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Manufacturing Cost Levelization Model – A User's Guide

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Abstract

The Manufacturing Cost Levelization Model is a cost-performance techno-economic model that estimates total large-scale manufacturing costs for necessary to produce a given product. It is designed to provide production cost estimates for technology researchers to help guide technology research and development towards an eventual cost-effective product. The model presented in this user's guide is generic and can be tailored to the manufacturing of any product, including the generation of electricity (as a product). This flexibility, however, requires the user to develop the processes and process efficiencies that represents a full-scale manufacturing facility.

The generic model is comprised of several modules that estimate variable costs (material, labor, and operating), fixed costs (capital & maintenance), financing structures (debt and equity financing), and tax implications (taxable income after equipment and building depreciation, debt interest payments, and expenses) of a notional manufacturing plant. A cash-flow method is used to estimate a selling price necessary for the manufacturing plant to recover its total cost of production. A levelized unit sales price ($ per unit of product) is determined by dividing the net-present value of the manufacturing plant's expenses ($) by the net present value of its product output. A user defined production schedule drives the cash-flow method that determines the levelized unit price. In addition, an analyst can increase the levelized unit price to include a gross profit margin to estimate a product sales price.

This model allows an analyst to understand the effect that any input variables could have on the cost of manufacturing a product. In addition, the tool is able to perform sensitivity analysis, which can be used to identify the key variables and assumptions that have the greatest influence on the levelized costs. This component is intended to help technology researchers focus their research attention on tasks that offer the greatest opportunities for cost reduction early in the research and development stages of technology invention.

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Introduction

The Manufacturing Cost Levelization Model is an analytical method for estimating all of the manufacturing costs necessary to produce a given product and computes a levelized cost per-unit of that manufactured product. Levelized cost is the minimum per-unit price ($/unit of product) necessary to recover all of the costs associated with manufacturing the product over an assumed financial cycle and manufacturing facility lifetime. Manufacturing costs typically includes: a) manufacturing facility capital investments; b) raw material and energy purchases; c) fixed & variable operations and maintenance costs including labor; d) financing costs, and e) taxes. Engineering economic methods are used to project each of these costs into cash flows over the life-time of the manufacturing facility. Because taxes are a function of product sales revenue, the levelized cost is the per-unit sales prices where the net present value (NPV) of all costs (including taxes) equals the NPV of all sales revenues. Thus, the levelized cost is the NPV of all of the cost cash flows divided by the NPV of the product units produced. It can be thought of as the minimum per-unit product sales price that pays all expenses including raw materials, labor wages, debt service for both loans (debt) and owner's investments (equity), and taxes – but no profit above just these cash flow expense items.

The model is designed to reflect a notional manufacturing facility specific to the production of a technology or product. Although the model can be utilized to estimate the production cost of any manufactured product, it is specifically designed to help guide technology R&D research. Estimating the production cost implications of research at an early-stage can help researchers develop processes and designs that minimize the eventual manufacturing costs and increase the likelihood of successful technology deployment. Utilizing the model does require the development of the core components of any specific manufacturing processes: the manufacturing equipment, raw materials cost, labor costs, etc. Several methods are embedded in the model to help a technology researcher produce ballpark estimates quickly. However, the accuracy of these core components determines the accuracy of the levelized cost estimate and therefore the model should be utilized over the course of R&D allowing it to evolve along-side the R&D process and guide research focus towards the most significant cost drivers.

This guide will allow a user to get started by introducing and reviewing the overall structure of the model and basic calculation of the levelized cost. Because this model is an excel file, a researcher or analyst can tailor the model to be as detailed and dynamic as their cost analysis requires. Please contact the authors for a copy of the generic model.

Notional Manufacturing Facility Modeling

The Manufacturing Cost Levelization Model is designed to reflect a notional manufacturing facility specific to the production of a technology or product. It is critical for the user to account for all of the processes necessary to transform raw materials into a finished product ready to be shipped to a customer or retail sales location. In general, manufacturing facilities are typically comprised of the following steps:

1. Raw material receiving and storage,
2. Means of transferring raw materials to processing equipment,
3. Processing equipment
4. Assembly equipment
5. Packaging equipment
6. Finished product storage and shipping
7. Plant management offices and employee facilities

As raw materials progress from storage, through processing equipment, and into final product assembly and packaging, there are typically yield losses in many manufacturing process equipment.

The accuracy of the levelized cost estimates is dependent on the user's ability to capture all of the equipment requirements for the manufacturing plant, as well as the yields for each of the pieces of equipment. The model provides a wide range of manufacturing equipment and their costs, as well as allowing the user to add specialty equipment unique to any manufacturing processes. Similarly, the model provides a limited range of raw materials and their costs, but also allows the user to add additional raw materials and costs. All of the capital cost investments, raw material purchases, and labor costs required to manufacture any given product must be recouped through finished product sales.

