Design for Manufacturing and Assembly Cost Estimate Methodology for Transportation Fuel Cell Systems

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This article presents a design for manufacturing and assembly (DFMA) methodology for estimating the capital costs of new, emerging energy technologies built at varying rates of mass-production. The methodology consists of four major steps: (1) System Conceptual Design, (2) System Physical Design, (3) Cost Modeling, and (4) Continuous Improvement to Reduce Cost. The article describes the application of this methodology to a specific case study of automotive fuel cell systems (FCSs). Because any alternative automotive technology must compete with the very mature and widespread gasoline internal combustion engine, it is vitally important to identify the performance, design, and manufacturing conditions needed to reduce automotive FCS costs. Thus, a DFMA-style analysis is applied to the cost to manufacture a polymer electrolyte membrane (PEM) FCS for cars, at varying rates of production (between 1,000 and 500,000 vehicles per year). The results of this kind of DFMA-style analysis can be used to elucidate key cost drivers at varying levels of production for new energy technologies. [DOI: 10.1115/1.4025624]

Keywords: design for manufacturing and analysis (DFMA), fuel cell, polymer electrolyte membrane (PEM), automotive applications, capital cost, mass-production, transportation systems, fuel cell stack, balance of plant (BOP), car, materials cost, manufacturing cost, tooling cost, assembly cost

Introduction

FCSs for transportation applications are a longstanding area of fuel cell (FC) product development. Numerous prototype vehicles exist for a variety of transportation applications [1] and research continues into improving the competitiveness of FCs as compared to the internal combustion engine (ICE). Research indicates that switching from standard ICE vehicles to hydrogen-fueled fuel cell vehicles (FCVs) could significantly reduce greenhouse gas emissions, air pollution emissions, and ambient air pollution, particularly if the hydrogen fuel is derived from either wind-powered electrolysis or steam reforming of natural gas [2,3]. Related literature investigates a greater variety of FCV types, including trucks with fuel cell auxiliary power units [4], fuel cell powered trains [5], fuel cell scooters [6], and other motive power. Additional research conducts a life cycle assessment of the entire energy supply chain [7] from well-to-wheels. To better assess the potential usefulness and market-worthiness of fuel cells for transportation applications, this work describes a DFMA-style [8] methodology for estimating the cost to manufacture transportation FCSs. An example case study is discussed for an 80 kilowatt-electric (kWe) FCS for a light duty automobile. This kind of DFMA-style methodology can be used to evaluate the impact of annual production rate on FCS capital cost, and differentiate between a nascent and a mature product manufacturing base.

A case study is discussed for the manufacturing costs of transportation FCSs based on a low temperature PEM FCSs. The FCSs consume a hydrogen gas fuel stream from an onboard compressed hydrogen storage system. This discussion does not include an analysis of costs for either the electric drive train or the hydrogen storage medium. This DFMA-style methodology facilitates analyzing capital costs at annual production rates from 1,000 to 500,000 FCSs per year. FCS stack and balance of plant designs and performance parameters are discussed. Methods of cost-modeling are explained.

Methodology

A DFMA-style methodology can be applied to analyze the cost to manufacture automotive FCS designs at varied rates of production. The methodology consists of four major steps: (1) System Conceptual Design, (2) System Physical Design, (3) Cost Modeling, and (4) Continuous Improvement to Reduce Cost.

(1) System Conceptual Design. A key goal of the system conceptual design step is to validate a chemical engineering process plant model of a FCS. In this step, design and performance criteria are identified. Design criteria include considerations such as rated electrical output (80 kWe net power for automobiles), system size and weight, etc. To meet these design criteria, a specific drive train is then conceptually developed.

Specific designs are developed for the four main fuel cell subsystems: the fuel cell stack sub-system, the fuel delivery subsystem, the electrical management sub-system, and the thermal management sub-system. A chemical process plant model is developed in Aspen HYSYS™ to quantify important performance parameters such as net system electrical efficiency, mass and energy flow rates of various streams, and temperature, and pressure at any point in the system. Figure 1 is a schematic diagram of the example automotive FCS modeled and primarily describes the chemical process plant model. This figure shows compressed hydrogen gas being depressurized, filtered, and diverted to the anode side of a PEM fuel cell stack. Air is filtered, compressed, cooled, and humidified before entering the cathode side of the fuel cell stack. The oxygen-depleted air in the cathode exhaust is then expanded in a turbo-compressor. Heat released by the exothermic electrochemical reactions within the fuel cell stack preheats inlet streams and is carried away by a liquid coolant system that removes FCS heat to the ambient environment by forced convection. Unconsumed hydrogen in the anode exhaust gas is either purged or recycled to the fuel cell stack inlet. A secondary liquid cooling loop cools the air inlet to the fuel cell stack and cools the electric motor contained within the turbo-compressor.

