LSM TEA Full
Software User Guide

April 2022
Version: 1.1.3

Laboratory for Sustainable Manufacturing (LSM) – Purdue University

Acknowledgement

This software development was supported by the Critical Materials Institute, a Department of Energy Innovation Hub led by the U.S. Department of Energy's Ames Laboratory and supported by DOE's Office of Energy Efficiency and Renewable Energy's Advanced Manufacturing Office, which supports early-stage research to advance innovation in U.S. manufacturing and promote American economic growth and energy security. CMI seeks ways to reduce supply risks on rare-earth metals and other materials critical to the success of clean energy technologies.

Developers

Geyan Zheng

Muhammad Raziq Raif Ramli

Yazin Farook

Sidi Deng

John W. Sutherland

Table of Content

Terminologies and Abbreviations

TEA: techno economic assessment
VBA: visual based applications
GUI: graphical user interface

NPV: net present value
End: the cash and cash equivalents at the end of each year
IRR: internal rate of return
NCF: net cash flow
MARS: the modified accelerated cost recovery system
CoC: cash on cash return
BEP: break-even point
OPEX: operating expenses or expenditure
CAPEX: capital expenses or expenditure
R&D: research and development

The official title of the software is “LSM TEA Full.” However, throughout this document, it is sometimes referred to as “TEA software,” or just “software.”

1. Introduction

1.1 Motivation and Objective

Techno-economic assessment (TEA) is a technique used to evaluate the economic performance of a project, process, or technology by implementing production cost modeling and financial analysis. For a new technology at its development stage, a TEA can provide insightful support to the following:

- evaluate economic feasibility;
- identify bottlenecks (large costs);
- explore improvement opportunities by evaluating alternative approaches (e.g., different feedstock, material, process flow settings).

In short, TEAs can expedite the progress of projects moving towards commercialization and provide guidelines for identifying economically feasible settings. TEAs are emerging as an indispensable tool to ensure the industrial implementation of newly developed technologies, the economic consulting itself could have already constituted a cost factor. Therefore, researchers are encouraged to conduct economic evaluations on their own.

In light of this, the motivation behind the development of TEA software is to offer a supporting toolkit to help researchers/scientists perform TEAs on their own projects. The software platform aims to propose a generalized TEA prototype that adapts to most scenarios. It is envisioned that the software can assist in making more economically informed decisions, hence advance the Technology Readiness Level (TRL) of the projects undertaken.

This specific software version is named "LSM TEA Full." The software includes a user-friendly platform with a graphical user interface (GUI) frontend, which enables interactions with users. The existing TEA methods are codified into the backend of the application, which generates TEA output based on the input from users.

1.2 Scope and Utilities

LSM TEA Full software is a stand-alone TEA software, with a primary emphasis on TRL (4-6) projects. The software has a user-friendly graphical interface that allows users to design and customize process flow diagrams by interacting with GUI elements. In particular, the software features a canvas that provides a graphical representation of interconnected system components. TEA reports are generated based on lab data and other relevant information input from the users through the interface.

Features of the software include:

- Drag & Drop: By selecting and connecting various blocks elements on the main canvas of the software, users can develop a flow diagram representation of the system.
- Save & Load: The software can save the current progress into individual "tea" files, and then load these saved versions for later work.
- Compatibility with Excel: the software enables users to generate a Microsoft Excel workbook that contains TEA output reports.
- Competitive Technology comparison: the software can run multiple TEA scenarios to enable comparisons of technologies in development with other competitive technologies.

2. First-Time Users

2.1 Installation and Structure of Files

(1) Windows Users

Download and unzip the **LSM TEA Full Win** package. Once this is done, open the extracted folder (see Figure 1).

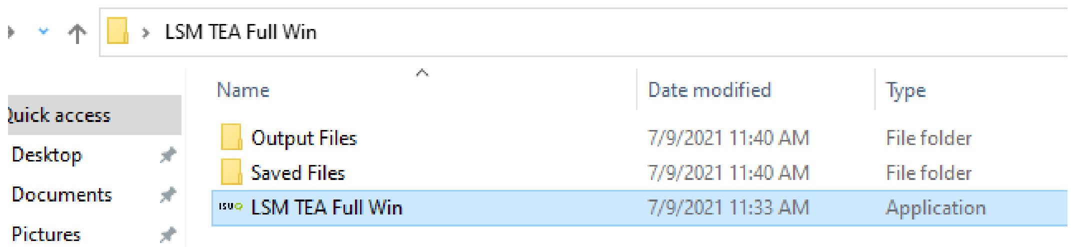

Figure 1. Software Main Folder (Windows)

Click the executable file **LSM TEA Full Win** to initiate the software. If a security warning pops up, please choose **Run anyway**.

(2) Mac Users

Download and unzip the **LSM TEA Full Mac** package. Once this is done, open the extracted folder and click the executable file **LSM TEA Full Mac** (see Figure 2).

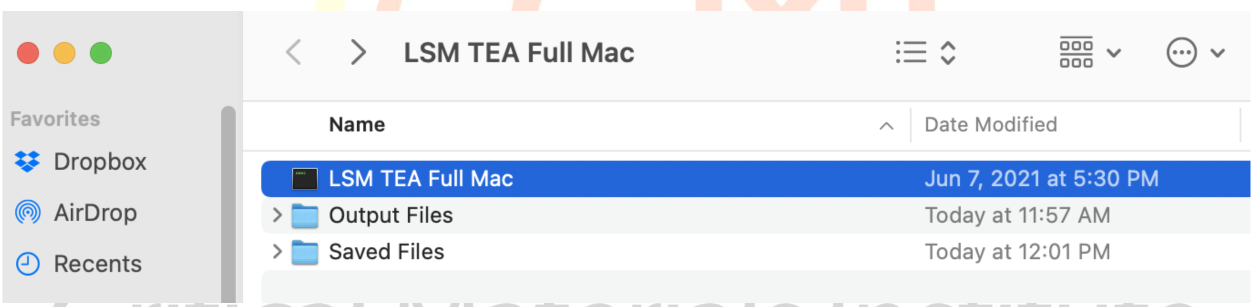

Figure 2. Software Main Folder (Mac)

A security warning might pop up first. Please click the question mark icon in the warning message and change the **Mac Security and Privacy** settings by following the prompts on screen, as illustrated in Figure 3.

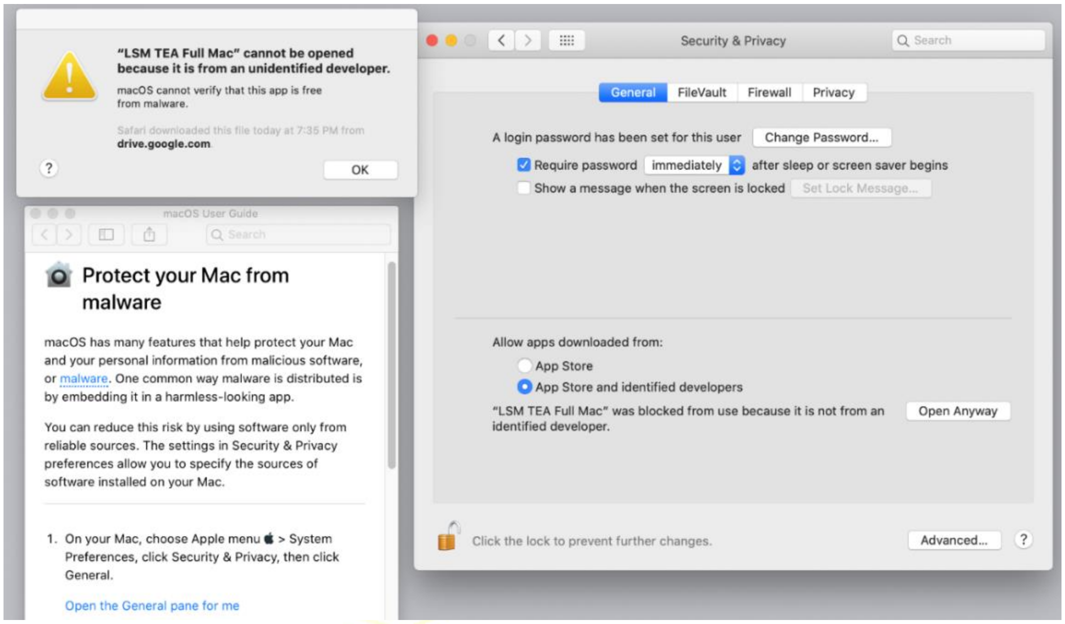

Figure 3. Mac Security & Privacy Settings

For the remainder of this instruction, all interface demonstrations will follow the Windows case.

2.2 Layout of the Main Interface

The initialization of the software could take up to 20 seconds on Windows (however, it only may only 2-3 seconds on Mac). Please wait until the main interface of the software shows up. Figure 4 demonstrates the layout of the GUI components in the main interface, as a TEA project is in progress.