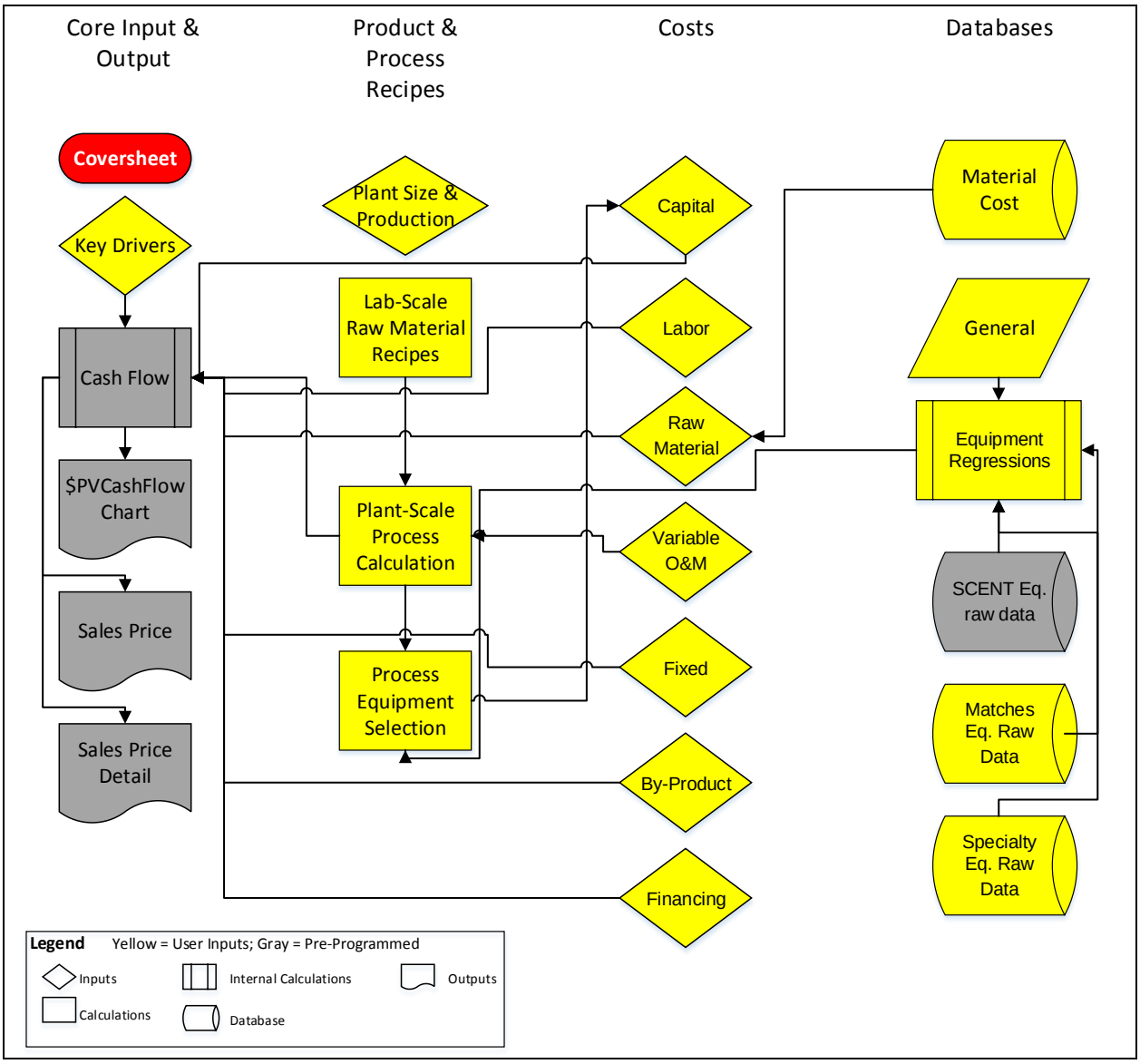
Model Structure

The model is an M.S. Excel (Excel 2013) file consisting of multiple inter-related calculation worksheets (aka "tabs"). With the exception of the coversheet and output chart tabs, each tab is dedicated to a specific function for determining the levelized cost estimate. Table 1 shows the tabs in the model and indicates if user inputs are required. Figure 1 provides a graphical flow diagram of the model structure.

Table 1 – Plant Economics Levelization Model tabs

Tab	User Input?	Description
Core Input & Output		
Coversheet	Yes	General Information
Key Drivers	Yes	Selection of recipe and materials costs assumptions
Cash Flow	No	Pro forma engineering economics cash flow & levelized cost calculations
$PVCaskFlowChart	No	Output chart of cash flow over the facility lifetime
SalesPrice	No	Output chart of final sales price broken into cost segments
SalesPriceDetail	No	Output chart of final sales price broken into cost segments of higher granularity
Product & Process Recipes		
Plant Size & Production	Yes	Plant size & production inputs
Lab-Scale Raw Material Recipes	Yes	Laboratory-scale Lab-Scale Raw Material Recipes by process
Plant-Scale Process Calculation	Yes	Detailed calculations of each plant process and efficiencies per recipe scenario. Process details including material recipes, process conditions, and quantities.
Process Equipment Selection	Yes	Process equipment selection by process, costs, and capacities
Costs		
Capital	Yes	Capital costs summed by process and multipliers and building cost inputs
Labor	Yes	Labor cost inputs
Raw Material	No	Aggregated Plant-scale raw material costs by process
Variable O&M	Yes	Variable operations and maintenance cost inputs
Fixed	Yes	Fixed cost inputs
By-Product	Yes	By-product or co-product (Negative Values = Costs; Positive Values = Income)
Financing	Yes	Financing inputs
Databases		
Material Cost	No	Database of material costs
General	Yes	Miscellaneous plant and equipment information
Equipment Regressions	Yes	Regressions of process equipment costs as a function of scale (from the SCENT, Matches, or Specialty databases)
SCENT Eq. raw data	No	Database of process equipment costs derived from the SCENT Model [1]
Matches Eq. Raw Data	Yes	Database of process equipment costs from the Matches website for estimating equipment cost [2]
Specialty Eq. Raw Data	Yes	Database of specialty process equipment costs

Figure 1 – Model Structure Flow Diagram



Spreadsheet Model Tab Descriptions

With the exception of the Coversheet Tab, the Levelized Sales Price ($/unit of product) is displayed on the top left of each worksheet tab. This allows the user to instantaneously see the resulting levelized sales price as modifications are made throughout the model. Because this value is repeated on each tab of the model, it is not described in each worksheet tab descriptions below.

Coversheet Tab

The coversheet has one user input (the Plant Type), a listing of the spreadsheet tabs and their general content and function, and the color scheme used throughout the model. The Plant Type can be any input that best describes the notional manufacturing plant (e.g., "vehicle battery plant"). Once the Plant Type is defined, it is propagated throughout the model in each of the tabs as well as the output graph. The contents and color scheme are provided for information only; they do not require any user input.

Key Drivers Tab

Table 2 – Components of the Key Drivers Tab

Key Variable	Description
Working Recipe Selection	User Input to select a user developed scenario results
Raw Material Unit Costs Basis	User Input to select a user developed raw material cost basis
Cost Sensitivity Table	Sensitivity table for low, medium, and high costs for any variable the user defines
Profit Adjustment to Sales Price	User defined profit above labor payments and equity return

The Key Drivers Tab allows the user to: a) select a user defined in the Recipe Selection variable; b) select the Raw Material Unit Costs Basis from the raw material cost database; c) conduct aggregated scenario analysis on key cost drivers that contribute to the levelized cost results, and d) adjust the levelized cost to include profit above labor payments and equity return.

The two primary variables on this tab (i.e. Recipe Selection, and Raw Material Unit Costs Basis), both have respective dropdown menus that are defined by: a) the recipes developed in the "Raw Material Recipe" and "Plant-Scale Process Calculation" tabs, and b) "Material Cost" database tab.

The Cost Sensitivity Table allows the user to select several aggregate cost sensitivity variables and observe the effect on the levelized sale price results. The aggregate costs sensitivity variables are: a) Capital Equipment Costs, b) Building Costs, c) Fixed O&M Costs, d) Process Yields, e) Material Costs, and f) Variable O&M Costs. The Cost Sensitivity Table allows the user to input multiplier percentages for each aggregate sensitivity variable and select between a low, medium, or high multiplier that are applied to the aggregate sum of their respective costs. For example, the Capital Equipment Cost sensitivity variable applies the low, medium, or high multiplier to the sum of all process equipment costs. The medium setting is the default setting (i.e. 100%). Additional variables can be added to the table with careful programming to ensure that they are applied to a cost component of interest to the user.

The user can also obtain results for a chosen sales price above the model's levelized sales price under the "Profit Adjustment to Sales Price" key variables (the "Product sales price % above levelized sales price" variable), or determine a sales price necessary to achieve net profit within a

desired number of years (the “Number of year to achieving a net profit” variable). The core functionality of these two variables are contained in the Visual Basic Macro “CellChange”, which utilizes M.S. Excel’s “Goal Seek” function.

A duplicate of the levelized sales price chart contained in the “SalesPriceDetail(M^2)” chart tab is displayed on this tab to help the user see the results of changes made on this tab. However, the chart contained in the “SalesPriceDetail(M^2)” chart tab should be used when presenting results.

