the user enters all the possible workstations and storage areas, workstation output queue names, and product sources included in the overall recycling process. The names do not need to be entered in any particular order. The sample entries for this tutorial are displayed in Figure 13, and descriptions of each entry are displayed in Table 2.

NOTE: *The "none" entry under "Workstation Output Queue Names" is a default option. Do not change this in the spreadsheet.*

	A	B	C
1	**WORK STATIONS AND STORAGE AREAS**	**WORK STATION OUTPUT QUEUE NAMES**	**PRODUCT SOURCES**
2	Residential FIFO	none	Residential product
3	Sorting Station	inventory production items	
4	Inventory Production	dismantling wip items	
5	Dismantling WIP	shredder wip items	
6	Dismantling Station	shredder output	
7	Shredder WIP	magnetic sorter output	
8	Shredding Machine	shred manual sorting output	
9	Magnetic Sorting Machine		
10	Shred Manual Sorting		
11	Finished Goods Storage		

Figure 13. General data spreadsheet tab.

Table 2. Descriptions of sample entries for General Data spreadsheet.

Entry	Description
Workstations and Storage Areas	
Residential FIFO	Residential first-in-first-out
Sorting Station	E-waste sorting station
Inventory Production	Products in good conditions are refurbished
Dismantling WIP	Storage area where materials wait until they are pulled into the dismantling station
Dismantling Station	E-waste dismantling station
Shredder WIP	Storage area where materials wait until they are pulled into the shredding machine
Shredding Machine	E-waste shredding
Magnetic Sorting Machine	Magnetic sorting of e-waste for ferrous type materials
Shred Manual Sorting	Manually sort out the materials which are not supposed to be in the finished goods
Finished Goods Storage	Storage for finished recycled products

Entry	Description
Workstation Output Queue Names	
None	No output queue for this workstation
Inventory Production Items	Outputs to be sent to the inventory production station
Dismantling WIP Items	Outputs to be sent to the dismantling WIP storage area
Shredder WIP Items	Outputs to be sent to the shredder
Shredder Output	Outputs from the shredder
Magnetic Sorter Output	Outputs from the magnetic sorter
Shred Manual Sorting Output	Outputs from the manual sorting station
PRODUCT SOURCES	
Residential product	E-waste sourced from residents

3.1.2 Product Source: "Product source1"

The "Product source1" spreadsheet is used to define information about the product being recycled (see Figure 14). Descriptions of each category for which the user provides information are shown in Table 3. For this tutorial, only one product source is being introduced into the recycling process: residential product. If more product sources (e.g., business product) were to be entered into the process, then the user would create additional spreadsheet tabs, including one for each source.

Table 3. List of categories for the Product source1 spreadsheet with descriptions.

Category	Description
TYPE*	Type of process element being addressed
NAME*	Name of product from Product Sources list established in General Data spreadsheet
INITIAL LOCATION	The location where the product is stored upon arrival. This is the starting point of the process.
PRODUCT CATEGORIES*	Product categories comprising the overall product source
PRODUCT MASS	Mass of each product category within the product (lbs/item)

Category	Description
PRODUCT CATEGORY PROBABILITY	Probability of a particular product category. If there are 100 units of product, how many units would be CRT TV, LCD TV, desktop, laptop, etc. (%)
PROBABILITY OF HAVING BATTERY	Probability that the product contains a battery (%)
PROBABILITY OF HAVING CRT TUBE	Probability that the product contains a CRT tube (%)
BATTERY PERCENTAGE OF PRODUCT MASS	Percentage of product mass comprised by battery (%)
CRT TUBE PERCENTAGE OF PRODUCT MASS	Percentage of product mass comprised by CRT tube (%)
* Controlled with a drop-down menu.	

	A	B	C	D	E	F	G	H	I	J
1	TYPE	Product Source								
2	NAME	Residential product								
3	INITIAL LOCATION	Residential FIFO								
4	PRODUCT AMOUNT (LBS)	500,000								
5	PRODUCT CATEGORIES	crt_tv	crt_monitor	lcd_tv	lcd_monitor	desktop	laptop	printer	small_cee	peripherals
6	PRODUCT MASS	68.28	33.48	26.4	12.5	19.4	4.9	17.9	0.5	0.5
7	PRODUCT CATEGORY PROBABILITY	2.76%	0.25%	1.64%	0.81%	1.40%	0.66%	1.78%	45.33%	45.37%
8	PROBABILITY OF HAVING BATTERY	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	90.0%	50.0%
9	PROBABILITY OF HAVING CRT TUBE	100.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10	BATTERY PERCENTAGE OF PRODUCT MASS	0.0%	0.0%	0.0%	0.0%	0.0%	14.0%	0.0%	20.0%	10.0%
11	CRT TUBE PERCENTAGE OF PRODUCT MASS	60.0%	60.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
12	CRT TUBE PROCESSING COST PER LB	0.11	0.11	0	0	0	0	0	0	0
13	BATTERY PROCESSING COST PER LB	0	0	0	0	0	0.1	0	0.05	0.1

Figure 14. “Product source1” spreadsheet.

3.1.3 Manual Workstations: “Workstation1” and “Workstation2”

The “Workstation1” (see Figure 15) and “Workstation2” (see Figure 16) spreadsheets define information about Manual Workstations in the recycling process. Descriptions of each category for which the user provides information are listed in Table 4. In this tutorial, Workstation1 is a Sorting Station and Workstation2 is Inventory Production.

Table 4. List of categories for the Manual Workstation spreadsheets.

Category	Description
TYPE*	Type of process element being addressed
NAME*	Name of process unit
NO OF OPERATORS	Number of operators required for the process unit

Category	Description
OPERATOR WAGE RATE	Operator wage rate ($/hr)
INPUT QUEUE CAPACITY	Capacity of input queue for this process unit (lbs)
PRODUCT CATEGORIES*	Product categories comprising the overall product source
PROCESSING TIME	Time required to process a product at this process unit (min/item); if a product category is not processed in this workstation, enter 0
NON SHREDDABLE OUTPUT PROBABILITY	Probability of generating non shredable output from this workstation (%); if a product category is not processed in this workstation, enter 0
NON SHREDDABLE OUTPUT PERCENTAGE	Weight of non shredable output of the total weight of the product in percentage generated from this workstation; if a product category is not processed in this workstation, enter zero percentage
OUTPUT QUEUE NAMES	Name of the possible output queues except the non-shredable output
OUTPUT QUEUE CAPACITIES	Capacity of output queue for this process unit (lbs)
OUTPUT QUEUE PROBABILITY	Probability an item will be placed in a specific output queue after processing (%)
* Controlled with a drop-down menu.	

	A	B	C	D	E	F	G	H	I	J
1	TYPE	Manual Work Station								
2	NAME	Sorting Station								
3	NO OF OPERATORS	5								
4	OPERATOR WAGE RATE	10								
5	INPUT QUEUE CAPACITY	5000								
6	PRODUCT CATEGORIES	crt_tv	crt_monitor	lcd_tv	lcd_monitor	desktop	laptop	printer	small_cee	peripherals
7	PROCESSING TIME	0.2	0.1	0.2	0.1	0.2	0.1	0.1	0.1	0.1
8	NON SHREDDABLE OUTPUT PROBABILITY	0%	0%	0%	0%	0%	0%	0%	0%	0%
9	NON SHREDDABLE OUTPUT PERCENTAGE	0%	0%	0%	0%	0%	0%	0%	0%	0%
10	OUTPUT QUEUE NAMES	inventory production items	dismantling wip items							
11	OUTPUT QUEUE CAPACITIES	6000	5000							
12	OUTPUT QUEUE PROBABILITY									
13	crt_tv	0%	100%							
14	crt_monitor	0%	100%							
15	lcd_tv	0%	100%							
16	lcd_monitor	0%	100%							
17	desktop	60%	40%							
18	laptop	75%	25%							
19	printer	0%	100%							
20	small_cee	0%	100%							
21	peripherals	0%	100%							

Figure 15. “Workstation1” spreadsheet.