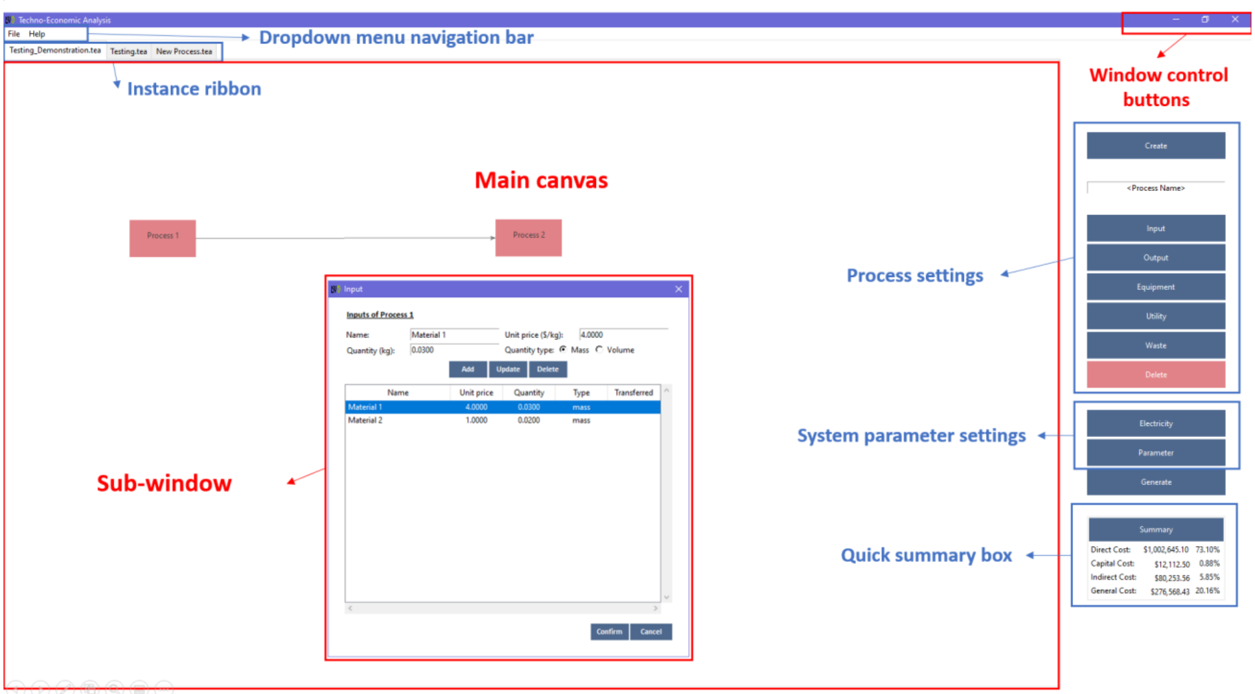

Figure 4. Software Main Interface

The functionality and utility of each area in Figure 4 is briefly explained below.

- Main Canvas: design and customize a process flow diagram by dragging and dropping process blocks here
- Sub-window: each sub-window collects a specific category of information from users. For example, for each consumed material, users can input relevant information (e.g., name, quantity, and price) through the input sub-window.
- Dropdown menu navigation bar: basic commands as in common software
- Instance ribbon: select and click tabs to switch between different project designs for comparison. Drag tabs to arrange the sequence of the tabs, and right-click to close a tab.
- Window buttons: minimize, resize, or close the interface
- Process settings: users can customize the detailed information associate with a selected process.
- System parameter settings: user can set up global TEA variables here, e.g., lab and industrial scale units, plant life, and tax rates.
- Quick summary box: this section presents a simplified cost breakdown to provide a quick overview of the backend calculation.

2.3 TEA Calculation Model

First it should be noted that there is no standard procedure for conducting TEAs. The ways of performing TEAs can vary depending on the system boundary and complexity of the system being investigated. The software is based upon a general TEA framework developed by Laboratory for Sustainable Manufacturing (LSM) at Purdue University, which has already been applied in multiple publications [1]–[3]. The detailed calculation and breakdown of system components are thoroughly explained in the software help files (to be discussed later). For a quick overview, the key components that underpin the TEA calculation model are illustrated in Figure 5.

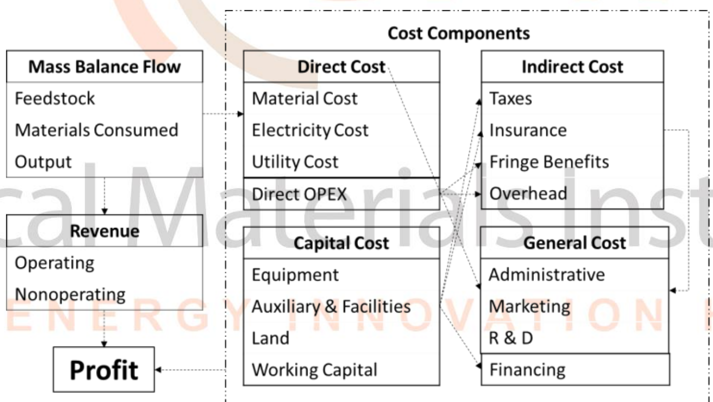

Figure 5. TEA System Model Structure

The software will generate two separate TEA reports, a preliminary TEA spreadsheet, and a comprehensive TEA spreadsheet, which will be discussed in detail in Section 4. TEA Outputs.

3. Operating the Software

3.1 Basic Commands

Use the dropdown menus at the top of the interface to execute basic software commands.

(1) File Menu

Click **File** to view commands regarding file management and editing, as shown in Figure 6. Their functionalities are listed below:

- **New**: start a new process flow design
- **Open**: open an existing process flow design from a .tea file stored in the path "\dist\Saved Files"
- **Save**: save the current progress in an associated .tea file; the first time executing this command will create a new .tea file in the path "\dist\Saved Files"
- **Save as**: make a copy of the file with a different name
- **Copy processes**: copy the process blocks in current canvas
- **Paste processes**: insert the duplicated process blocks stored clipboard at current canvas
- **Clear workspace**: delete all process blocks in current canvas

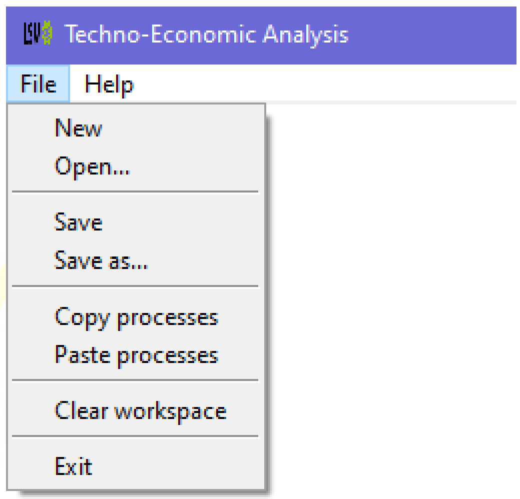

Figure 6. Dropdown Menu - File

(2) Help Menu

To learn the TEA calculation model that the software is based on, users can refer to the supporting information provided by developers. Click **Help** to select help files to open, as shown in Figure 7.

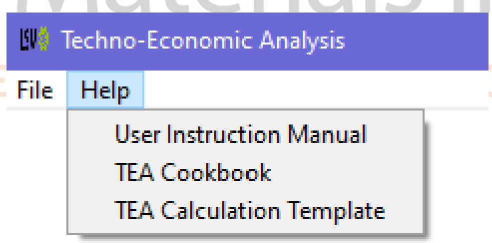

Figure 7. Dropdown Menu - Help

First, users can get access to this instruction manual by clicking the first command. The **TEA Cookbook** command will open a document that comprehensively explains the underlying economic concepts and the calculation model behind the TEA structure in Figure 5.

Additionally, the TEA Cookbook file is accompanied by a TEA output spreadsheet where the notations of variables precisely matches their definitions in TEA Cookbook file. Click **TEA Calculation Template** to open the spreadsheet. This template is of the same format as the software output, and the detailed calculation formulas are enclosed in cells.

3.2 Designing Process Flow Diagram

To start a new TEA project, click **File > New** command to start a new workspace. The main canvas is empty by default.

(1) Create a New Process Block

Click the blue **Create** button at the top of the right panel to create a new process block on canvas, as shown in Figure 8. The default name of the first block created is "Process 1." A selected block is indicated by a highlighted blue border.

Figure 8. Creating the First Process Block

(2) Reposition a Process Block

- First, left-click on a process block and hold the left-click button
- Then, drag the block to a different position
- Finally, release the left-click button

(3) Make Connections Between Blocks

To connect two process blocks (denoted as upstream block and downstream block respectively), first right-click on the upstream block, then right-click on the downstream block. An arrow will show up indicating the connecting relationship, as can be seen in Figure 9.

Figure 9. Connecting Two Process Blocks

Note that making a connection will make it easy for user to transfer the output(s) from process as the input(s) of the second process. For more detail please see 3.7 (2) Intermediate Outputs.

(4) Rename a Process Block

A newly created process block will be automatically named with a number index (e.g., Process 2) based on the sequence of creation. However, users can always customize the name of each block if desired.

Left-click to select a process block, and the selection is indicated by a highlighted border. The current name of the process is shown in the text entry below the **Create** button. To rename the process block, type in the new name in the entry then press enter (or click anywhere in main canvas). A renamed process along with its name entry is shown in Figure 10.

Figure 10. Renaming a Process Block

(5) Delete a Process Block

To delete a process block, left-click to select the block, then click the red **Delete** button at the bottom of the panel for process settings, as shown in Figure 4. Once a process block is deleted, all its associated connecting arrows will be removed.