Cash Flow Tab

Table 3 – Components of the Cash Flow Tab

Cash Flow Categories	Description
Capital Expenditures	Initial capital expenditures necessary to build the manufacturing facility
Sales Revenue	Annual Sales Revenue over the life of the facility
Manufacturing Cost	Annual Manufacturing Cost over the life of the facility
Financing	Annual Financing over the life of the facility
Annual Depreciation	Annual Depreciation over the life of the facility
Taxes	Annual Taxes over the life of the facility
After-Tax Cash Flow	Annual After-Tax Cash Flow over the life of the facility
Discounting to Present Value (PV)	Annual Discounting to Present Value (PV) over the life of the facility
Levelization of All-In Cost & Benefits	Annual Levelization of All-In Cost & Benefits over the life of the facility
Estimated Unit Costs	Annual Estimated Unit Costs over the life of the facility
MACRS Schedule	Annual MACRS Schedule over the life of the facility
Graph Data	Data graphed in $PVCashFlowChart Chart Tab
Annual Unit Costs ($/m^2)	Data graphed in SalesPrice Chart Tab

The Cash-Flow Tab contains a calculation table that relies on the time value of money and cash flow analysis (standard engineering economics principles) to calculate the levelized sales price. All of the user inputs throughout the model are applied to the notional manufacturing facility timeline to provide annual projections of production output, costs, and revenues. Each of the components of production output, revenue, costs, and taxes are grouped by rows with annual values calculated in the columns of the table. Each cash flow category listed in Table 3 have multiple rows in the cash flow table in the model. No user input is required on this tab, but all calculations can be viewed by selecting any of the cells in the Cash-Flow Tab.

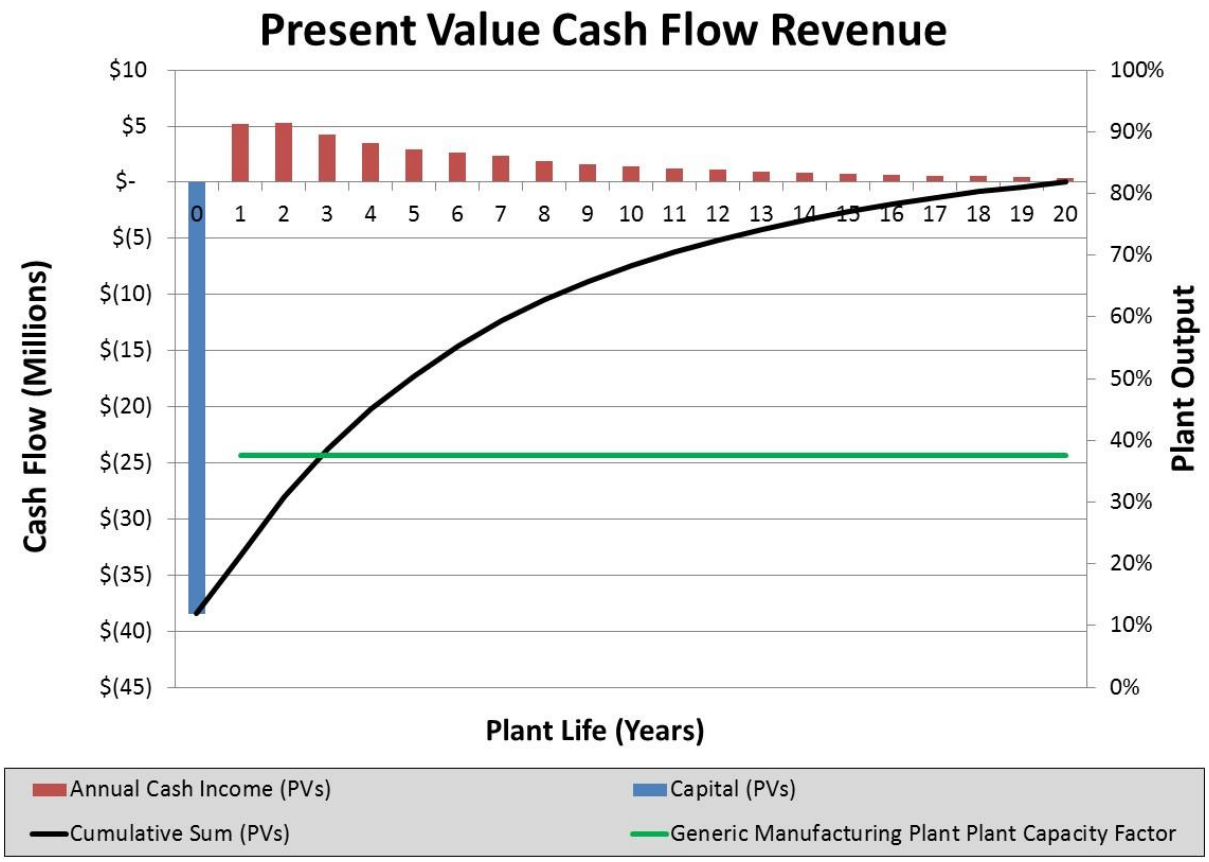
Annual expenses are converted to year zero dollars using a user specified Weighted Average Cost of Capital (WACC) discount rate, then summed to find the NPV of all expenses. Annual production is also projected and discounted to a total PV. The NPV of expenses is then divided by the PV of the output to find the per-unit pre-tax price. Finally, this price is scaled up to include the Tax Rate, resulting in the levelized sales price that includes tax costs associated with product sales revenues.

$PVCashFlowChart Tab

The $PVCashFlowChart Tab is an output chart tab showing the cash flow of the plant over time. The horizontal axis of the graph is time, from year of construction to end of plant life, and the

vertical axes are cash flow on the left and plant capacity factor on the right. Figure 2 presents an example of the cash flow chart imbedded in the model.