	A	B	C	D	E	F	G	H	I	J
1	TYPE	Manual Work Station								
2	NAME	Inventory Production								
3	NO OF OPERATORS	5								
4	OPERATOR WAGE RATE	10								
5	INPUT QUEUE CAPACITY	5000								
6	PRODUCT CATEGORIES	crt_tv	crt_monitor	lcd_tv	lcd_monitor	desktop	laptop	printer	small_cee	peripherals
7	PROCESSING TIME	0	0	0	0	4	5	0	0	0
8	NON SHREDDABLE OUTPUT PROBABILITY	0%	0%	0%	0%	90%	80%	0%	0%	0%
9	NON SHREDDABLE OUTPUT PERCENTAGE	0%	0%	0%	0%	20%	30%	0%	0%	0%
10	OUTPUT QUEUE NAMES	shredder wip items								
11	OUTPUT QUEUE CAPACITIES	4000								
12	OUTPUT QUEUE PROBABILITY									
13	crt_tv	100%								
14	crt_monitor	100%								
15	lcd_tv	100%								
16	lcd_monitor	100%								
17	desktop	100%								
18	laptop	100%								
19	printer	100%								
20	small_cee	100%								
21	peripherals	100%								

Figure 16. “Workstation2” spreadsheet.

3.1.4 Dismantling Station: “Dismantling1”

The “Dismantling1” spreadsheet (see Figure 17), which contains information on a dismantling station, has the same categories as the Manual Workstations (see Table 4) except for the Output Queue Probability.

	A	B	C	D	E	F	G	H	I	J
1	TYPE	Dismantling Station								
2	NAME	Dismantling Station								
3	NO OF OPERATORS	7								
4	OPERATOR WAGE RATE	10								
5	INPUT QUEUE CAPACITY	5000								
6	PRODUCT CATEGORIES	crt_tv	crt_monitor	lcd_tv	lcd_monitor	desktop	laptop	printer	small_cee	peripherals
7	PROCESSING TIME	2	2	2	2	3	4	2	0.2	0.2
8	NON SHREDDABLE OUTPUT PROBABILITY	100%	100%	100%	100%	50%	100%	100%	80%	60%
9	NON SHREDDABLE OUTPUT PERCENTAGE	60%	60%	15%	10%	10%	10%	20%	15%	10%
10	OUTPUT QUEUE NAME	shredder wip items								
11	OUTPUT QUEUE CAPACITY	4000								

Figure 17. “Dismantling1” spreadsheet.

3.1.5 Shredding Workstations

The “Shredding Workstations” spreadsheet (see Figure 18) is a default tab which contains information about the different shredding workstations contained in the e-waste recycling process. Descriptions of each category are shown below in Table 5.

Table 5. List of categories for the Shredding Workstations spreadsheet.

Category	Description
NAME*	Name of shredding workstation
INPUT QUEUE CAPACITY	Capacity of input queue for this process unit (lbs); UNIT: lbs; if a machine's input is directly connected to a conveyor, the input queue capacity is the amount of materials the conveyor can move in one minute
PROCESSING CAPACITY	Processing capacity for this process unit (lbs/min)
OUTPUT QUEUE CAPACITY	Capacity of output queue for this process unit (lbs); must be greater than or equal to processing capacity; if a machine's output is directly connected to a conveyor, the output queue capacity equals the amount of materials the conveyor can move in one minute
OUTPUT QUEUE NAME*	Name of the output queue for shredding workstation
NO OF OPERATORS	Number of operators at shredding workstation
OPERATOR WAGE RATE	Operator wage rate at shredding workstation ($/hour)
SORTING FACTOR	Percentage of materials sorted by weight (%)
ENERGY CONSUMPTION RATE	Rate of energy consumed at shredding workstation (kWh)

* Controlled with a drop-down menu.

	A	B	C	D	E
1	NAME	INPUT QUEUE CAPACITY	PROCESSING CAPACITY	OUTPUT QUEUE CAPACITY	OUTPUT QUEUE NAME
2	Shredding Machine	200	200	200	shredder output
3	Magnetic Sorting Machine	200	200	200	magnetic sorter output
4	Shred Manual Sorting	200	200	200	shred manual sorting output

	F	G	H	I
	NO OF OPERATORS	OPERATOR WAGE RATE	SORTING FACTOR	ENERGY CONSUMPTION RATE
	1	10	0%	400
	0	0	10%	300
:	2	10	20%	0

Figure 18. “Shredding Workstations” spreadsheet (split into two screenshots due to size).

3.1.6 Storage Areas

The "Storage Areas" spreadsheet (see Figure 19) is a default tab which contains information about different storage areas throughout the e-waste recycling process. Descriptions of each category are shown in Table 6.

Table 6. List of categories for the Storage Areas spreadsheet.

Category	Description
NAME*	Name of storage area
TYPE*	Type of storage area; "Continuous Storage": stores uncountable materials (e.g., dismantled or shredded materials); "Unit Storage": stores countable items (e.g., TV, laptop, printer, etc. before dismantling)
NO OF OPERATORS	Number of operators at storage area
OPERATOR WAGE RATE	Operator wage rate at storage area ($/hour); if there is no operator in this station, wage rate can be entered as 0
STORAGE CAPACITY	Capacity for storage area (pieces for "Unit Storage" type, lbs for "Continuous Storage" type)

* Controlled with a drop-down menu.

	A	B	C	D	E
1	NAME	TYPE	NO OF OPERATORS	OPERATOR WAGE RATE	STORAGE CAPACITY
2	Residential FIFO	Unit Storage	2	10	500,000
3	Dismantling WIP	Unit Storage	0	0	100,000
4	Shredder WIP	Continuous Storage	1	10	200,000
5	Finished Goods Storage	Continuous Storage	0	0	10,000,000

Figure 19. "Storage Areas" spreadsheet.

3.1.7 Material Movement

The "Material Movement" spreadsheet (see Figure 20) is a default tab which is used to establish the order of the e-waste recycling process. Descriptions of each category are shown in Table 7.

Table 7. List of categories for the Material Movement spreadsheet.

Category	Description
NAME	Name of material movement (LOADING STATION NAME to UNLOADING STATION NAME)
LOADING STATION NAME*	Name of loading station
LOADING STATION OUTPUT QUEUE NAME*	Name of loading station output queue
UNLOADING STATION NAME*	Name of unloading station
MOVING CAPACITY	Moving capacity for material movement (lbs/hour)

* Controlled with a drop-down menu.