Table 1 indicates several of the key design assumptions made for the PEM FCV system. Reference to existing transportation FCSs is made to assure the performance parameters are consistent with expected values for systems with similar performance and operational goals. The system conceptual design also facilitates

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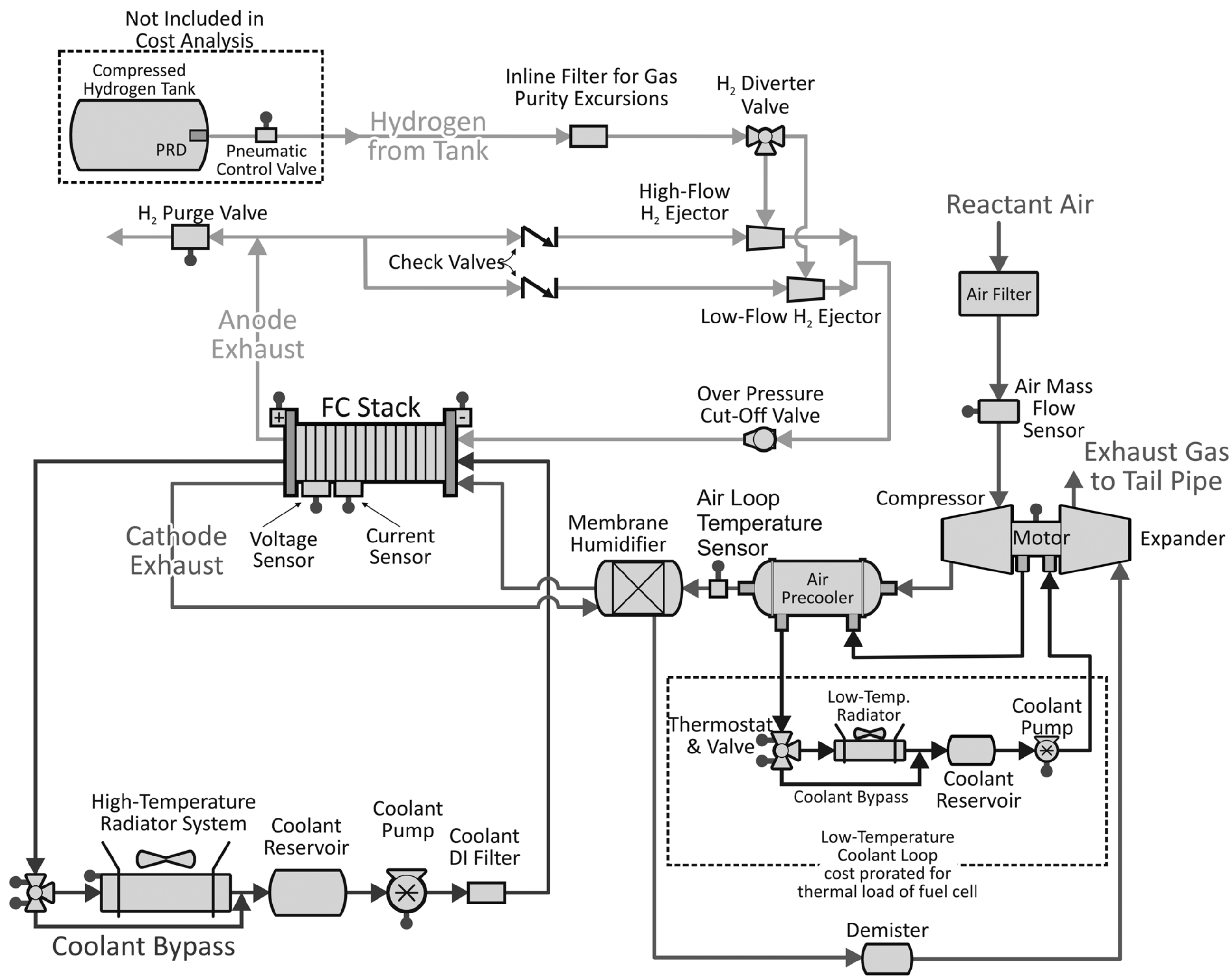

Fig. 1 System design diagram for 80 kWe automobile system showing mass flows, pressures, and temperatures

the next stage, the system physical design, by identifying all required system components and their physical constraints, for example volumes and weights, mass flow quantities, operating temperatures, and heat exchanger areas.