Figure 2 – Cash Flow Chart Output Example



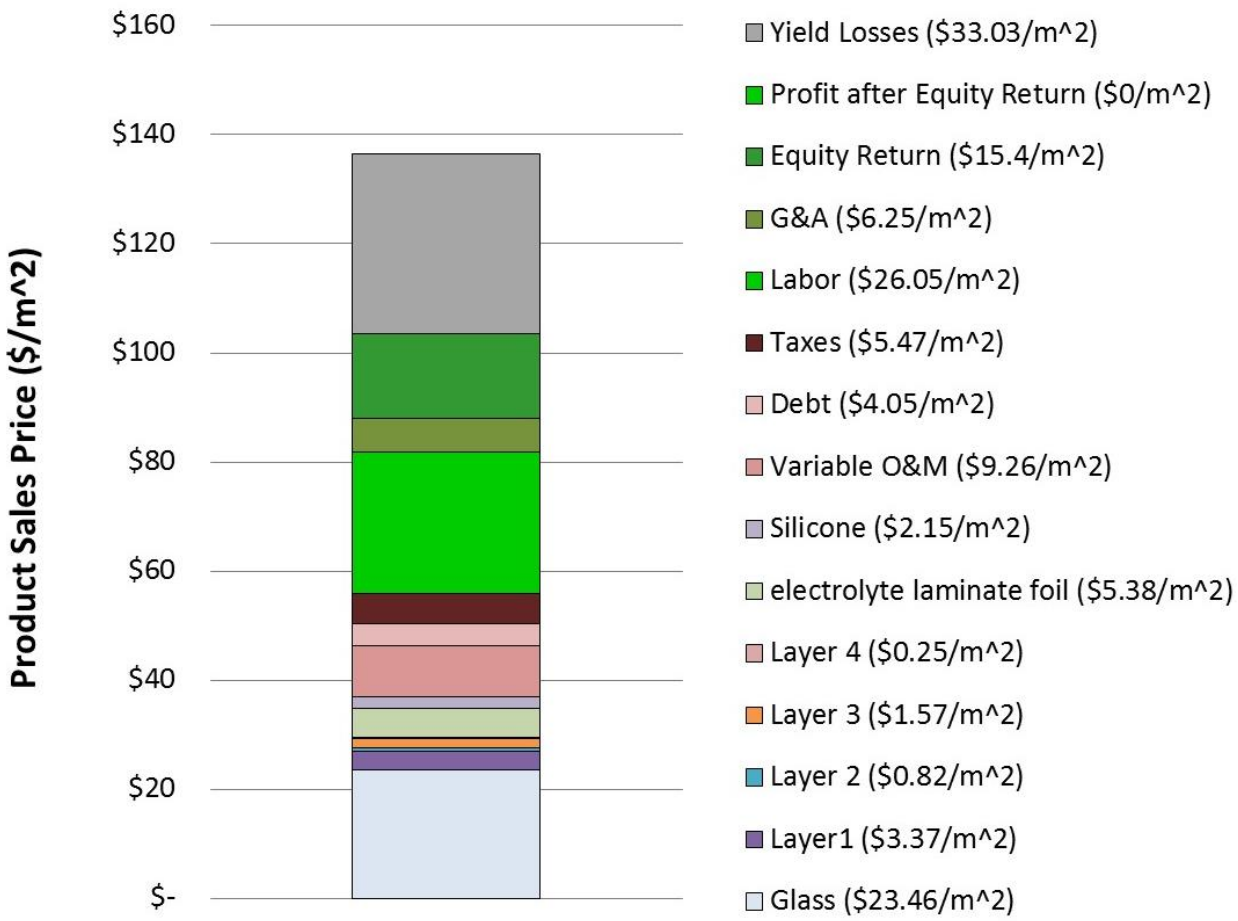
SalesPrice Tab

The SalesPrice Tab is an output chart tab showing the broad components that make up the resulting sales price. These include materials, fixed operating costs, variable O&M, debt, taxes, labor, general management and administration labor ("G&A"), equity return, and profit. For the levelized sales price, profit should be zero, and will only be non-zero if the user has imposed a "Product sales price % above levelized sales price" or "Number of year to achieving a net profit" on the "Key Drivers" tab.

SalesPriceDetail Tab

The two SalesPriceDetail chart tabs, for different production units, show the same information as the SalesPrice chart, but with more granular cost segmentation for the materials component by process. Figure 3 presents an example of the sales price chart imbedded in the model.

Figure 3 – Sales Price Detail Chart Output Example



Plant Size and Production Tab

The Plant Size & Production tab allows the user to input several inputs that begin to define the notional manufacturing facility. The first set of inputs are for the notional manufacturing facilities' output capacity size and operations parameters (e.g., plant capacity factor, days of operation per week, and hours of operation per day).

The next set of inputs are for the productivity and costs forecasts over the lifetime of the manufacturing facility. This allows the model to factor in a start-up period when the new facility might operate below its output rated capacity and incur costs below those during normal operations. It also allows the model to factor in cost escalations over time with each cost component (e.g., labor, fixed, etc.) having a separate escalation rates. All escalation rates are annually compounding, and represent an escalation when positive and degradation when negative. Descriptions of these inputs are described in Table 4.

Table 4 – Plant Size and Production User Inputs

Input	Description
Operating Lifetime	The expected time from when the plant begins manufacturing product to when it is decommissioned. The tool can process lifetimes up to 50 years.
Annual Production Rated Capacity	The maximum production level of the plant in its full operation.

Input	Description
Plant Capacity Factor	The percent of rated capacity expected to actually be produced each year.
Plant Weeks of Operation Per Year	
Plant Days of Operation Per Week	
Plant Hours of Operation Per Day	
Product Output Productivity Change Rate	Rate at which production is expected to change after the initial start-up period. Accounts for general improvement in plant efficiency/utilization.
Productivity Start Up Period	Number of years before production output reaches the full Plant Capacity Factor.
Productivity Start Up Period Beginning Output Percent	Percent of Annual Production Rated Capacity produced at Plant Start Up. Output ramps linearly over Productivity Start Up Period.
Percent of Labor Costs at Plant Start Up	Percent of total labor costs incurred at start up. Ramps linearly over Productivity Start Up Period.
Labor Costs Escalation Rate	Rate at which labor costs change after the initial start-up period. Accounts for rising costs in labor expenses.
Percent of Fixed Costs at Plant Start Up	Percent of total fixed operating costs incurred at start-up. Ramps linearly over Productivity Start Up Period.
Fixed Costs Escalation Rate	Rate at which fixed costs change after the initial start-up period. Accounts for rising costs in fixed operating expenses.
Material Costs Productivity Start Up Period Beginning Output Percent	Percent of total material costs incurred at start up. Ramps linearly over Productivity Start Up Period
Material Costs Escalation Rate	Rate at which material costs change after the initial start-up period. Accounts for rising costs in material prices.
Variable O&M Costs Productivity Start Up Period Beginning Output Percent	Percent of total variable operating costs incurred at start up. Ramps linearly over Productivity Start Up Period.
Variable O&M Costs Escalation Rate	Rate at which variable costs change after the initial start-up period. Accounts for rising costs in variable operating expenses.
By-Products Productivity Start Up Period Beginning Output Percent	Percent of total by-product capacity produced at start up. Ramps linearly over Productivity Start Up Period
By-Products Output Escalation Rate	Rate at which by-product production will change after the initial start-up period. Accounts for changes in amount of by-product produced.

Lab-Scale Raw Material Recipes Tab

The “Lab-Scale Raw Material Recipes” tab contains a list of each raw material input to the notional manufacturing facility. Raw materials can include chemical feedstocks, raw metals, water, or any other material purchases necessary to produce the product. The recipe inputs on this tab determined by laboratory-scale R&D results. The user can enter quantity of each material used and their recycle rates, if applicable, for each process. The user can add columns for various recipe iterations stemming from R&D advancements and iterations. The “Working Recipe” variable at the top of the tab reflects the working recipe selected on the “Key Drivers” tab. The working recipe number identifies which laboratory-scale recipe the levelized cost results will be based upon and loads this recipe from the user input columns to the “working recipe” columns.

Table 5 shows the column heading used in the “Lab-Scale Raw Material Recipes” tab. Materials are selected from a drop down menu that contains all of the raw materials pre-populated in the

“Materials Cost” database tab. If materials that are not pre-populated in the “Materials Cost” database tab are used in a recipe, then the material must be added to the “Materials Cost” database tab before selecting it in the “Lab-Scale Raw Material Recipes” tab.

The last four column headings can be copied to columns as need to create additional recipes. However, the format and order of the pasted columns should remain in this format and order with only the heading name modified (e.g., “Recipe 2 …”, etc.)

Table 5 – Raw Material Recipe Tab Column Headings

Column Headings	Description
Process Number	Unique Process number for each lab-scale formulation
Material	Material name used in formulation (Dropdown list of Materials from the “Material Cost” database tab)
Working Recipe Annual Volume (L)	Annual plant-scale volume (in liters) of the material per the working recipe
Annual Cost Share	Annual cost share of the material in the process number
Unit Conversion to Liters	Converts recipe input from units to liters based on the material's density
Working Recipe Step	Step in the formulation that the material is added per the working recipe
Working Recipe Quantity	Quantity of material used in the formulation (before conversion to liters) per the working recipe
Working Recipe Recycle %	Recycle rate of the material per the working recipe
Working Recipe Units	material units input to the recipe per the working recipe
Recipe R Quantity	Laboratory-scale data input for recipe R
Recipe R Step	Step in the formulation that the material is added for recipe R
Recipe R Recycle %	Recycle rate of the material for recipe R
Recipe R Units	Material Quantity units (e.g., grams, liters, etc.) for recipe R

Laboratory-scale raw material inputs in this tab are used in the next tab “Plant-Scale Process Calculations” when scaling-up lab-scale recipes to the notional manufacturing facility scale. The critical link between many of the model’s tab is the “Process Number” in the first column of this tab. Once the user provides recipe-specific production-scale up calculations in the “Plant-Scale Process Calculations” tab, the Raw Material Recipe tab displays each raw material’s annual costs on an annual cost share basis (i.e. the contribution of each raw material used in a process to the total annual cost of the raw material across all processes).