	A	B	C	D	E
1	NAME	LOADING STATION NAME	LOADING STATION OUTPUT QUEUE NAME	UNLOADING STATION NAME	MOVING CAPACITY
2	res FIFO to sorting	Residential FIFO	none	Sorting Station	500
3	sorting station to inventory production	Sorting Station	inventory production items	Inventory Production	333
4	sorting station to dismantling wip	Sorting Station	dismantling wip items	Dismantling WIP	333
5	inventory production to shredder wip	Inventory Production	shredder wip items	Shredder WIP	333
6	dismantling wip to dismantling station	Dismantling WIP	none	Dismantling Station	333
7	dismantling station to shredder wip	Dismantling Station	shredder wip items	Shredder WIP	333
8	shredder wip to shredding machine	Shredder WIP	none	Shredding Machine	83
9	shredding machine to magnetic sorter	Shredding Machine	shredder output	Magnetic Sorting Machine	200
10	magnetic sorter to shred manual sorting	Magnetic Sorting Machine	magnetic sorter output	Shred Manual Sorting	200
11	shred manual sorting to finished goods storage	Shred Manual Sorting	shred manual sorting output	Finished Goods Storage	200

Figure 20. “Material Movement” spreadsheet.

3.2 Inputs

The inputs required for entry into the process model window are shown in Figure 21 and described in detail below.

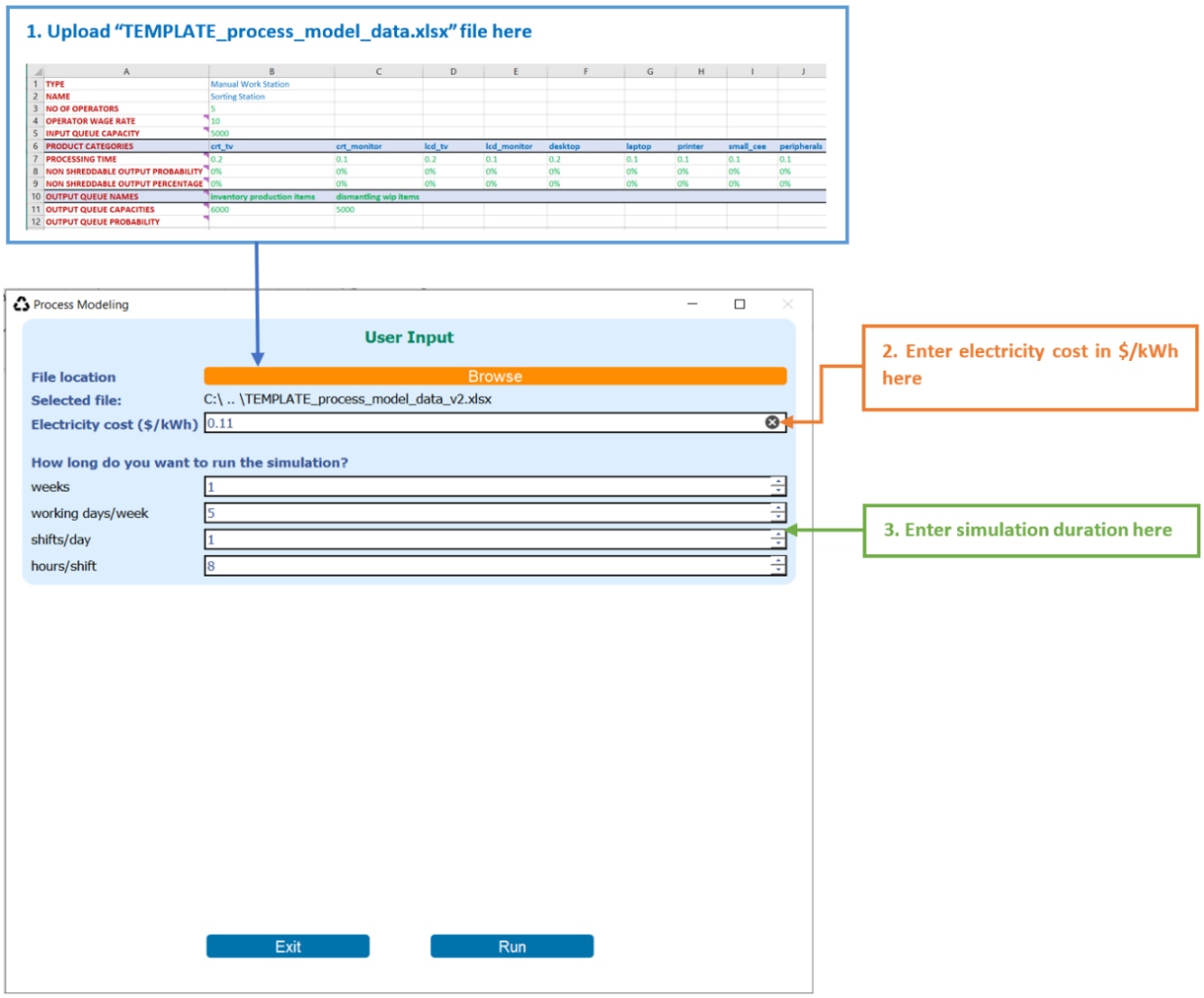

Figure 21. Window displayed when the Process Model is selected.

1. File location
   The user browses for the "TEMPLATE_process_model_data.xlsx" Excel file described in the section above and inserts it here.

2. Electricity cost ($/kWh)
   The user enters the electricity cost in $/kWh.

3. How long do you want to run the simulation?
   The user enters the number of weeks, working days per week, shifts per day, and hours per shift for the e-waste recycling process of interest.

3.3 Outputs

The outputs from the process model are shown in Figure 22 and described in detail below.