3.3 System Parameters Setting

Before starting to specify the detail information for each process block, it is necessary to set up the basic assumptions of the TEA project. The TEA assumptions are made by customizing system parameters, such as plant life, units, and various contingency rates. These parameters are considered as global variables because they do not associate with any specific process block, and they are applied across the whole project.

As shown in Figure 4, look for the zone labeled as "system parameter settings," at the bottom right, then click the button named **Parameter**. A sub-window of system variables with their default values will pop up, which can be seen from Figure 11.

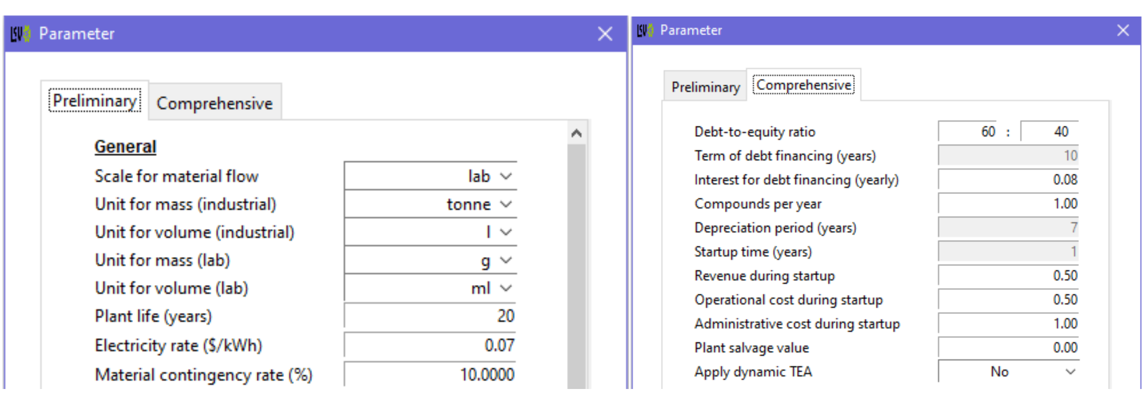

Figure 11. Parameter Sub-window

There are two sets of system parameters, the ones in the **Preliminary** tab are related to preliminary TEA output, the ones in **Comprehensive** tab are related to comprehensive TEA output. Please refer to section 4 for a brief description of preliminary & comprehensive TEAs.

Users can find detailed explanation for each system parameters can be by accessing the help files through the **Help** dropdown menu at the top of the main interface. For new users, it is recommended to use the default setting to test the result and make modifications if necessary. However, users should pay special attention to the settings for some critical parameters that are deterministic for a TEA project, which will be discussed below.

(1) Scale and Unit Settings

The parameters that define the scale and unit of the TEA are contained in the top five rows of the "Preliminary" tab, which are shown in the left screenshot in Figure 11.

The first parameter **Scale for material flow** has two options, **lab** and **industrial**. If **lab** is selected, it means that all the material flow data will be input in a laboratory scale. On the other hand, if **industrial** is selected, the software will treat all the material flow data as in an industrial scale. Generally, it is recommended to select **lab** if users only have experimental results.

The material flow data for most solid materials are considered as **mass** data, which share the same **unit for mass**. On the other hand, user may need to specify the **unit for volume** for each liquid/gas input if necessary.

If a user chooses the industrial-scale as the input environment for material flow data, the settings for lab-scale units can be ignored. However, if a user chooses the lab-scale instead, it is still required to specify the industrial scale units. This is because economic metrics in a TEA report are calculated from industrial scale mass flow. In this case, although TEA project is set in a lab-scale environment, the software will automatically convert the lab scale data to an industrial scale at the backend. This scale-conversion is based on the feedstock setting, which will be discussed below.

(2) Feedstock Settings

In the context of the software, the feedstock of a technology is considered to be the primary input material, which will be set as the **standard** for calculation and scaling. It is recommended to set the input material with the most dominant amount as the feedstock. The parameter settings related to feedstock are at the bottom of the **Preliminary** tab in the **Parameter** sub-window, which is shown in Figure 12.

Feedstock	
Name	Feedstock
Unit price (/g)	0.00
Quantity type	mass
Industrial-scale quantity (tonne)	100.0000
Lab-scale quantity (g)	100.0000
Collection fee ($/tonne)	566.50

Figure 12. Parameter Settings for Feedstock

Users should specify both the lab-scale quantity and industrial-scale quantity for the feedstock material. At the backend, the software will calculate a scale factor as:

$$\frac{\text{Industrial-scale quantity}}{\text{lab-scale quantity}}.$$

Note that for both numerator and denominator, the conversion between their associate units has been accounted for. As discussed above, if a user selects the **lab** option in scale setting, the software will multiply all the mass flow data by this scale factor to generate industrial-scale data. On the other hand, if a user selects the **industrial** option in the scale setting, the scale factor can be considered as 1 since in this case the industrial-scale and lab-scale are essentially equivalent.

3.4 Material/Utility/Waste Information

Material cost, utility cost, and waste management cost are three essential components in direct cost calculation. The software calculates these cost components based on the mass flow data input from users through the process flow diagram. Users are required to customize the material/utility/waste information for each process blocks.

Recall that the feedstock quantity is predetermined in the parameter setting. Accordingly, the mass flow data for other materials should be scale to the amount that are required to process that exact amount of feedstock.

(1) Input Material Customization

Materials that used to process the feedstock are the major inputs of the process and they constitute the material cost component in direct cost. The terms “materials” and “inputs” can sometimes be interchangeable.

Select the process to be customized, then click on the **Input** button in the right panel as shown in Figure 4. A sub-window to customize input material information will pop up, as presented by an example setup in Figure 13.

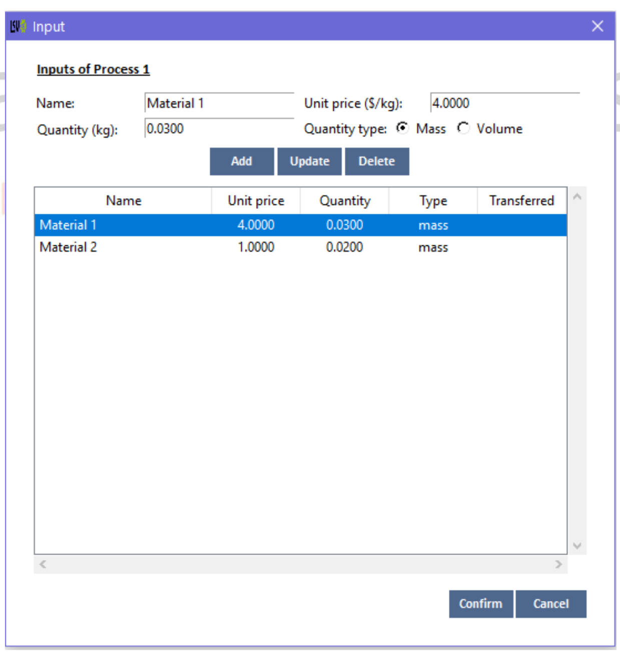

Figure 13. Input Material Information Settings

(i) To add a new material, input its name, unit price, quantity (for liquid/gas material whose quantity is measured with volume unit, check **Volume** as quantity type), then click the **Add** button. Then the material just added will show up in the table dialog below. Note that the units for price and quantity are automatically annotated based on the unit setups in parameter settings. Please make sure to click **Confirm** once it is finished.

(ii) To make modification to an existing material, click the corresponding item in table dialog to select it. Its current information will show in the entries above. Modify the entries to desired value, then click **Update > Confirm**.

(iii) To delete a material, click the corresponding item in table dialog to select it, then click the "delete" button. The material will be removed from the table dialog. Click **Confirm** when finished.

(2) Utility Customization

Utilities expense is the cost incurred by using supplemental resources such as water, natural gas, and other auxiliaries. Technically speaking, in terms of calculation, there is no difference between utility cost components and input material cost components. However, it should be noted that the utility resources are considered as nonessential inputs, and the TEA output generated by the software will separate the utility cost from material cost for clarity.

The customization for the utility cost follows a very similar way as that of the material cost. First, Select the process to be customized, then click on the **Utility** button in the right panel as shown in Figure 4. A sub-window to customize input material information will pop up, as exemplified in Figure 14.