Cost information is pulled from the “Material Cost” tab based on the quantities prescribed in the “Plant-Scale Process Calculations” tab.

Plant-Scale Process Calculation Tab

The Plant-Scale Process Calculation tab contains user inputs and calculations for each process in the notional manufacturing facility. These inputs and calculations scale-up laboratory-scale material recipes (input in the “Raw Material Recipe” tab) to manufacturing-scale production levels. This tab allows the user to define product specifications, process equipment steps and efficiencies, or facility logistics for each raw material recipe developed in the “Raw Material Recipe” tab. Similar to the “Raw Material Recipe” tab, the “Plant-Scale Process Calculation” tab requires a separate column for each scenario that corresponds to each unique recipe scenario defined in the “Raw Material Recipe” tab. As R&D evolves, new recipe scenario calculations

track the progress of R&D. The model does not limit the number of recipes a user can create & each separate recipe can reflect minor modifications of recipe raw material inputs or process equipment.

Process steps in the “Plant-Scale Process Calculation” tab can include: a) raw material receiving, storage, and handling, b) liquid and solid raw material processing, c) process integration and intermediate process product blending, d) product assembly, e) product packaging, storage and shipping, and d) facility utilities such as boilers and waste-handling. Each process or major piece of processing equipment should have a dedicated process number and set of calculations unique to each scenario. In the case of liquid processing, a processing step can focus on the main reactor or processing tank or vessel, and any additional ancillary processing equipment necessary to support the main reactor/tank/vessel, such as pumps, heat exchangers, centrifuges, etc. can be defined and selected in the “Process Equipment Selection” tab.

The plant-scale process scenario calculations can be complex as necessary to adequately capture all the manufacturing processes that transform raw materials into finished products. Each scenario’s calculations should be standalone (i.e. contained within a single column) such that when the working scenario is selected on the “Key Drivers” tab, the working scenario’s calculation in this tab are only inter-related to processes defined within the scenario’s unique column. As many rows can be used as needed to capture all of the processes and details necessary for each process. When adapting the model to a new manufacturing product, the first recipe scenario should develop as much detail of the manufacturing process steps as possible. Once the initial recipe and associated processing steps and equipment are established, subsequent recipes can copy the process steps and equipment calculations into a new column to represent a modified recipe and the user can modify any parameter in the calculations of the new scenario. This allows the user to retain and re-use, calculation developed in previous scenario as much as possible.

Table 6 – shows the column heading used in the “Plant-Scale Process Calculation” tab. Columns A, B, C, and D are dedicated to process numbers, variable descriptions, variable units, and working recipe values, respectively. In some instances, a recipe scenario might require a process step that is not required by other recipes. Similarly, a process calculation might require different variables between recipe scenarios. In either of these instances, variable rows can be left blank for a given recipe scenario. When a recipe scenario is comprised of empty row calculations, then the scenario will exclude those calculations and or that process step.

Table 6 – Plant-Scale Process Calculation Tab Column Headings

Column Headings	Description
Process number	Unique Process number for each plant-scale process
Variable Description	Description of the variable developed in the rows of calculations
Variable Units	Units for the variable calculated in the row
Working Recipe R	Pulls the calculated value in each row from Recipe R column's calculation
Recipe R	Unique Process Calculations for Recipe R scenario

The functionality of other tabs within the model requires the user to calculate several critical parameters for each process step developed in this tab. These critical parameters are: a) unique process number, b) process name specific to each scenario, c) If necessary, a process scale

variable that serves as a multiplier to scale lab-scale raw material inputs in the “Lab-Scale Raw Material Recipes” tab to plant-scale, d) “Process P Equipment Capacity” (e.g., liters/batch, etc.), e) process efficiencies and their relation to other process steps. The most critical parameter is the “Process P Equipment Capacity” variable. The numeric value of this variable should reflect the main piece of processing equipment in the processing step and the capacity size for which it will operate. For example, a reactor that takes several chemical input, allows for a chemical reaction to take place, and sends the resulting chemical to another processing step could be the main piece of equipment for the process number. The equipment capacity would be the maximum size of a batch, or continuous flow rate that the reactor will operate at. This could be derived by summing all of the annual plant-scale inputs to the reactor, and then dividing by the number of batches per year, of the hours of operation per year. Regardless of how the numeric value is derived, equipment capacity value and units are passed to the “Process Equipment Selection” tab where the process equipment cost is calculated based on the capacity value and units.

Manufacturing process steps are often inter-related such that materials flow from one process step to the next. In this respect, the logical progression of this tab starts with raw material inputs to the manufacturing processes at the top of the tab and works downward in the tab to conclude with finished product shipping at the bottom of the tab’s rows. This logical progression configuration can be tailored to fit any user’s logical progression of how each manufacturing process transforms raw materials into finished products.

Each process step is numbered in the first column of the tab and the process numbers are used throughout the model to account for process equipment sizing and costs. Each processing step allows the user to input process step efficiencies which accumulate upwards in the tab to determine the quantities of raw material purchases necessary to produce the specified quantity of product output. For example if material is lost in the final step of production, more material will need to be produced prior to this step to ensure product output is achieved. The user is responsible for ensuring the efficiencies are mapped to the appropriate process steps. A method for doing this is provided in the initial version of the tool and consists of two related tables per process. In the first table, the process specific efficiency is input and the associated process that it relates to is defined. The second table sums the accumulated efficiencies downstream (lower in the worksheets scenario rows) up to each process. For example, if the notional facility has P number of process steps and the final process step (process P) is 90% efficiency (i.e., 10% loss of product in process P), then the process P-1 must have 11% more processing capacity to ensure that the product output (defined in the “Plant Size & Production” tab) is achieved. Likewise, if process P-1 also has an efficiency of 90%, then process P-2 must have 23% more processing capacity (1/90%/90% = 123%). Accumulating all of the efficiency losses from the last process to the first process, the raw material purchase requirements passed to the “Raw Material” cost tab reflect the accumulated losses throughout the manufacturing plant.

Process Equipment Selection Tab

The Process Equipment Selection Tab allows the user to select and assign process equipment to the processes established in the “Plant-Scale Process Equipment” tab and estimates the capital cost of the processing equipment per each process step. Table 7 shows the column headings for the table contained in this tab.