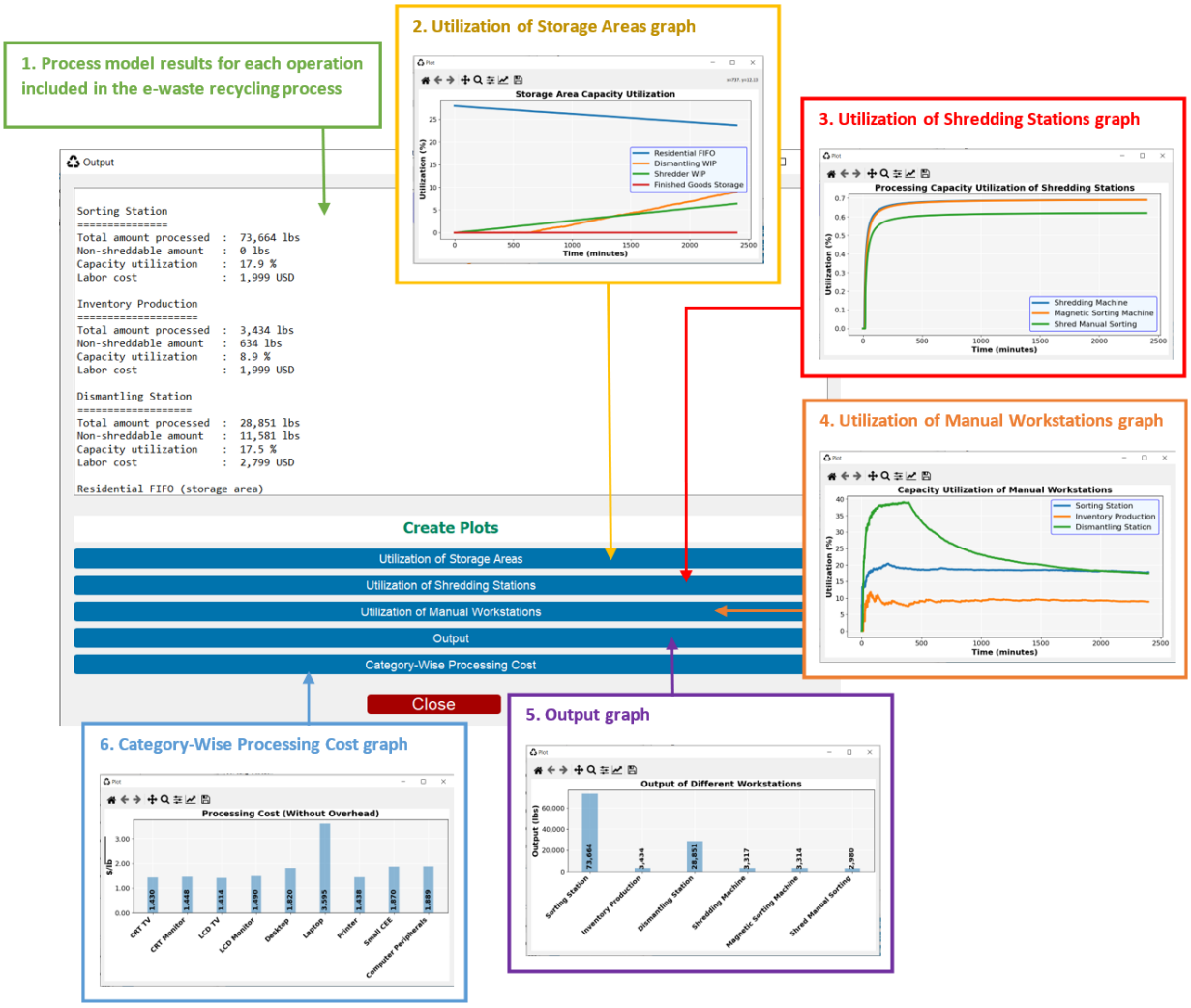

Figure 22. Process Model Output window.

1. Process Model Output

The Process Model outputs data for each operation in the e-waste recycling process and displays options for different plots of the data. For each unit, the total amount of e-waste processed (lbs), non-shredable e-waste amount (lbs), capacity utilization (%), and labor cost (USD) are shown. For this tutorial, the following operations in the recycling process are listed in the output window (i.e., all the operations included in the Figure 11 process diagram):

- Sorting Station
- Inventory Production
- Dismantling Station

- Residential FIFO (Storage Area)
- Dismantling WIP (Storage Area)
- Shredder WIP (Storage Area)
- Finished Goods Storage (Storage Area)
- Shredding Machine
- Magnetic Sorting Machine
- Shred Manual Sorting.

2. Plot: Utilization of Storage Areas.

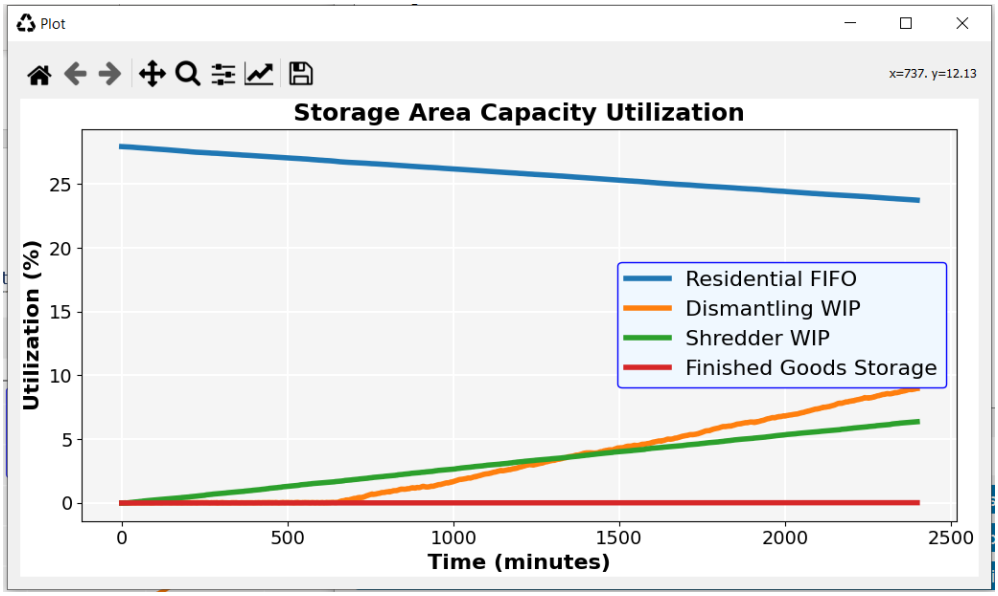

Figure 23. Storage area capacity utilization (%) over time.

3. Plot: Utilization of Shredding Stations.

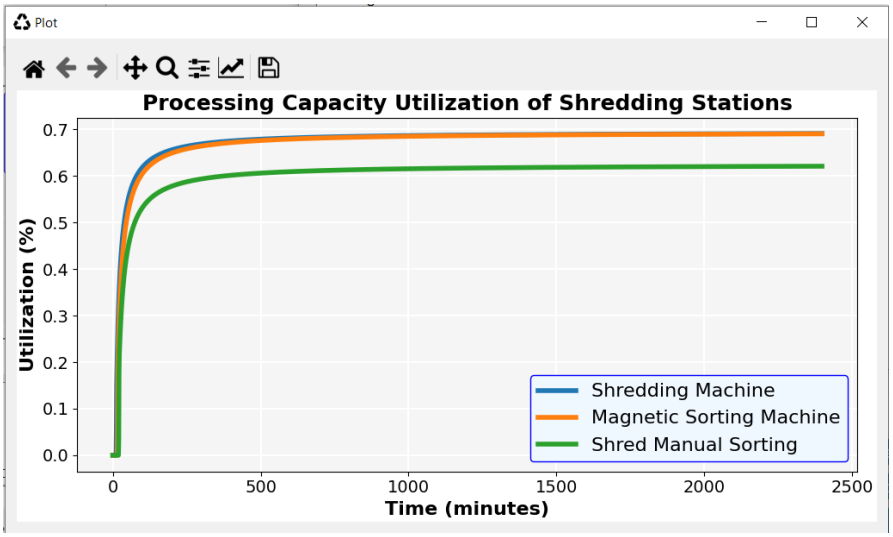

Figure 24. Shredding station capacity utilization (%) over time.

4. Plot: Utilization of Manual Workstations.

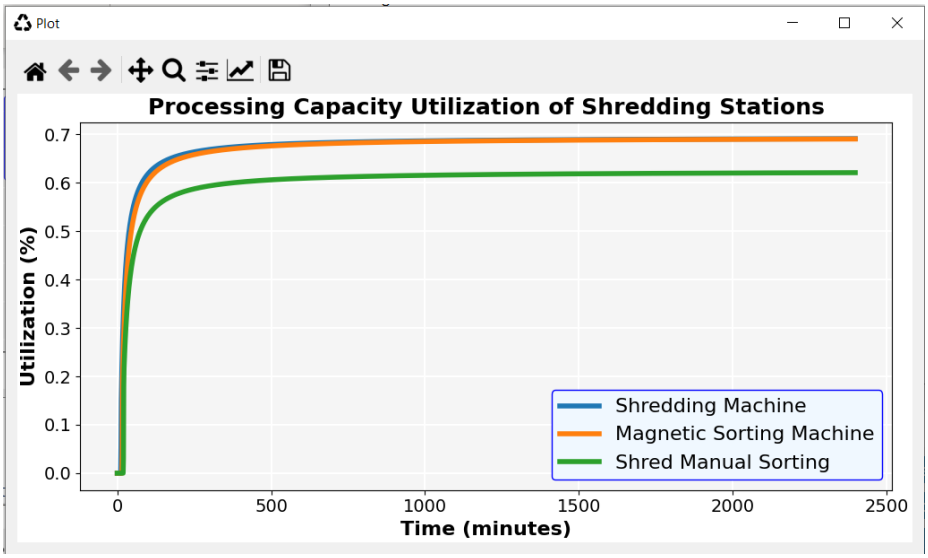

Figure 25. Manual workstation capacity utilization (%) over time.