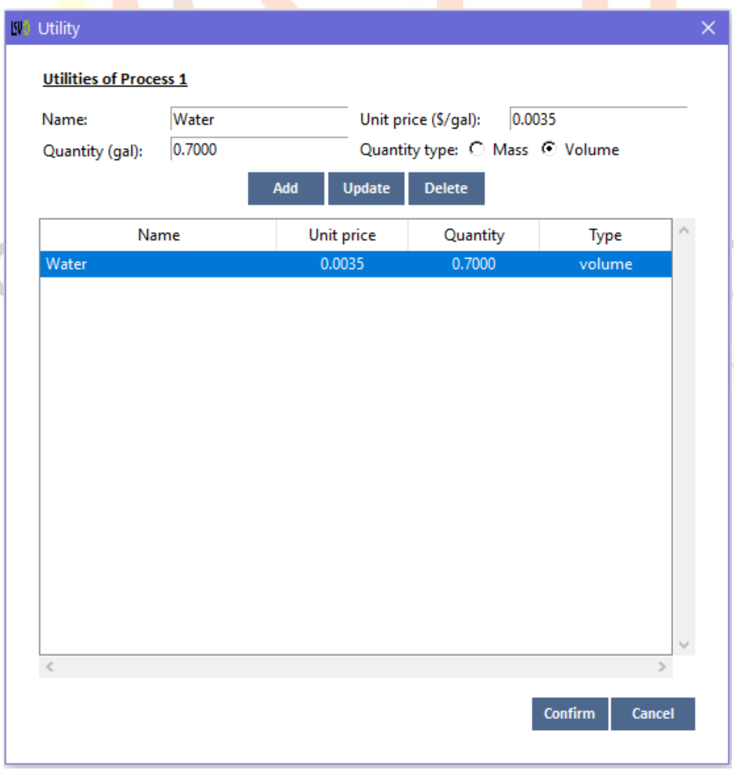

Figure 14. Utility Information Settings

Suppose in a laboratory environment it requires 0.7 gallons of water, a new utility named "Water" may be added with its quantity set as 0.7. Then value of the water rate depends on the assumptions of the process and can be adjusted as needed. The **Update** and **Delete** commands are executed the same way as in the input material customization. Once all utilities are listed, click "Confirm" to continue.

(3) Waste Customization

The waste management fee is calculated based on the weight/volume of the waste generated from all processes. The customization for waste information follows similar steps as explained in the customization processes for input materials and utilities. A simple example of waste information customization is shown in Figure 15.

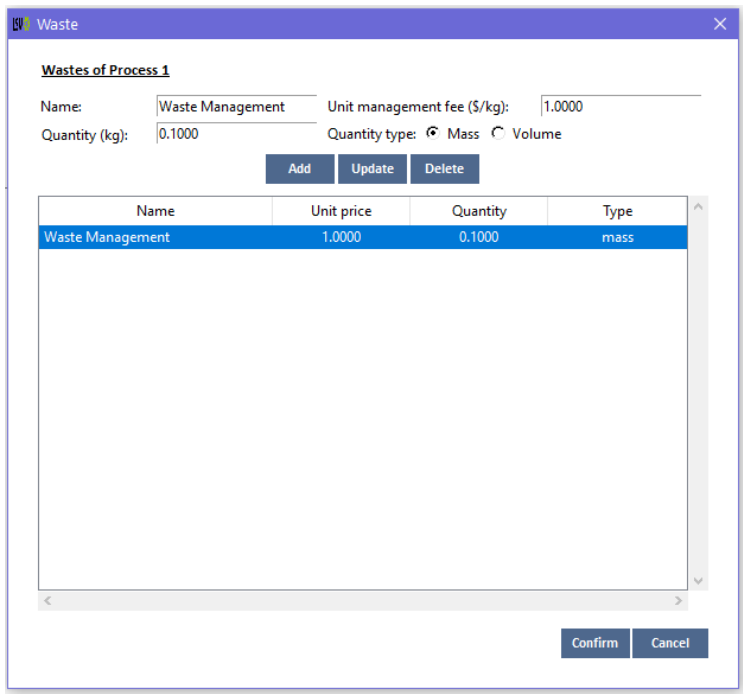

Figure 15. Waste Information Settings

Users may specify the waste generated for each specific process if possible. However, if it is too difficult to track down detailed data of waste, users are recommended to assign all the waste components in the last process block. This is because waste management fee is considered as one single index in **1.4 Direct OPEX** section of the TEA output, which will only be presented as a grand total with no detailed process-wise breakdown (see Figure 28 in section 4).

3.5 Equipment Information

Users should also configure equipment information for each process, basing on which the software will calculate the capital cost (CAPEX) of the whole project. To customize the equipment for a unit operation, left-click the corresponding process block, then left-click Equipment button on the right of the main interface as shown in Figure 4. A sub-window for equipment information will pop out, and users are required to enter the following information associate with each equipment:

- Name: name of the equipment
- Capital Price ($): the one-time purchasing price of the equipment
- Power (kW): the electricity power of the machine, related to the electricity calculation. Please input "0" here if the equipment does not require electricity or its power is not specified.

Figure 16 demonstrates an example of equipment information. This sub-window operates the same way as other sub-windows discussed previously.

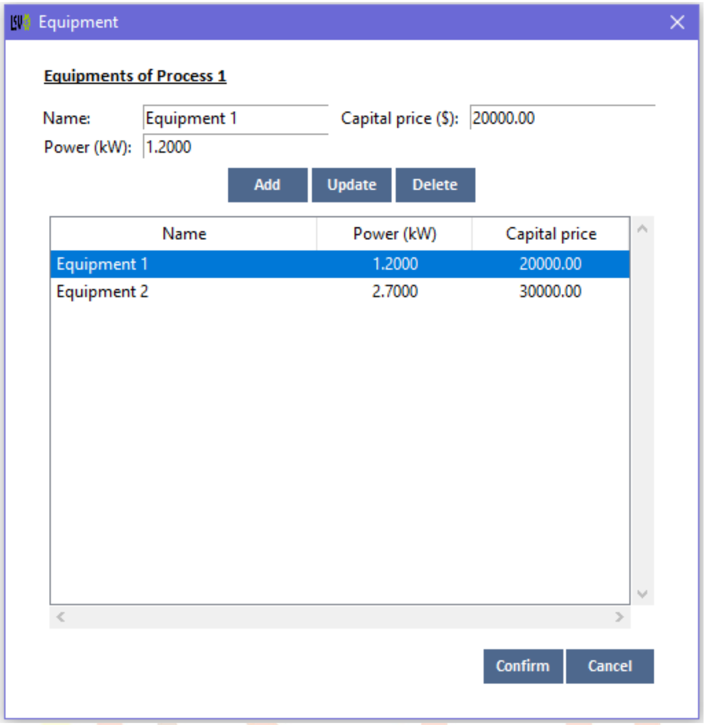

Figure 16. Equipment Information Settings

3.6 Electricity Cost Information

The last piece of information required to calculate production cost is the electricity cost. It is considered as a system setting so it is not associated with a specific block. To tailor the calculation for electricity cost, users can directly click on the Electricity button from the main interface (see Figure 4) without selecting a process. The electricity information setup for a case study is presented in Figure 17.

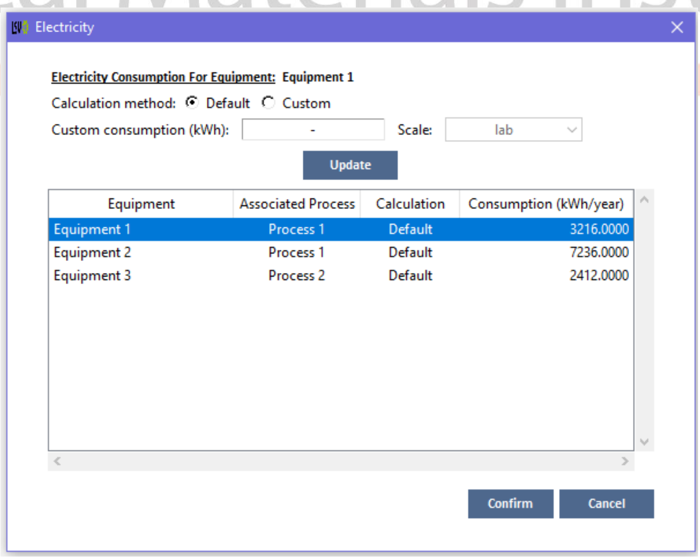

Figure 17. Electricity Information Settings

The software assumes that the electricity cost of the facility is determined by the equipment selected by users. As can be seen from Figure 17, the existing information for all existing equipment (see 3.5 Equipment Information) is automatically listed in the table dialog. By default, the electricity consumption is directly calculated based on:

- the power of machines, which is setup through the **Electricity** sub-window
- and number of working hours, which is setup through the **Parameter** sub-window

Alternatively, users can manually input an electricity consumption value for each equipment. To do this, select a piece of equipment that needs to be customized, in the **calculation method** selection row, check **Custom.** Enter a modified value, which can be either in lab-scale or industrial-scale, specified from the **Scale** dropdown list. Click **Update** to record the new consumption value in the table dialog below, then click **Confirm**. For example, compared to the electricity setting in Figure 17, suppose a user already assumes that the annual electricity cost for Equipment 2 is 5000 kWh, then the electricity setting can be updated to the new configurations shown in Figure 18.