Table 7 – Process Equipment Selection Tab Column Headings

Column Headings	Description
Process Number	Unique Process number for each plant-scale process
Equipment Type	Description of the Equipment (Dropdown list of Equipment from the Equipment Regressions cost tab)
Installed Equipment Cost	Calculated Installed Equipment cost based on the Capacity, the equipment cost regression and Number of Equipment required
Recipe Capacity	Pulls the calculated equipment capacity from the Plant-Scale Process Calculation tab
Recipe Capacity Units	Pulls the equipment capacity units from the Plant-Scale Process Calculation tab
Process Description	Pulls the Process Description from the Plant-Scale Process Calculation tab
Use Conversion Factor?	Boolean variable that allows the use of a user defined unit conversion factor
Unit Conversion	User input conversion factor necessary to translate the Recipe Capacity to the Equipment Capacity Units
Capacity	If Use Conversion Factor? = TRUE: Multiplies the Recipe Capacity by the Unit Conversion factor from the Unit Conversion Column
Equipment Capacity Units	Pulls the equipment capacity cost units from the Equipment Regressions tab
Equipment Cost Capacity Range	Pulls the equipment cost capacity range from the Equipment Regressions tab
Number of Equipment Installed	IF Capacity < Equipment Cost Capacity Range: 1, else ROUNDUP Capacity/Equipment Cost Capacity Range
Constant	Pulls the power regression constant from the Equipment Regressions tab
Exponent	Pulls the power regression exponent from the Equipment Regressions tab

In order to select process equipment, the process equipment must be contained in the "Equipment Regression" tab. This tab is outlined below, and a new user of this Levelization tool will need to use these two tab in together to: a) first, capture the costs associated with a particular type or piece of processing equipment in the "Equipment Regression" tab (described below), and b) select the equipment and assign it to a process in this tab. The following description of this tab assumes that the processing equipment is already contained in the "Equipment Regression" tab.

The user first selects the process step that an individual piece of process equipment will be associated with. The table automatically looks in the "Plant-Scale Process Calculation" tab to find the process step equipment capacity (i.e., "Process P Equipment Capacity") value and puts it in the "Recipe Capacity" column along with the equipment capacity units placed in the "Recipe Capacity Units" column. The process step name, as defined in the "Plant-Scale Process Calculation" tab is also looked up and displayed in the "Process Description" column in the table. Once the user selects the desired piece of process equipment from the dropdown list in the "Equipment Type" column, the table populates the "Equipment Capacity Units", "Equipment Cost Capacity Range", the regression "Constant" and "Exponent" from the "Equipment Regression" tab. If the "Recipe Capacity Units" and the "Equipment Capacity Units" are not the same, then the user can either: a) alter the recipe capacity units on the "Plant-Scale Process Calculation" tab, or b) enter a unit conversion factor in the "Unit Conversion Factor" column, and select "TRUE" in the "Use Conversion Factor?" column. Thus, the value in the "Capacity" column should be in the same units of the "Equipment Capacity Units".

The table then compares the “Capacity” to the “Equipment Cost Capacity Range” to determine how many pieces of the equipment should be purchased. The resulting “Installed Equipment Cost” is defined by Equation 1.

Equation 1

$$Installed\ Equipment\ Cost = N \times C \times Pc^{E}$$

Where:

N = “Number of Equipment Installed”

C = the regression “Constant”

Pc = “Capacity”

E = the regression “Exponent”

Additional pieces of ancillary equipment (e.g., pumps, heat exchangers, filters, etc.) that support the main process piece of equipment can be selected in a similar way. First select the process step, and then apply the appropriate “Unit Conversion Factor” to convert the “Recipe Capacity Units” to the “Equipment Capacity Units”. This allows the user to enter as many pieces of equipment associated with the process as need to properly account for processing equipment. Minor pieces of processing equipment such as control valves, piping and instrumentation are captured by a capital cost multiplier in the “Capital Cost” tab. However, if this level of granularity is desired, this type of equipment can be added using the method described here, with the user ensuring that the corresponding minor pieces of equipment are placed in the “Equipment Regression” tab.

If a process requires more than one major piece of processing equipment, the user can decide to split the process step into multiple steps in the “Plant-Scale Process Calculation” tab and then return to this tab to select the additional process step and assign processing equipment to it.

Capital Costs Tab

The Capital Costs tab aggregates the equipment costs entered on the previous tabs, and allows the user to input additional capital costs necessary to build the manufacturing facility. Capital costs can include the manufacturing processing equipment, additional estimated facility equipment (e.g. warehouse, steam plant, waste handling, etc.) and cost multipliers which capture additional costs (e.g., engineering and construction, contingencies, etc.). Each of the categories can be expanded in order to capture any anticipated cost that will determine the financial capital required to build the facility. Total capital cost can be manipulated as a whole using the “Capital Equipment Costs”, and “Building Costs” rows of the Key Variables Cost Sensitivity Table on the “Key Drivers” tab. Table 8 shows the column and section headings that structure the user inputs for this tab.

Table 8 – Capital Cost Tab column and section headings

Column Headings	Description
Process #	Unique Process number for each plant-scale process

Column Headings	Description
Process Description	Name of the process (defined on Lab-Scale Raw Material Recipes tab)
Cost	Estimated Process Equipment Costs Summed by Process
Notes & Comments	Allows the user to include notes or references
Section Headings	**Description**
Estimated Process Equipment	Estimated Process Equipment Sum by Process
Additional Estimated Equipment	Additional Capital Cost Multipliers and costs
Building Cost	Estimated Building Costs
Capital Cost Multipliers	Construction and Engineering Capital Cost Multipliers and Costs
Total Depreciable Capital	Depreciable Capital Sums
Construction Working Capital Expenditure	Additional Construction Working Capital Cost Multipliers and Expenditures (included in Capital Costs)

The Estimate Process Equipment section does not require user input; instead aggregates the process equipment costs from the Process Equipment Selection Tab per process step. If additional process steps are modeled in the previous tabs, this sections should be expanded (or contracted) to aggregated all modeled process steps.

The Additional Estimated Equipment allow the user to input cost multipliers to the total process equipment costs to capture additional facility processes such as utilities, that might not be modeled explicitly in the Process Equipment Selection Tab. However, if these processes are modeled in the previous tabs, the user can enter 0% for the cost multipliers so that the modeled processes are not counted twice.

The Building Cost section allows the user to input the cost of the facility buildings and land improvements. These are additional costs that are added to the total capital costs, but has a dedicated depression rate as defined by U.S. tax codes[3].

Similarly, Capital Cost Multiplier section allows the user to input additional capital costs for: a) state-specific construction premiums, b) contingency, c) architecture, construction management, and engineering costs, and d) facility site work. These are standard capital cost additions common to constructing a manufacturing facility.

Total Depreciable Capital sums the depreciable capital costs from the user inputs on previous tabs and input in previous sections of this tab.

The final section of this tab, Construction Working Capital Expenditures allows the user to input a percentage for additional working capital in the final year of the facility construction.

Labor Costs Tab

Labor costs are captured by two components: Direct Labor and Management (G&A) (sales, general and administration). Direct labor is the salary & wage payments to employees that operate the manufacturing facility, and G&A costs are for sales, general plant management and administration. Total labor cost can be manipulated as a whole using the “Labor Costs” row of the Key Variables Cost Sensitivity Table on the “Key Drivers” tab. Both of these cost categories

are tax deductible expenses and affect the tax payments. Table 9 shows the column and section headings on the Labor Cost Tab.

Table 9 – Labor Cost Tab Column and Section Headings

Column Headings	Description
Category	Description of variables
Quantity	Quantity of the variable
Units	Units of the variable
Cost per Unit ($/Unit)	Cost per Unit ($/Unit) of the variable
Total Cost	Total Cost = Quantity * Cost per Unit
Section Headings	**Description**
Direct Labor	Direct Labor Cost Category
Management (G&A)	Management and G&A Cost Category

Both labor and G&A costs can be estimate as variable cost functions of the manufacturing facility output, or as fixed costs estimate independent of the manufacturing facility output. If the labor cost components are variable costs, they should be entered as a function of production output (e.g. $/unit, or $/capacity factor). However, some of these costs might be fixed (e.g., sales could be independent of plant output), or linear but with a fixed component (e.g., at least one employee is required regardless of output). In these cases, fixed labor or SG&A can be independent of production, or have a linear function with a non-zero y intercept (the fixed portion of the variable cost).