5. Plot: Output.

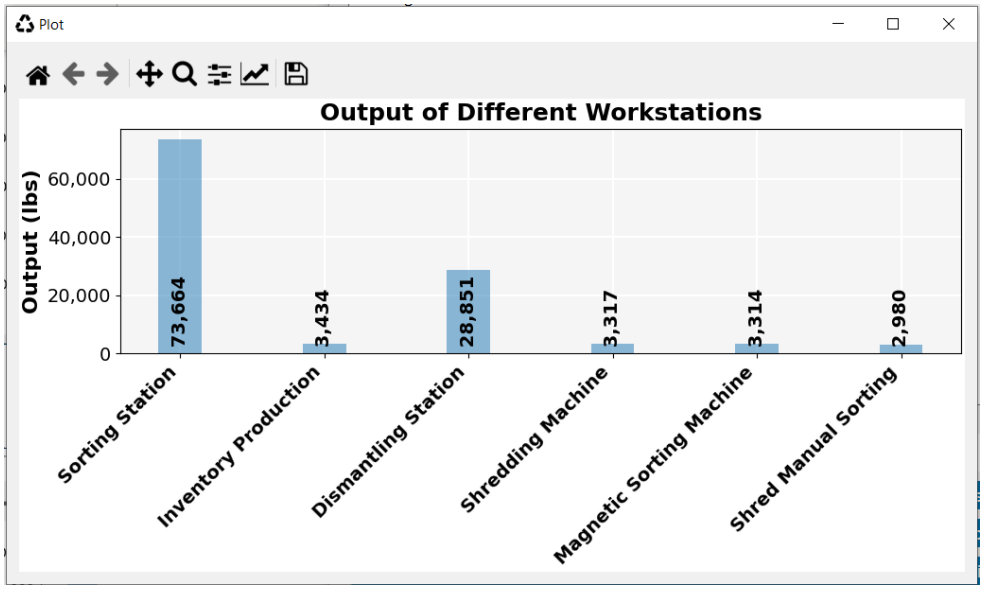

Figure 26. Outputs (lbs) for different workstations.

6. Plot: Category-Wise Processing Cost.

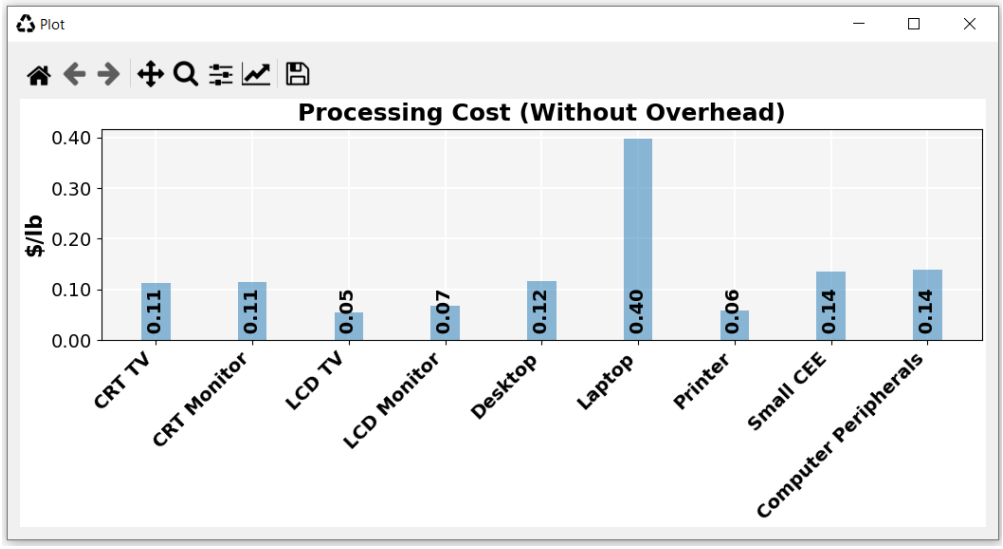

Figure 27. Processing cost per lb for different e-waste products.

4. ECONOMIC MODEL

4.1 Window for Choosing Options

Selecting the Economic Model will display a window asking the user to choose between two options (see Figure 28). The first option is to run the model independently. This will open another window in which the user must manually enter all the requested data parameters. On the other hand, if the user has already run the process model, the results from this model can be migrated to the economic model. A new window will be opened with the applicable data automatically filled in. The user will need to manually enter the remaining data parameters to run the model.

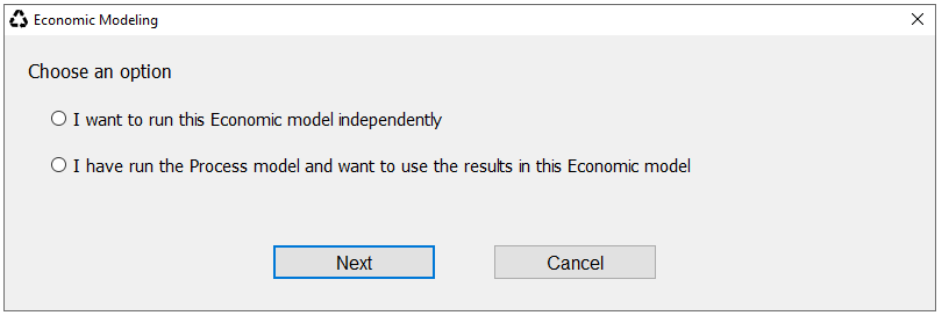

Figure 28. Window view when the Economic Model option is selected.

4.2 Input Option 1: Run Model Independently

Running the Economic Model independently requires the user to manually input the requested data shown in Figure 29. Following is a description of the different parameters required for each section.