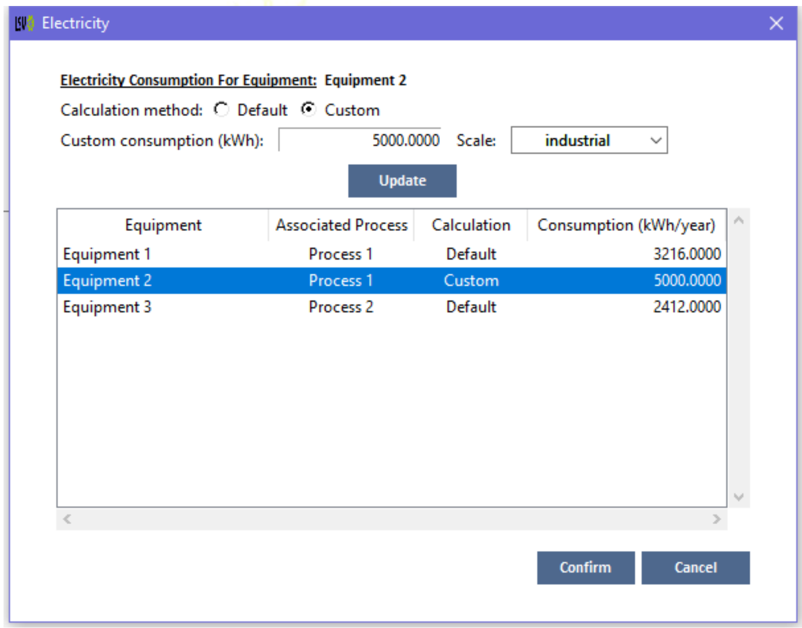

Figure 18. Customized Electricity Settings

3.7 Product and Revenue Information

(1) Normal System Outputs

As illustrated in Figure 5, once the technology is implemented in an industrial facility, the revenue gained from operating the plant mainly consists of 2 parts:

- Sales revenue: revenue gained from selling the products/merchandises produced
- Nonoperating Income: revenue arising from side or minor activities, typical examples include capital gains from stock market, tipping fee, etc.

The software makes it easy for user to set up sales revenue by directly entering the product information through the **Output** sub-window associated with each process. The **Output** sub-window is composed of a left panel and a right panel. The left panel is for the settings of normal single-process-associated output, which is demonstrated in Figure 19.

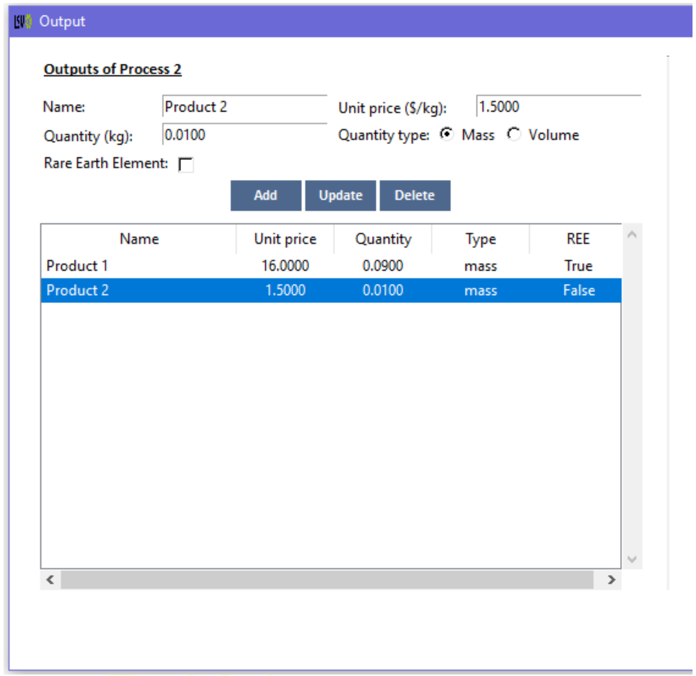

Figure 19. Normal Output Setting (Left Panel of Output Setting)

The layout and processing steps of this panel is very similar to other sub-windows associated with a specific process block (except for the REE features, which will be covered in 3.7 (3) Dynamic Feature for REE Products). The software will use the price and quantity inputs from users to calculate the revenue gained from selling each product. The summation of the revenue gained from all product will be the total sales revenue.

If it is necessary to include the nonoperating income to the revenue, user can design an abstract "product" whose name can be set as the category of a nonoperating income source (e.g., tipping fee). Users are suggested to assign it a customized price value, with a quantity value of 1. The revenue gained from this nonoperating income source will be added up to the sales revenue to obtain the total revenue.

(2) Intermediate Outputs

As explained in (3) Make Connections Between Blocks, once two processes are connected, users can transfer the output(s) of the upstream process as the input of the downstream process. In contrast to normal system outputs, these outputs are named as "intermediate outputs."

The intermediate outputs have two special features:

- They are also included in the input list for their downstream processes, but they will not be part of the material cost calculation.
- They can be partially (0-100%) sold to gain revenue, depending the proportion that serves as the input material for the downstream process.

The settings for intermediate outputs can be done through the right panel of the **Output** sub-window. Consider an example where Process 1 is the upstream process and Process 2 is the downstream process as shown in Figure 9. Assume that X is an output from Process 1 such that 60% of X will be transferred to Process 2 as input material, and 40% of X will be sold to the market.

To design this scenario, first, in the output settings for process 1, add an output named “X.” Once the output X is selected, on the right-hand side panel, a dialog list of downstream processes associated with process 1 will show up (For this case, Process 2 is the only downstream process). Click to select “Process 2” from the list, then type in “60” in “Percentage to transfer” entry, then click the **Transfer** button. The resultant interface is shown in Figure 20.

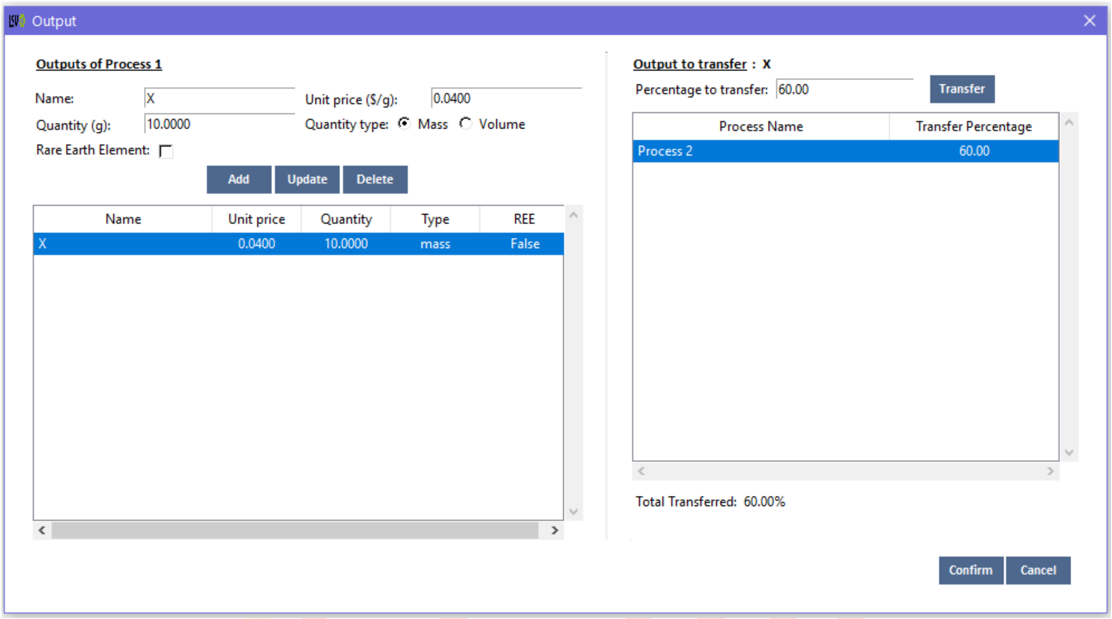

Figure 20. Intermediate Output Setting - Transfer

Now if users examine the input settings for the downstream Process 2, as is evident in Figure 21, the material X is already in the input material list with 60% of its produced quantity.

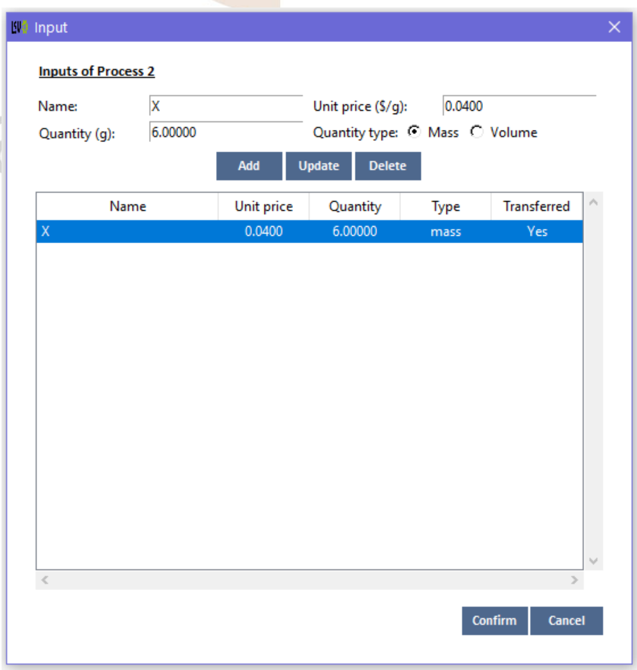

Figure 21. Intermediate Output Setting – Downstream Process Inputs

The remaining 40% of X will be treated as normal system output by the software, which will be included in the revenue calculation. Note that if an intermediate output is 100% transferred, it will not be included in both cost and revenue calculations, and it will only be listed for the completeness of a mass flow.

(3) Dynamic Feature for REE Products

One special feature of the software is that the market dynamics of REE products can be incorporated into the TEA framework. This feature is called "dynamic TEA," which assumes a generally increasing tendency for REE products in the future [4].