The version of the tool described in this report uses a linear regression function to estimate variable costs as a function of production. Under each of the section headings, percentages of capacity output are entered into the "Units" column, and estimate numbers of labor, and G&A personal are entered in the "Quantity" column. Regression coefficients for a 2nd order polynomial regression equation are shown in the "Quantity" column below these inputs and the used to estimate the number of personal as a function of manufacturing facility output. The resulting estimates are multiplied by the "Direct Labor Avg. Salary" and "Management (G&A) Avg. Salary inputs, and their respective benefits (as a percentage of salary) to provide the respective labor costs.

This tab can be modified to enable as much detail as needed. But the resulting total annual labor costs should be placed in the "PlantLaborCost" cell and the resulting total G&A costs should be placed in the "PlantGACost" cell. These two cell are used in the cash flow tab calculations.

Raw Material Costs Tab

The Raw Material Costs Tab is a calculated tab which sums up all of the costs for each process that has a raw material input, as defined in the "Lab-Scale Raw Material Recipes" tab, by summing the raw material costs from the "Lab-Scale Raw Material Recipes" tab. The cost for each process is then normalized by plant output to give per-unit costs. The sum of these process totals are the total material cost used in further calculations. Total material cost can be manipulated as a whole using the "Material Costs" row of the Key Variables Cost Sensitivity

Table on the “Key Drivers” tab. These cost categories are tax deductible expenses and affect the tax payments. Table 10 shows the column headings of the Raw Material Costs Tab.

Table 10 – Raw Material Costs Tab column headings

Column Headings	Description
Process Number	Description of variables
Process Description	Quantity of the variable
Cost ($/Unit)	Cost per Unit ($/Unit) of the variable
Total Cost	Total Cost = Quantity * Cost per Unit
Notes & Comments	Allows the user to include notes or references

Variable O&M Tab

Variable operations and maintenance (O&M) costs are costs that change in proportion to the manufactured product output. This can include energy costs (electricity and fuels), waste disposal, maintenance on equipment that occurs in proportion to production, etc. Although labor and raw material inputs are variable O&M costs, they are critical enough to the overall cost of manufacturing to have their own dedicated tabs (Labor Tab & Materials Tab). Total variable O&M cost can be manipulated as a whole using the “Variable O&M Costs” row of the Key Variables Cost Sensitivity Table on the “Key Drivers” tab. Variable costs are tax deductible expenses and affect the tax payments.

Column Headings	Description
Category	Description of variables
Quantity	Quantity of the variable
Units	Units of the variable
Cost per Unit ($/Unit)	Cost per Unit ($/Unit) of the variable
Total Cost	Total Cost = Quantity * Cost per Unit
Notes & Comments	Allows the user to include notes or references

Typically, variable O&M costs are estimated based on the operating condition of process equipment. For example, electric motor driven systems are typically sized by engineering calculation that determine their maximum capacity size (kW), and then their operating conditions (hour of use per year) are used to estimate their electricity requirements. Similarly, the operating conditions of fuel fired furnaces can be used to estimate their fuel requirements. However, the version of the model documented by this report does not have a sufficient level of detail to estimate these loads. Likewise, variable maintenance on process equipment can be estimated using engineering rules of thumb, but this too is not attempted in this version of the model. However, this level of detail can be added in subsequent projects as need by the user and analyst.

In place of this detail, the version of the tool described in this report uses a linear regression function to estimate variable O&M costs as a function of production (similar to the variable labor costs discussed in the “Labor Cost Tab” of this report). Percentages of capacity output are entered into the “Units” column, percentages of the “Non-Linear Variable O&M Base Cost at full capacity” (e.g. $/unit of output) are entered into the “Quantity” column. Regression

coefficients for a 2nd order polynomial regression equation are shown in the "Quantity" column below these inputs and are used to estimate the quantity of variable O&M as a function of manufacturing facility output. The resulting estimates are multiplied by the "Non-Linear Variable O&M Base Cost at full capacity" in the "Cash Flow" tab.

Fixed Tab

Fixed costs are costs that do not change in proportion to the manufactured product output. This can include property taxes & insurance, rent, and operation and maintenance (O&M) that occurs independent of production. Fixed costs are tax deductible expenses and affect the tax payments.

Column Headings	Description
Category	Description of variables
Quantity	Quantity of the variable
Units	Units of the variable
Cost per Unit ($/Unit)	Cost per Unit ($/Unit) of the variable
Total Cost	Total Cost = Quantity * Cost per Unit
Notes & Comments	Allows the user to include notes or references

Fixed costs are estimated as a percent of the total cost of installed equipment, and property tax and insurance can be estimated as a percent of the total manufacturing plant costs. This tab can be modified to enable as much detail as needed. But the resulting total annual fixed costs should be placed in the "PlantFixedCost" cell which is used in the cash flow tab calculations.

By-Product Tab

By-products are any additional outputs from the manufacturing facility that results in an additional revenue. Examples could be scrap or waste materials which have a market value and are anticipated to result in additional revenue when sold. By-product revenues are taxable income and affect the levelized cost of the main product output.

Column Headings	Description
Category	Description of variables
Quantity	Quantity of the variable
Units	Units of the variable
Cost per Unit ($/Unit)	Cost per Unit ($/Unit) of the variable
Total Cost	Total Cost = Quantity * Cost per Unit
Notes & Comments	Allows the user to include notes or references

By-products should be entered as a revenue and can be a function of production (e.g., $/unit production).

Financing Tab

Column Headings	Description
Category	Description of variables
Value	Quantity of the variable
Notes & Comments	Allows the user to include notes or references
Section Headings	**Description**

Column Headings	Description
Sales Price	Product Sales Price % above "Break Even" Sales Price
Financing Assumptions	Debt and Equity rates (%s), Debt to Equity Ratio, Weighted Average Cost of Capital (WACC)
Tax Depreciation Assumptions	Equipment and Building life for depreciation
Tax Assumptions	Tax Rate

Financing Assumptions

Building or buying a manufacturing facility requires initial financial capital. Financial capital can be borrowed (debt), owner investment (equity), and is commonly a combination of the two. Although both have similar cash flow calculations components (i.e., principle and interest payments), they are treated separately due to their respective tax implications. Principle payments re-pay the financial capital borrowed (in the case of debt), or invested (in the case of equity), while interest payments pay for the ability to use the financial capital. Only the interest associated with debt is a tax deductible expense. These two types of financing (debt and equity) can have payment schedules (period over which they are re-paid and interest rates) and therefore have separate inputs on the Financing Tab. Each has a life (period over which they are re-paid) input and an interest rate input. A debt to equity ratio splits the financial capital requirement for building the facility into debt and equity portions. For example, a debt to equity ratio of 30% means that 30% of the financial capital requirements is borrowed (or debt), leaving the remaining 70% an investment by the manufacturing facility owner (equity).

The cash flow calculations sum the net-present-value (NPV) of all costs, revenues, and output using the Weighted Average Cost of Capital (WACC) discount rate, which is the weighted average of debt and equity interest rates. The WACC is calculated using Equation 2.