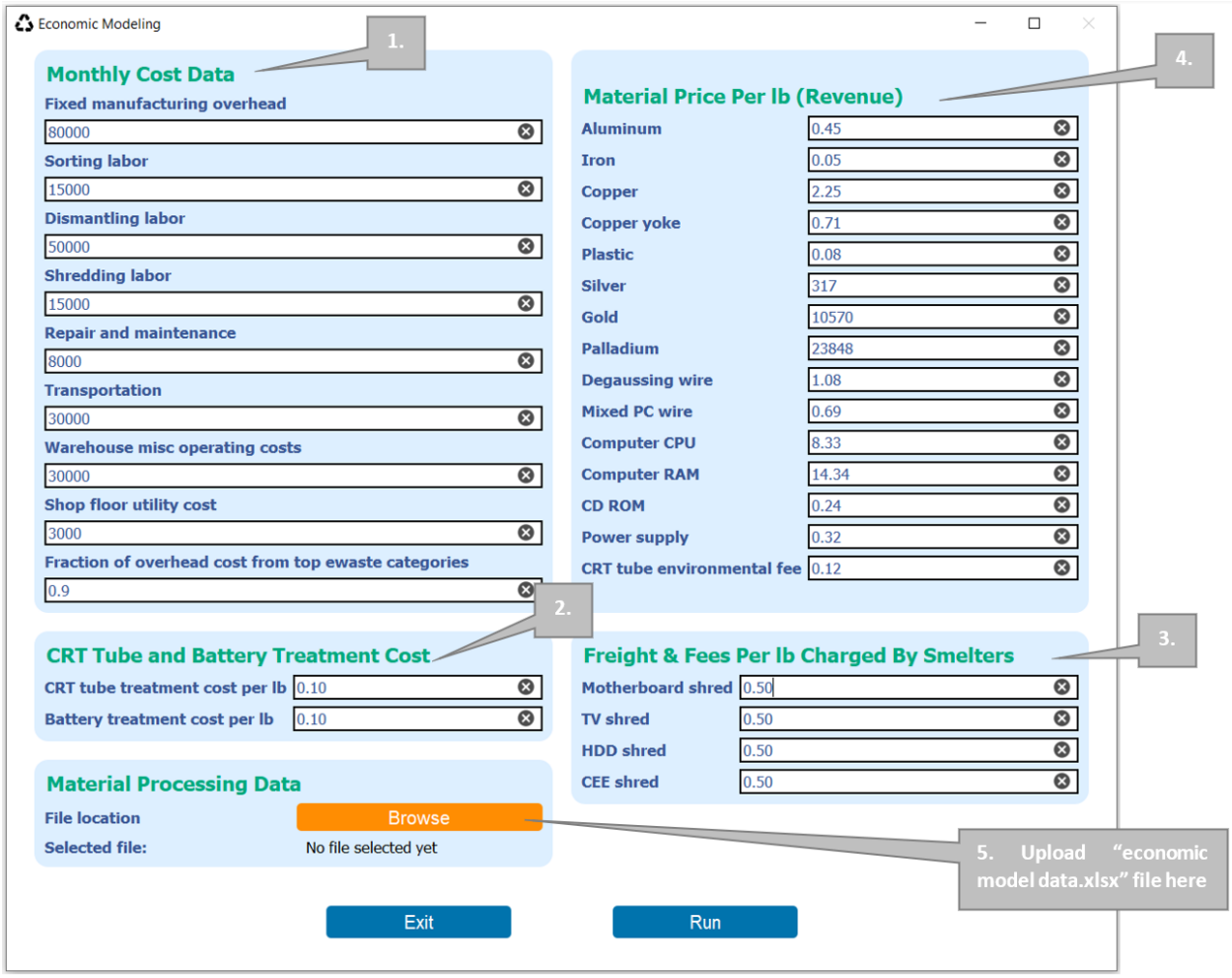

Figure 29. Inputs for running the Economic Model independently.

1. Monthly cost data.
   The monthly cost data for the e-waste recycling process consists of the parameters listed in Table 8. In addition, rolling over the name of each parameter in the model window will display this information.

Table 8. Monthly cost data parameters for the Economic Model.

Parameter	Description
Fixed manufacturing overhead	Insurance, property tax, safety and environmental cost, compliance fee, auditing fee, rent, supervisors' salary, EHS personnel salary, housekeeping, etc. ($/month)
Sorting labor	Sorting labor salary ($/month)
Dismantling labor	Dismantling labor salary ($/month)
Shredding labor	Shredding labor salary ($/month)

Parameter	Description
Repair and maintenance	Machinery repair and maintenance expenses ($/month)
Transportation	Fuel, driver salary, truck maintenance ($/month)
Warehouse misc operating costs	Any other costs related to warehouse operation e.g., storage cost, forklift driver salary, forklift fuel, etc. ($/month)
Shop floor utility cost	Electricity, water, gas, etc. ($/month)
Fraction of overhead costs from top e-waste categories	What fraction of the total overhead cost comes from the top e-waste categories? (value from 0 to 1)

2. CRT tube and battery treatment cost.
   The CRT tube and battery treatment costs consist of the parameters listed in Table 9.

Table 9. CRT tube and battery treatment cost parameters for Economic Model.

Parameter	Description
CRT tube treatment cost per lb	Cost of treating one lb of cathode ray tubes ($/lb) charged by the third-party processing stakeholders
Battery treatment cost per lb	Cost of treating one lb of batteries ($/lb) charged by the third-party processing stakeholders

3. Freight and fees per lb by smelters.
   The freight and fees per pound by smelters consist of the parameters listed in Table 10.

Table 10. Parameters related to freight and fees per pound charged by smelters for Economic Model.

Parameter	Description
Motherboard shred	Freight and treatment cost charged by smelters for motherboard shred ($/lb)
TV shred	Freight and treatment cost charged by smelters for TV shred ($/lb)
HDD shred	Freight and treatment cost charged by smelters for HDD shred ($/lb)
CEE shred	Freight and treatment cost charged by smelters for CEE shred ($/lb)

4. Material price per lb.
The material price per pound section consists of the parameters listed in Table 11.

Table 11. Material price per pound (revenue) parameters for Economic Model.

Parameter	Description
Aluminum	Selling price of aluminum per pound ($/lb)
Iron	Selling price of iron per pound ($/lb)
Copper	Selling price of copper per pound ($/lb)
Copper yoke	Selling price of copper yoke per pound ($/lb)
Plastic	Selling price of plastic per pound ($/lb)
Silver	Selling price of silver per pound ($/lb)
Gold	Selling price of gold per pound ($/lb)
Palladium	Selling price of palladium per pound ($/lb)
Degaussing wire	Selling price of degaussing wire per pound ($/lb)
Mixed PC wire	Selling price of mixed PC wire per pound ($/lb)
Computer CPU	Selling price of computer CPU per pound ($/lb)
Computer RAM	Selling price of computer RAM per pound ($/lb)
CD ROM	Selling price of CD ROM per pound ($/lb)
Power supply	Selling price of power supply per pound ($/lb)
CRT tube environmental fee	CRT tube processing fee received by the recycling company ($/lb)

5. Material processing data.
In addition to the data parameters that must be entered directly in the Economic Model, the user must provide material processing data. This data is entered into an Excel file named "TEMPLATE_economic_model_data.xlsx" (Figure 30). Within the Excel file, the user clicks on the triangle symbols on the top right corner of each cell for more information on each variable that needs to be entered. Alternatively, the descriptions for each variable are shown in Table 12.