Users can label an output product as "REE" through the checkbox **Rare Earth Element** in Figure 19. By doing so, the price of a labeled product will be dynamically updated in the revenue calculation every year. In other words, the annual revenue gained from selling REE products can be considered as "dynamic revenue" that will be constantly changing over the plant life.

Users are free to choose whether to apply the dynamic feature through: [open **Parameter** sub-window] – [click **Comprehensive** tab] – [click **Apply Dynamic TEA** dropdown list] – [select **Yes**/**No**], as shown in Figure 22.

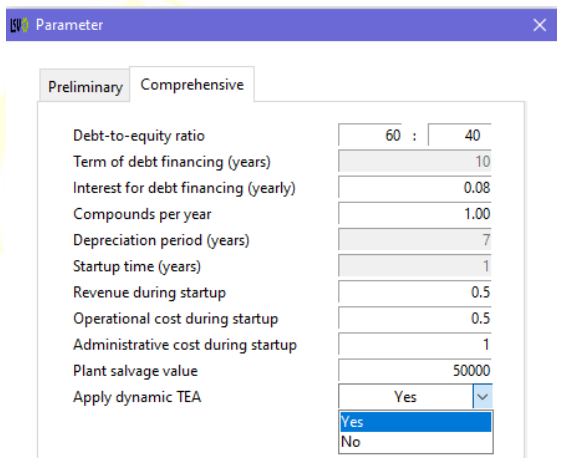

Figure 22. Dynamic TEA Option Setting

By default, the dynamic feature is turned off. Once a user decides to apply dynamic TEA, the prices of all the products marked as REE will be adjusted in revenue calculation (see 4.2 Comprehensive TEA Output). If a user chooses to not apply dynamic TEA, the products marked as REEs will only be treated as normal products and their prices will not be adjusted.

3.8 Final Check and Generating Output

The quick summary box at the bottom right of the main interface will provide a brief overview of the breakdown of operational cost, which is shown in Figure 23.

Summary		
Direct Cost:	$1,004,710.87	72.81%
Capital Cost:	$13,808.25	1.00%
Indirect Cost:	$81,384.06	5.90%
General Cost:	$280,040.75	20.29%

Figure 23. Quick Summary Box

Apart from the quick summary, it is also suggested to go through the following settings before generating the result:

- Lab/industrial unit settings in **Parameter** > **Preliminary**
- Electricity and equipment configurations in **Electricity**
- The input material(s) for each process (select a process, then click **Input**)

To generate the TEA output, click the **Generate** bottom above the quick summary table.

4. TEA Outputs

The software generates an Excel workbook which contains two separate TEA reports: a preliminary TEA spreadsheet and a comprehensive TEA spreadsheet.

Preliminary TEA is a TEA framework that evaluates the economic performance of a project on an annual basis, which concentrates on production cost modeling, with simplified financial analysis. The preliminary TEA is based on static cost benefit analysis, which will return an "averaged" annual profit as an indicator for economic feasibility. In other words, every monetary metrics presented in preliminary TEA can be interpreted as an annual estimation.

Comprehensive TEA is a TEA framework that concentrates on long-term financial analysis, with the considerations of the time value of money, inflation, and market dynamics. The comprehensive TEA is based on the results from the preliminary TEA. Metrics including Net Cash Flow (i.e., NCF, where the dynamic price feature can be reflected), internal rate of return (IRR), payback period will be generated.

Here this instruction manual will only demonstrate the breakdown of the TEA outputs with a summarizing explanation of each section. For a quick overview of the TEA structure please refer to Figure 5. The detailed calculation principles and related references can be found in the help files (including a TEA Cookbook document and a calculation template spreadsheet) that are accessible through the **Help** dropdown menu in the software.

4.1 Preliminary TEA Output

The preliminary TEA result is exported as a spreadsheet titled "Preliminary TEA" in the output workbook.

Section 0. Preparation

This section lists the customized settings of all system parameters that have been applied to generate preliminary TEA results, as shown in Figure 24.

0. Preparation				
		Attribute	Amount	Units
Target Production	Feed	Lab Scale Feedstock	0.1	kg/lab_batch
		Total Feedstock	100	tonne/year
		Scale Factor	1000000	
	Time	Operational days	335	days/year
		Plant Life	20	years
		Working Hours	8	hours/day
System Variable		Number of Operators	2	#
		Number of Shifts	1	#
		Salary	41770	$/year/operator
		Income Tax Rate	35	%
		Collection Fee	566.5	$/tonne

Figure 24. Preliminary TEA – Preparation

Section 1. Cost Analysis – Direct Cost

Direct cost consists of the cost components that can be measured and allocated to a specific activity (i.e., a process block) . The direct cost is categorized into 4 parts by the software, which are presented in four subsections in the spreadsheet.

(1) 1.1 Material Cost

Materials cost is the cost from purchasing feedstock and other input materials. As shown in Figure 25, this subsection presents the breakdown of material cost components, with detailed information of each individual material. The total material cost with contingency rate applied is shown in the last row.

1. Cost Analysis - Direct Cost			
1.1 Material Cost			
	Attribute	Value	Unit
Material Cost	Feedstock		
	Feedstock	5	$/kg
		0.1	kg/lab batch
		0.5	$/lab batch
		5000	$/tonne
		100	tonne/year
		500000	$/year
	Process - Process 1		
	Material 1	4	$/kg
		0.03	kg/lab batch
		0.12	$/lab batch
		4000	$/tonne
		30	tonne/year
		120000	$/year
	Material 2	1	$/kg
		0.02	kg/lab batch
		0.02	$/lab batch
		1000	$/tonne
		20	tonne/year
		20000	$/year
	Process - Process 2		
	Material 3	2	$/kg
		0.03	kg/lab batch
		0.06	$/lab batch
		2000	$/tonne
		30	tonne/year
		60000	$/year
	Contingency Rate	10	%
	Total Material Cost	700000	$/year
	Total Material Cost with Contingency	770000	$/year

Figure 25. Material Cost Output

(2) 1.2 Electricity Cost

Recall that the electricity cost was calculated based on equipment information. Consequently, in the output spreadsheet the electricity cost is broken down in terms of machine, as presented in Figure 26,

1.2 Electricity Cost			
	Attribute	**Value**	**Unit**
Electricity Cost	Electricity rate	0.07	$/kWh
	Process - Process 1		
	Equipment 1	1.2	kW
		3216	kWh/year
		225.12	$/year
	Equipment 2	2.7	kW
		7236	kWh/year
		506.52	$/year
	Process - Process 2		
	Contingency Rate	25	%
	Total Electricity Cost	731.64	$/year
	Total Electricity Cost with Contingency	914.55	$/year

Figure 26. Electricity Cost Output

(3) 1.3 Utility Cost
The utility cost output shares the same format as that of the material cost. An example is shown in Figure 27.

1.3 Utility Cost			
	Attribute	**Value**	**Unit**
Utility Cost	**Process - Process 1**		
	Water	0.001	$/kg
		0.7	kg/lab batch
		0.0007	$/lab batch
		1	$/tonne
		700	tonne/year
		700	$/year
	Contingency Rate	25	%
	Total Utility Cost	700	$/year
	Total Utility Cost with Contingency	875	$/year

Figure 27. Utility Cost Output

(4) 1.4 Direct OPEX
"Direct OPEX" is the last section of direct cost. It is a collection of multiple operating cost components, including labor cost, logistics cost and waste management, that may vary by the production target. The total direct cost is given at the end of this section, as can be seen from Figure 28.

1.4 Direct OPEX			
	Attribute	**Value**	**Unit**
Direct OPEX	Waste Management	400	$/year
	Collection Cost	56650	$/year
	OPEX for Pretreatment	80	$/year
	Salary	41770	$/year
	Number of Shifts	1	#/day
	Number of Operators	2	operators/shift
	Operating Labor	83540	$/year
	Operating Supervision	16708	$/year
	Quality Control	16708	$/year
	Maintenance Labor	5450.63	$/year
	Maintenance Material	3633.75	$/year
	Operating Supplies	1514.06	$/year
	Contingency Rate	25	%
	Total Direct OPEX	184684.44	$/year
	Total Direct OPEX with Contingency	230855.55	$/year
Total Direct Cost		1002645.097	$/year

Figure 28. Direct OPEX Output

Section 2. Cost Analysis – Capital Cost

Capital cost (a.k.a., CAPEX) contains the cost components for equipment, installation, auxiliary services, facilities, land, etc. The calculation of capital cost is primarily based on the equipment information input from users. As shown in Figure 29, in the preliminary TEA, every capital cost component is an averaged value on an annual basis.