Equation 2

$$WACC = (1 - dte) * i_e + dte * i_d$$

Where:

WACC = Weighted Average Cost of Capital

dte = debt to equity ratio

i_e = equity interest rate

i_d = debt interest rate

Tax Depreciation Assumptions

Equipment and building are depreciable assets with tax implications. Depreciable assets are those that have diminishing value over time due to their use, such as equipment and buildings. In U.S. tax codes, the cost of these assets are allocated to annual value reductions over the life of the equipment and accounted as a cost that offsets income revenue.

Because equipment and buildings have different lifetimes, tax codes have differing depreciation rates (or schedules) for each. Process equipment is typically assigned a 7 year depreciation schedule, building a 39 year schedule, and steam generation and boilers a 20 year schedule.

These schedules are selected in the financing tab for each of these three asset categories. The cash flow calculations use MACRS[1] depreciation schedules as defined by U.S. tax codes for 2013 and can be found on U.S. Internal Revenue Service (IRS) [3].

Tax Rate Assumption

The tax rate is the percentage of taxable income that is paid by business. The default value used in the model is the marginal effective tax rate of 39.55%.

Material Cost

The Material Cost Tab contains a complete cost database for all materials called on in the "Lab-Scale Raw Material Recipes" tab.

Column Headings	Description
Material Name	Name of the Material
Annual Purchase Volume (L)	Annual Purchase Volume summed from all processes
Material Cost	Material Cost = Annual Purchase Volume (L) * Working Cost per Unit
# Purchases per Year	Defined in the Plant-Scale Process Calculation tab
Material type	General raw material category (e.g., organic compound, metal salt, etc.)
Chemical Formula	Chemical Formula
CAS Number	The Chemical Abstract Service (CAS) unique # for chemical compounds and sequences
Density	Raw material's density
Density Units	Generally in g/cm^3
Working Cost per Unit	Converts the cost in the Selected Cost per Unit column to $/liter
Working Cost Units	Units that the working cost is given in (e.g., $/gram, $/liter, etc.)
Selected Cost per Unit	Pulls from the cost database selected by the user (Raw Material Unit Costs Basis on: Key Drivers tab
Selected Cost Units	Units that the working cost is given in (e.g., $/gram, $/liter, etc.)
Cost per Unit (EC)	Older database of raw material costs
EC Units	Older database of raw material costs units
SHOEI "Vendor A" Prices	SHOEI "Vendor A" Prices
SHOEI "Vendor A" Price Units	SHOEI "Vendor A" Price Units
Minimum Price from SA	Minimum price from Sigma Aldrich (U.S. High Quality) (from several purchase quantity quotes)
Minimum Price from SA Units	Minimum price from Sigma Aldrich Units
Minimum Price from BOCSCI	Minimum price from BOCSCI (from several purchase quantity quotes)
Minimum Price from BOCSCI Units	Minimum price from BOCSCI Units
Minimum Price from Alibaba	Minimum price from Alibaba (China) (from several purchase quantity quotes)
Minimum Price from Alibaba Units	Minimum price from BOCSCI Units
SCENT Tool (2014 USD)	Minimum price from SCENT Tool (EU) (from several purchase quantity quotes)
SCENT Tool units	Minimum price from SCENT Tool (EU) Units

[1] MACRS – Modified Accelerated Cost Recovery System

Column Headings	Description
Regression Discount	Linear Regression on Log Scale Data from Sigma Aldrich and Alibaba (Discount Variable)
Regression Intercept	Linear Regression on Log Scale Data from Sigma Aldrich and Alibaba (Intercept Variable)
Regression Units	Linear Regression on Log Scale Units
Embodied Energy (MJ) per kg	Embodied Energy (MJ) per kg

Raw material costs are always difficult to estimate because different suppliers of raw materials often provide a range of price quotes, and they are often dependent on the purchase volumes, purity levels, and other market conditions. The version of the model documented in the report, has several raw material supplier quotes for the materials required for the first case study through which the model was developed. However, other products will likely have unique raw material recipes that will require prices quote.

For this version of the model, raw chemical inputs quotes were obtained from Sigma Aldrich, BIOSCI, and Alibaba. For many of the raw chemicals, price quotes were dependent of purchase volumes. This allowed for log-log regressions to capture the variance in price quotes across the purchase volumes quoted. Thus, this tab includes regression results for many of the raw chemicals, and the user can select which price quotes to use on the "Key Input" tab using the "Raw Material Unit Costs Basis".

General

The General Tab allows the user to store useful miscellaneous information needed for calculations on other tabs. This could include equipment efficiencies.

Equipment Regressions

The Equipment Regressions tab compiles information from the "SCENT Eq. raw data", "Matche Eq. raw data", and "Specialty Eq Raw Data" tabs. This creates one cost regression equation for each piece of equipment.

Column Headings	Description
Equipment	Unique Equipment Name
Units	Capacity units for capital cost estimates
Size Range Low	Equipment capacity size range (Low)
Size Range High	Equipment capacity size range (high)
Constant	Power regression (constant)
Exponent	Power regression (exponent)
R^2	R squared, is a number that indicates how well data fit a statistical model (0=poor, 1= perfect)

SCENT Eq. raw data

A database of the equipment costs estimates taken from the SCENT model [1]. The database is referenced in the "Equipment Regressions" tab.

Matche Eq. Raw Data
A database of the equipment costs estimates taken from the Matche website [2]. The database is referenced in the “Equipment Regressions” tab.

Specialty Eq Raw Data
A database of specialty equipment costs that are not provided in either of the SCENT or Matche database. The specialty equipment is unique to the manufacturing process & product modeled. Specialty equipment cost quotes can be obtained from vendors of the specialty equipment. This can be as detailed as necessary to capture the size of the equipment, operating conditions, and capital cost for purchasing and installing the specialty equipment.

Conclusions

The Manufacturing Cost Levelization Model is an analytical method for estimating all of the manufacturing costs necessary to produce a product and computes a levelized cost per-unit of the manufactured product. Levelized cost is the minimum per-unit price ($/unit of product) necessary to recover all of the costs associated with manufacturing the product over an assumed financial cycle and manufacturing facility lifetime. Manufacturing costs typically includes: a) manufacturing facility capital investments; b) raw material and energy purchases; c) fixed & variable operations and maintenance costs including labor; d) financing costs, and e) taxes. Engineering economic methods are used to project each of these costs into cash flows over the life-time of the manufacturing facility. The model is designed to reflect a notional manufacturing facility specific to the production of a technology or product.

This guide allows a user to get started by introducing and reviewing the overall structure of the model and basic calculation of the levelized cost. Because this model is an excel file, a researcher or analyst can tailor the model to be as detailed and dynamic as their cost analysis requires.

Although the model can be utilized to estimate the production cost of any manufactured product, it is specifically designed to help guide technology R&D research. Estimating the production cost implications of research at an early-stage helps researchers develop processes and designs that minimize the eventual manufacturing costs and increase the likelihood of successful technology deployment.

Utilizing the model requires the development of the core components of any specific manufacturing processes: the manufacturing equipment, raw materials cost, labor costs, etc. Several methods are embedded in the model to help a technology researcher get started and an example of a notional manufacturing process is imbedded in the current version of the model. However, the accuracy of these core components determines the accuracy of the levelized cost estimate and therefore the model should be utilized over the course of R&D allowing it to evolve along-side the R&D process and guide researcher’s focus on the most significant cost drivers.

References

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