	A	B	C	D	E	F	G	H	I	J
1	Variable	crt_tv	crt_monitor	lcd_tv	lcd_monitor	desktop	laptop	printer	small_cee	computer_peri
2	recycled_amount_bus	xxxxxxx	xxxxxxx	xxxxxxx	xxxxxxx	xxxxxxx	xxxxxxx	xxxxxxx	xxxxxxx	xxxxxxx
3	recycled_amount_res	xxxxxxx	xxxxxxx	xxxxxxx	xxxxxxx	xxxxxxx	xxxxxxx	xxxxxxx	xxxxxxx	xxxxxxx
4	perc_remarketable_items	xxxxxxx	xxxxxxx	xxxxxxx	xxxxxxx	xxxxxxx	xxxxxxx	xxxxxxx	xxxxxxx	xxxxxxx
5	dismantling_time_per_item_in_minutes	xxxxxxx	xxxxxxx	xxxxxxx	xxxxxxx	xxxxxxx	xxxxxxx	xxxxxxx	xxxxxxx	xxxxxxx
6	weight_per_item_in_lbs	xxxxxxx	xxxxxxx	xxxxxxx	xxxxxxx	xxxxxxx	xxxxxxx	xxxxxxx	xxxxxxx	xxxxxxx
7	motherboard_perc	0.0000%	0.0000%	0.0000%	0.0000%	9.4000%	13.7000%	0.0000%	0.0000%	0.0000%
8	Fe_perc_motherboard	0.0000%	0.0000%	0.0000%	0.0000%	1.3000%	3.7000%	0.0000%	0.0000%	0.0000%
9	Al_perc_motherboard	0.0000%	0.0000%	0.0000%	0.0000%	1.8000%	1.8000%	0.0000%	0.0000%	0.0000%
10	Cu_perc_motherboard_shred	0.0000%	0.0000%	0.0000%	0.0000%	20.6000%	20.1000%	0.0000%	0.0000%	0.0000%
11	Ag_perc_motherboard_shred	0.0000%	0.0000%	0.0000%	0.0000%	0.0585%	0.1151%	0.0000%	0.0000%	0.0000%
12	Au_perc_motherboard_shred	0.0000%	0.0000%	0.0000%	0.0000%	0.0246%	0.0659%	0.0000%	0.0000%	0.0000%
13	Pd_perc_motherboard_shred	0.0000%	0.0000%	0.0000%	0.0000%	0.0154%	0.0209%	0.0000%	0.0000%	0.0000%
14	hdd_perc	0.0000%	0.0000%	0.0000%	0.0000%	3.5000%	3.5000%	0.0000%	0.0000%	0.0000%
15	Fe_perc_hdd	0.0000%	0.0000%	0.0000%	0.0000%	13.0000%	13.0000%	0.0000%	0.0000%	0.0000%
16	Al_perc_hdd	0.0000%	0.0000%	0.0000%	0.0000%	17.4000%	17.4000%	0.0000%	0.0000%	0.0000%
17	Cu_perc_hdd_shred	0.0000%	0.0000%	0.0000%	0.0000%	2.2000%	2.2000%	0.0000%	0.0000%	0.0000%
18	Ag_perc_hdd_shred	0.00000%	0.00000%	0.00000%	0.00000%	0.01050%	0.01050%	0.00000%	0.00000%	0.00000%
19	Au_perc_hdd_shred	0.00000%	0.00000%	0.00000%	0.00000%	0.00160%	0.00160%	0.00000%	0.00000%	0.00000%
20	Pd_perc_hdd_shred	0.00000%	0.00000%	0.00000%	0.00000%	0.00170%	0.00170%	0.00000%	0.00000%	0.00000%

Figure 30. Material processing sample data contained in “economic model data.xlsx” Excel file.

Table 12. Economic Model data Excel spreadsheet variable list with descriptions.

Variable	Description
recycled_amount_bus	Monthly amount of business e-wastes (lbs) processed by the recycler
recycled_amount_res	Monthly amount of residential e-wastes (lbs) processed by the recycler
perc_remarketable_items	Percentage of received e-wastes which are re-marketable after refurbishing (%)
dismantling_time_per_item_in_minutes	Time required to dismantle an e-waste item (mins)
mass_per_item_in_lbs	Weight of e-waste item (lbs)
motherboard_perc	Percentage of e-waste weight coming from motherboards (%)
Fe_perc_motherboard	Percentage of iron in motherboard by weight (%)
Al_perc_motherboard	Percentage of aluminum in motherboard by weight (%)
Cu_perc_motherboard_shred	Percentage of copper in motherboard shred by weight (%)
Ag_perc_motherboard_shred	Percentage of silver in motherboard shred by weight (%)
Au_perc_motherboard_shred	Percentage of gold in motherboard shred by weight (%)
Pd_perc_motherboard_shred	Percentage of palladium in motherboard shred by weight (%)

Variable	Description
hdd_perc	Percentage of e-waste weight coming from hard disk drives (%)
Fe_perc_hdd	Percentage of iron in hard disk drive by weight (%)
Al_perc_hdd	Percentage of aluminum in hard disk drive by weight (%)
Cu_perc_hdd_shred	Percentage of copper in hard disk drive shred by weight (%)
Ag_perc_hdd_shred	Percentage of silver in hard disk drive shred by weight (%)
Au_perc_hdd_shred	Percentage of gold in hard disk drive shred by weight (%)
Pd_perc_hdd_shred	Percentage of palladium in hard disk drive shred by weight (%)
Fe_perc_cee	Percentage of iron in consumer electronics by weight (%)
Al_perc_cee	Percentage of aluminum in consumer electronics by weight (%)
Cu_perc_cee_shred	Percentage of copper in consumer electronics shred by weight (%)
Ag_perc_cee_shred	Percentage of silver in consumer electronics shred by weight (%)
Au_perc_cee_shred	Percentage of gold in consumer electronics shred by weight (%)
Pd_perc_cee_shred	Percentage of palladium in consumer electronics shred by weight (%)
tv_pcb_perc	Percentage of e-waste weight coming from televisions printed circuit boards (%)
Fe_perc_tv	Percentage of iron in television by weight (%)
Al_perc_tv	Percentage of aluminum in television by weight (%)
Cu_perc_tv_shred	Percentage of copper in TV shred by weight (%)
Ag_perc_tv_shred	Percentage of silver in TV shred by weight (%)
Au_perc_tv_shred	Percentage of gold in TV shred by weight (%)
Pd_perc_tv_shred	Percentage of palladium in TV shred by weight (%)

Variable	Description
Al_perc	Percentage of e-waste weight coming from aluminum (%)
Fe_perc	Percentage of e-waste weight coming from iron (%)
Cu_perc	Percentage of e-waste weight coming from copper (%)
plastic_perc	Percentage of e-waste weight coming from plastic (%)
screen_perc	Percentage of e-waste weight coming from screens (%)
CRT_tube_perc	Percentage of e-waste weight coming from cathode ray tubes (%)
Cu_yoke_perc	Percentage of e-waste weight coming from copper yokes (%)
degaussing_wire_perc	Percentage of e-waste weight coming from degaussing wires (%)
battery_perc	Percentage of e-waste weight coming from batteries (%)
cd_rom_perc	Percentage of e-waste weight coming from CD ROMs (%)
power_sup_perc	Percentage of e-waste weight coming from power supplies (%)
CPU_perc	Percentage of e-waste weight coming from central processing units (%)
RAM_perc	Percentage of e-waste weight coming from random access memory (%)
mixed_pc_wire_perc	Percentage of e-waste weight coming from mixed PC wires (%)

4.3 Input Option 2: Use Process Model Results

If the user choose option 2, then it will automatically capture some data like monthly recycled quantity, sorting labor cost, dismantling labor cost, shredding labor cost, electricity cost of the machines, CRT and battery treatment cost, etc. from the Process Model. Therefore, the Process Model must be run before choosing this option. The remaining data parameters for the Economic Model must be filled in by the user using the descriptions provided in Section 4.