2. Cost Analysis - Capital Cost		
Attribute	**Value**	**Unit**
Purchase (Equipments)		
Equipment 1 (Process 1)	1000	$/year
Equipment 2 (Process 1)	1500	$/year
Depreciable Cost		
Total Purchase	2500	$/year
Equipment installation cost	1750	$/year
Piping cost	775	$/year
Instrumentation and control	450	$/year
Electric equipments and materials	250	$/year
Buildings	950	$/year
Service facilities	1000	$/year
Fixed Capital Cost		
Total depreciable cost	7675	$/year
Land	150	$/year
Facility site improvement	250	$/year
Contingency Rate	0.25	$/year
Total Fixed Capital Cost	8075	$/year
Total Fixed Capital Cost with Contingency	10093.75	$/year
Startup Cost	0	$/year
Working Capital	2018.75	$/year
Total Capital Investment	12112.5	$/year

Figure 29. Capital Cost Output

Section 3. Cost Analysis – Indirect Cost

Indirect cost includes the expenditures that are difficult to allocate to a specific activity, which were calculated based on the system parameters predetermined by users. It consists of 4 categories:

- Property taxes (related to the capital cost)

- Insurance (related to the capital cost)
- Fringe benefits (related to operating labor and supervision, please check Figure 28)
- Overhead (related to operating labor and supervision, please check Figure 28)

An example of indirect cost output is given in Figure 30.

3. Cost Analysis - Indirect Cost			
	Attribute	**Amount**	**Unit**
Indirect Cost	Property taxes	4037.5	$/year
	Insurance	4037.5	$/year
	Fringe Benefits	22054.56	$/year
	Overhead (less fringe benefits)	50124	$/year
	Total Indirect Cost	80253.56	$/year

Figure 30. Indirect Cost Output

Section 4. Cost Analysis – General Cost

General cost has 4 components as listed below:

- Administrative cost (determined by both direct and indirect cost)
- Marketing cost (determined by both direct and indirect cost)
- Financing cost (determined by capital cost)
- R&D cost (determined by both direct and indirect cost)

Figure 31 provides an example breakdown of general cost.

4. Cost Analysis - General Cost			
	Attribute	**Amount**	**Unit**
General Cost	Administrative	48730.44	$/year
	Marketing	146191.32	$/year
	Financing	19380	$/year
	Research and development	62266.67	$/year
	Total General Cost	276568.43	$/year

Figure 31. General Cost Output

Section 5. Cost Summary

To help users quickly identify major cost components and bottlenecks, in this section of the preliminary TEA, some of the key cost indexes/metrics that have been listed above are reorganized and summarized.

(1) 5.1 Production Cost (Total Cost) Breakdown

This section provides the highest level of overview for the production cost. As can be seen from Figure 32, the metrics listed here are basically the grand costs at the end of section 1-4.

5. Cost Analysis - Total Cost and Breakdown			
5.1 Production Cost (Total Cost) Breakdown			
	Attribute	**Amount ($/year)**	**Percentage**
Production Cost	Direct Cost	1002645.1	73
	Capital Cost	12112.5	1
	Indirect Cost	80253.56	6
	General Cost	276568.43	20
	Total Cost	1371579.59	100

Figure 32. Production Cost (Total Cost) Breakdown

(2) 5.2 Direct Cost Breakdown

This subsection further breakdowns the "Direct Cost" component listed in Figure 32. As explained in Section 1. Cost Analysis – Direct Cost, there are four categories of direct cost, as shown in Figure 33.

5.2 Direct Cost Breakdown			
	Attribute	**Amount ($/year)**	**Unit**
Direct Cost	Materials	770000	77
	Electricity	914.55	0
	Utility	875	0
	Direct OPEX	230855.55	23
	Direct Cost	1002645.1	100

Figure 33. Direct Cost Breakdown

(3) 5.3 Material Cost Breakdown

Material cost tends to be the major cost contributor in most scenarios. Therefore, the software specifically provides material cost breakdown where the annual cost of each material is listed, as shown in Figure 34.

5.3 Material Cost Breakdown		
Attribute	**Amount ($/year)**	**Percentage**
Material 1	120000	17
Material 2	20000	3
Material 3	60000	9
Material Cost	770000	100

Figure 34. Material Cost Breakdown

Section 6. Revenue

This section lists the direct earnings from selling the outputs produced by the process under study. Note that users can customize indirect earnings items such as tipping fee, subsidies, tax benefits.

The revenue output from a case study is presented in Figure 35. Note that the materials with mass units and materials with volume units are separated in the output.

6. Revenue ($/year)						
Material (mass)	**Lab Output (kg/lab batch)**	**Industrial Output (tonne/year)**	**Unit Price ($/tonne)**	**Revenue ($/year)**	**Weight (%)**	**Unit Sales Price**
Product 1 (Process 2)	0.09	90	16000	1440000	90	14550
Product 2 (Process 2)	0.01	10	1500	15000	10	
Material (volume)	**Lab Output (l/lab batch)**	**Industrial Output (m3/year)**	**Unit Price ($/m3)**	**Revenue ($/year)**	**Weight (%)**	

Figure 35. Revenue Output

4.2 Comprehensive TEA Output

The comprehensive TEA is exported as a spreadsheet titled "Comprehensive TEA" in the output workbook. The metrics in a comprehensive TEA are calculated based on the preliminary TEA results, in conjunction with user-customized parameter settings that account for long-term financial factors.

Section 0. Preparation

This section summarizes the comprehensive TEA parameters along with some preliminary TEA metrics that will be used to calculate comprehensive TEA metrics. These numbers also provide a quick overview of the annual economic performance, as shown in Figure 36.

0. Preparation

0.1 Net cash flow assumptions

Category	Value ($)	Unit
Debt/Equity Ratio	1.5	
Term of Debt Financing, t	10	year(s)
Interest for Debt Financing, r	0.08	/year
Compounds per Year, n	1	
Plant Life	20	year(s)
Depreciation Period	7	year(s)
Income Tax Rate	0.35	
Startup Time	1	year(s)
Revenue During Startup	0.5	
Operational Cost During Startup	0.5	
Administrative Cost During Startup	1	
Plant Salvage Value	50000	

0.2 Defining Terms from Preliminary Cost-Benefit Assessment

Category	Value ($)
General Cost Except Financing	257188.43
Total Operational Cost	1082898.66
Revenue from REE	1440000
Revenue From By-products	15000

Figure 36. Preparation Table

Section 1. Capital Investment Financing

This section calculates some key comprehensive TEA indexes related to capital investment financing, based on the data from the last section. For example, the calculation results based on information in Figure 36 are shown in Figure 37.

1. Capital Investment Financing	
Category	**Value ($)**
Total Major Equipment Cost	62500
Equipment Installation Cost	43750
Piping Cost	19375
Instrumentation and Control	11250
Electric Equipment and Materials	6250
Buildings	23750
Service Facilities	25000
Total Depreciable Cost	191875
Land	3750
Facility Site Improvement	6250
Total Fixed Capital Cost	201875
Working Capital	40375
Total Capital Investment	242250
Finance Debt	145350
Finance Equity	96900

Figure 37. Capital Investment Financing

These results will also be used to further calculate other comprehensive TEA metrics in following sections.

Section 2. Cash on Cash Return (CoC)

Cash-on-cash return is a “quick and dirty” evaluation for the degree of profitability. It is calculated as:

$$\text{Cash on Cash Return (CoC)} = \frac{\text{Net operating income (NOI)}}{\text{Total cash invested}},$$

where NOI equals all revenue from the facility minus all necessary operating expenses. CoC ignores appreciation/depreciation, and the effect of compounding interest. An example of CoC output is given by Figure 38.

2. Cash on Cash Return (CoC)	
Category	**Value ($)**
Net Operating Income (NOI)	114912.91
Total Cash Invested	242250
Cash-on-cash Return (CoC)	0.47

Figure 38. Cash on Cash Return (CoC)

Section 3. Break Even Point (BEP)

There are two metrics to characterize BEP:

- BEP in Units
- BEP in Dollars

The index “BEP in Units” denote the break-even unit sales. This is the sales amount of unit products that is required to cover total costs (both fixed and variable costs). The index “BEP in Units” is given by the equation:

$$\text{Break Even Unit Sales} = \frac{\text{Total Fixed Costs}}{\text{Unit Revenue} - \text{Unit Variable Cost}}.$$

On the other hand, the index “BEP in dollars” is calculated as: $\text{BEP in Units} \times \text{Unit Revenue}$. See Figure 39 for an example of a BEP output.

3. Break Even Point (BEP)	
Category	**Value ($)**
Fixed Cost	368934.49
Unit Revenue	14550
Unit Variable Cost	13594.67
Unit Contribution Margin	955.33
BEP in Units	386.19
BEP in Dollars	5619002.63

Figure 39. Break Even Point (BEP)

Section 4. Net Cash Flow (NCF) plot

The detailed calculation for NCF at each year in the plant life can be found in the appendix tables on the right-hand side of the comprehensive TEA table, which is divided into 7 subsections. For demonstration purpose, in this instruction manual, only the cash flow results for the first three years are shown.

(1) 4.0 Inflation Rate:
This subsection presents the indexes that characterize price inflation and market dynamics of REE products. These indexes will be used to adjust the annual cost & revenue for each year in plant life. Figure 40 shows the index lists for the first three years.

4.0 Inflation Rate			
Year	1	2	3
Inflation (f)	0.0156	0.0156	0.0156
Accumulated Price Index	1.0156	1.0314	1.0475
Annual Revenue Index (d)	0.5	1.012	1.0254

Figure 40. Net Cash Flow – Inflation Rate

For year i, the ith element in the row "Accumulated Price Index" will be multiplied to cost/revenue in the first year to obtain a adjusted value. Moreover, if a user chooses to apply the dynamic feature, the ith element of in the row "Annual Revenue Index (d)" will also be multiplied to the revenue that particularly gained from selling REE products. The detailed explanation and calculation principles can be found in the supporting files that are accessible through the **Help** menu.

(2) 4.1 Debt Financing
For each year, the annual payment for debt financing can be divided into two parts:

- Towards Principal
- Interest

The due balance will finally be paid off in year 10. Please see Figure 41 as an example of the debt financing for a plant in its first three years.

4.1 Debt Financing			
Year	1	2	3
Annual Payment (A)	21661.44	21661.44	21661.44
Towards Interest (I)	11628	10825.33	9958.44
Towards Principal (P)	10033.44	10836.11	11703
Balance (B)	135316.56	124480.45	112777.45

Figure 41. Debt Financing

(3) 4.2 General Cost Except Debt Financing
Recall that in a preliminary TEA, the annual general cost consists of 4 parts:

- Administrative
- Marketing
- Financing
- R & D

Since the financing part has already been handled in "4.1 Debt Financing," it is excluded in this section. In a comprehensive TEA, the general cost for the first year will be adjusted using the indexes in section 4.0 to calculate the general cost of the following years in plant life. See Figure 42 for the results in the first three years as an example.

4.2 General Cost Except Debt Financing			
Year	1	2	3
Amount ($)	257188.43	261200.57	265275.3

Figure 42. General Cost Except Debt Financing

(4) 4.3 Total Operational Cost (Direct + Indirect)
The software adds the annual amount of direct and indirect cost obtained in Preliminary TEA as the total operational cost for the first year, and then apply the inflation rates to adjust it for the following years sequentially. As can be seen in Figure 43, the annual amount of each year is slightly different from one another.

4.3 Total Operational Cost (Direct + Indirect)			
Year	1	2	3
Amount ($)	1082898.66	1099791.88	1116948.63

Figure 43. Total Operational Cost (Direct + Indirect)

(5) 4.4 MACRS and Depreciation
Depreciation is one of the cost components subtracted from revenue to determine taxable income, it does change the cash that flows when taxes are paid.

The modified accelerated cost recovery system (MACRS) is the current tax depreciation system in United States [5]. Under this system, the capitalized cost (basis) of tangible property is recovered over a specific life by annual deductions for depreciation. The calculation for depreciation is based on the MACRS depreciation for 7-year personal property, on a half-year convention, as partly shown in Figure 44.

4.4 MACRS and Depreciation			
Year	1	2	3
MACRS	0.1429	0.2449	0.1749
Depreciation	27419	46990	33559

Figure 44. MACRS and Depreciation

(6) 4.5 Profit and Loss Statement
This section reorganizes and manipulates the indexes presented in previous subsections to obtain some key economic metrics (e.g., EBIDTA, net profits) that will be further used to calculate the net cash flow (NCF). Figure 45 shows an example output of profit and loss statement.

4.5 Profit and Loss Statement			
Year	1	2	3
Revenue	727500	1495180.14	1538408.76
Operation Cost	541449.33	1099791.88	1116948.63
Gross Profit	186050.67	395388.27	421460.13
Administration Cost	257188.43	261200.57	265275.3
EBIDTA	-71137.76	134187.7	156184.83
Interest Payments	11628	10825.33	9958.44
Depreciation	27418.94	46990.19	33558.94
Income Tax	0	26730.26	39433.61
Net Profit	-110184.7	49641.92	73233.85

Figure 45. Profit and Loss Statement

(7) 4.6 Net Cash Flow

The final subsection of Section 4 presents the summary results of net cash flow that is used to generate NCF plot, which is shown in Figure 46. Note that this table has one more column (denoted as "year 0") compared to the tables in previous subsections. It is a convention in economic analysis to treat beginning of the first year as year "zero."

4.6 Net Cash Flow				
Year	0	1	2	3
NCO	0	-82765.76	96632.11	106792.78
NCI	-96900	0	0	0
NCN	0	-10033.44	-10836.11	-11703
Begin	0	-96900	-189699.2	-103903.2
End	-96900	-189699.2	-103903.2	-8813.42
Change	-96900	-92799.2	85796	95089.78
NCF	-96900	-92799.2	85796	95089.78

Figure 46. Net Cash Flow

Based on the results above, an NCF plot is generated, which can be seen in Figure 47.

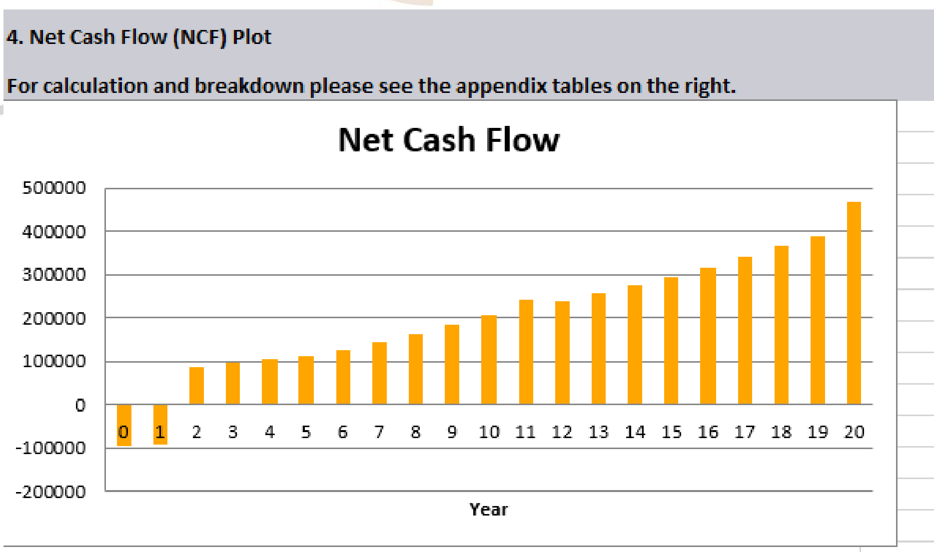

Figure 47. Net Cash Flow (NCF) Plot

Section 5. Net Present Value (NPV)

To find the net present value of cash flow for the entire plant life, every value of future cash flows must be converted to a value at the present time. NPV can be expressed as:

$NPV = \sum_i \text{Present value of (cash inflows - cash outflows)}_i$, or

$$NPV = \sum_i \frac{\text{net cash flow}_i}{(1+DR)^i},$$

where *i* is the “year number” and DR is the discount rate (it is assumed to be the interest in debt financing *r*). As can be seen in Figure 48, the software will only return one cell as the NPV output.

5. Net Present Value (NPV)	
NPV ($)	1498116.37

Figure 48. Net Present Value (NPV)

Section 6. Payback Period

Payback period measures the time required to recover the cost of an investment. There are two types of payback period: normal payback period and discounted payback period, and both are shown in Figure 49.

(1) Normal Payback Period

Normal payback period ignores the time value of money, which is obtained by investigating the “End” row in NCF table (please refer to Figure 46). The normal payback period is the year index of the first positive value in this series of numbers. As can be concluded from section 6.1 in Figure 49, the normal payback period for this example project is 4 years.

(2) Discounted Payback Period

Discounted payback period takes into consideration of the time value of money by applying discount rate. In section 6.2, the software listed the NPV value for each year, and the year index of the first positive NPV is the discounted payback period. As is evident in Figure 49, year 4 is the first time NPV becomes positive. Therefore, for this particular example, the discounted payback period is also 4 years.

6. Payback Period					
6.1 Normal Payback Period					
Year	0	1	2	3	4
End	-96900	-189699.2	-103903.2	-8813.42	93696.42
6.2 Discounted Payback Period					
Year	0	1	2	3	4
NPV	-96900	-182825.18	-109268.94	-33783.61	41564.18

Figure 49. Payback Period

Section 7. Internal Rate of Return (IRR)

The IRR (internal rate of return) is the rate of return that makes NPV = 0. IRR is a single number, an example of which is shown in Figure 50.

7. Internal Rate of Return (IRR)	
IRR (%)	46.8

Figure 50. Internal Rate of Return (IRR)

Reference

[1] V. S. Thompson *et al.*, “Techno-economic and Life Cycle Analysis for Bioleaching Rare-Earth

Elements from Waste Materials," *ACS Sustain. Chem. Eng.*, vol. 6, no. 2, pp. 1602–1609, 2018, doi: 10.1021/acssuschemeng.7b02771.

[2] H. Jin *et al.*, "Techno-economic Assessment for Integrating Biosorption into Rare Earth Recovery Process," *ACS Sustain. Chem. Eng.*, 2017, doi: 10.1021/acssuschemeng.7b02147.

[3] S. Deng *et al.*, "Applying design of experiments to evaluate economic feasibility of rare-earth element recovery," 2020, doi: 10.1016/j.procir.2020.02.005.

[4] S. Deng, D. Prodius, I. C. Nlebedim, A. Huang, Y. Yih, and J. W. Sutherland, "A dynamic price model based on supply and demand with application to techno-economic assessments of rare earth element recovery technologies," *Sustain. Prod. Consum.*, 2021, doi: 10.1016/j.spc.2021.04.013.

[5] Investopedia, "Modified Accelerated Cost Recovery System (MACRS)." https://www.investopedia.com/terms/m/macrs.asp.