4.4 Outputs

Whether option 1 (run model independently) or option 2 (use process model results) is selected for the economic model, the outputs window will display the same performance indicators since the same performance matrix is being calculated for both options. When the user selects the "Run" option in the input window, the model will display an output window (see Figure 31). The user can choose to view an item-wise plot of the data (see Figure 32), which displays the revenue, processing cost, and profit per pound for each e-waste item category. Alternatively, the user can choose to view an overall plot of the data (see Figure 33) which displays the overall revenue, processing cost, and profit per pound for all e-waste item categories.

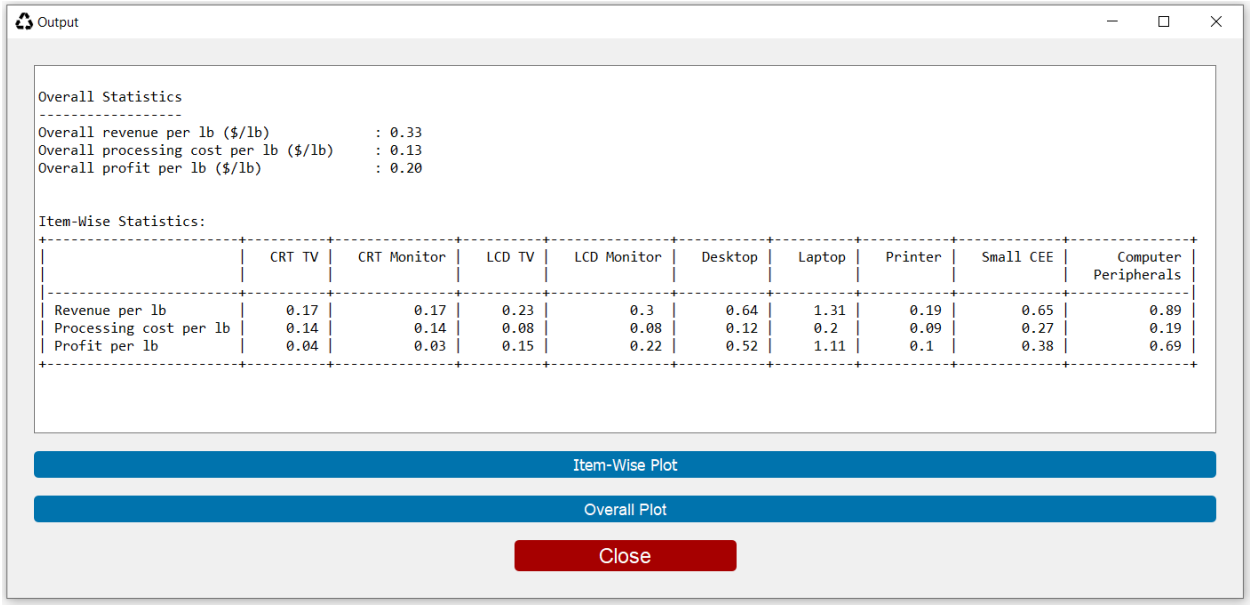

Figure 31. Economic Model Output window.

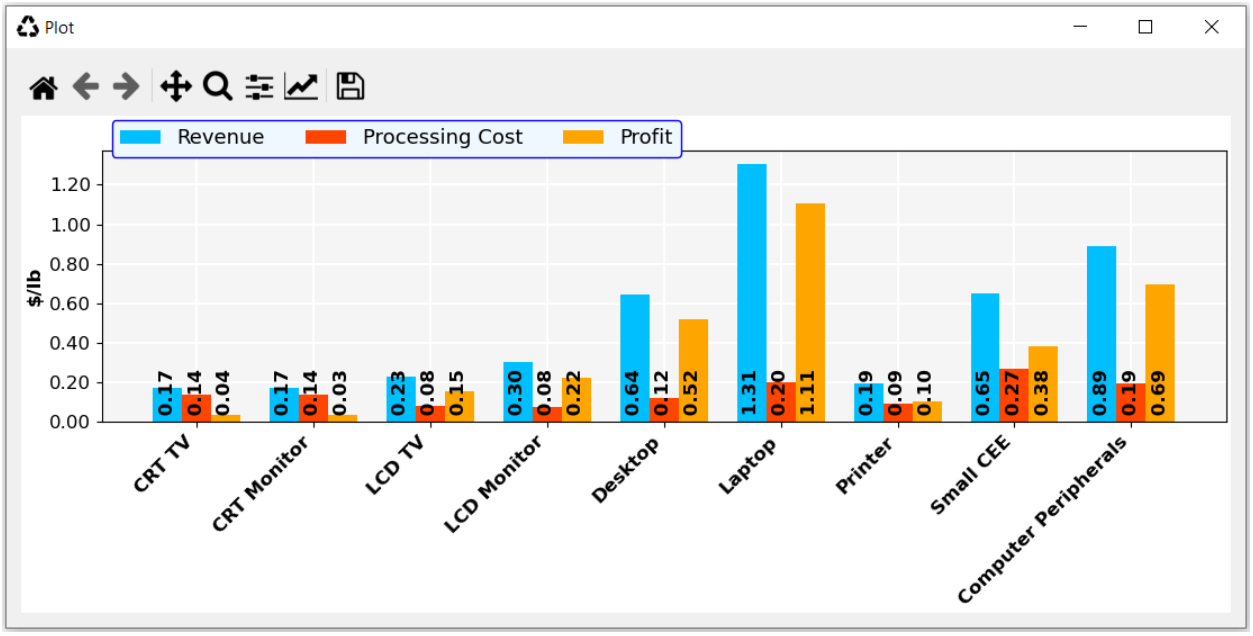

Figure 32. Economic Model item-wise plot.

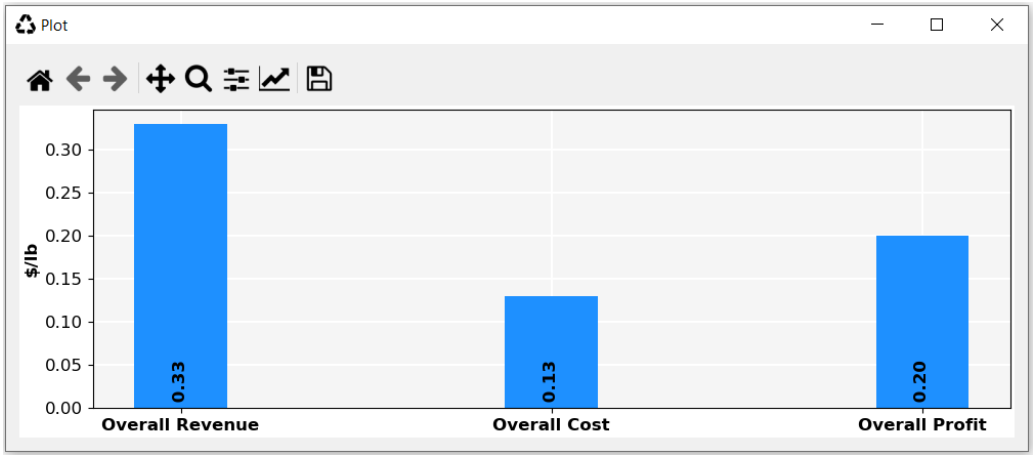

Figure 33. Economic Model overall plot.

5. ACKNOWLEDGEMENTS

This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Advanced Manufacturing Office Award Number DE-EE0007897 awarded to the REMADE Institute, a division of Sustainable Manufacturing Innovation Alliance Corp.

The authors would also like to thank Sunnking for their feedback during training sessions that helped improve the functionality of the applications.