(2) System Physical Design. A crucial aspect of the system physical design step is to identify a bill of materials (BOM) for all key subsystems. Table 2 shows an example of a BOM for an automotive FC stack. The table shows the quantity of each part used in the stack, the primary materials from which the part is formed, the feedstock material basic form (e.g., sheet, rod, powder, etc.), the finished product basic form, whether a decision was made to make the part internally or buy it from an external machine shop (i.e., make or buy decision), the part thickness, and the primary formation process for the part. The system physical design is strongly guided by the system conceptual design. The system physical design step involves designing the full system and its manufacturing process train in detail, including identifying all material needs, device geometry, manufacturing procedures, and assembly methods. This step is highly influenced by the authors' specific expertise in manufacturing methods and FCS design. Detailed feedback from industry partners is also included.

(3) Cost Modeling. Costs are modeled based on the system physical design. Two different approaches to cost modeling pervade:

(A) For nonstandard components, a detailed cost analysis is undertaken, in which all aspects of materials, manufacturing, tooling, and assembly costs are determined for the specific manufacturing process train designed in the previous step. Examples of nonstandard components include fuel cell stacks and membrane humidifiers.

(B) For standard components, the costs are based on price quotes, industry estimates, and reasonable projections of these to higher or lower manufacturing levels. Examples of standard components include pumps, fittings, and heat exchangers.

(A) Nonstandard Components: DFMA Analysis. When nonstandard components are needed, costs are derived based on conceptualization of a full physical, manufacturing process train. To do this, a costing methodology developed by Boothroyd-Dewhurst, Inc., is applied, known as DFMA. DFMA is implemented by hundreds of companies globally to various manufacturing processes, and particularly by the automotive industry. This paper's methodology blends standard DFMA techniques; in-house expertise in FCS design and cost modeling [9,10]; familiarity with manufacturing industry standards and best practices; and innovative applications of next-generation materials, technologies, and manufacturing methods not yet applied by industry.

In this approach, the estimated capital cost (C_{Est}) of manufacturing a device (i.e., the capital cost in units of U.S. dollars ($) per manufactured part) is quantified as the sum of materials costs (C_{Mat}), the manufacturing costs (C_{Man}), the expendable tooling costs (C_{Tool}), and the assembly costs (C_{Assy}).

Table 1 Table of PEM FCV system design assumptions

Power Density (milliWatts/square centimeter (mW/cm^2))	984
Total Platinum (Pt) Loading (milligrams (mg) Pt/cm^2)	0.196
Net Electric Power (kilowatts-electric-net (kW$_{e\text{-net}}$))	80
Gross Electric Power (kilowatts-electric-net (kW$_{e\text{-gross}}$))	88.24
Operating Pressure (atm)	2.5
Peak Stack Temperature (degrees Celsius (°C))	87
Active Cells	369
Electrolyte Material	Nafion™ on 25 micron expanded polytetrafluoroethylene (ePTFE)
Radiator/ Cooling System	Aluminum Radiator; Water/Glycol Coolant; De-ionized (Dl) Water Filter; Air Precooler
Bipolar Plates	Stamped Stainless Steel (SS) 316L with TreadStone Technologies Inc. Coating
Air Compression	Centrifugal Compressor; Radial Inflow Expander
Gas Diffusion Layers	Carbon Paper Macroporous Layer with Surface Treatments
Catalyst Application	Nanostructured Thin Film (NSTF)
Air Humidification	Membrane Humidifier
Hydrogen Humidification	None
Exhaust Water Recovery	None
Membrane Electrode Assembly (MEA) Containment	Screen Printed Seal on Membrane Electrode Assembly (MEA) Subgaskets, Gas Diffusion Layer (GDL) crimpted to Catalyst Coated Membrane (CCM).
Coolant & End Gaskets	Laser Welding / Screen-Printed Adhesive Resin
Freeze Protection	Drain Water at Shutdown
Hydrogen Sensors	2 for Fuel Cell System;1 for Passenger Cabin (not in cost estimate);1 for Fuel System (not in cost estimate)
End Plates & Stack Compression System	Composite Molded End Plates with Compression Bands
Stack Conditioning Time (hours)	5

$$C_{Est} = C_{Mat} + C_{Man} + C_{Tool} + C_{Assy} \quad (1)$$

The materials cost per part (C_{Mat}) is estimated by using the system physical design (material, geometry, and manufacturing method) to identify the amount of raw materials needed to make each part. This analysis also considers material wastage because of flash, scrap, or defects.

The manufacturing cost per part (C_{Man}) is estimated by defining a manufacturing process train to make all necessary parts (anything that cannot be purchased). This analysis considers the capital cost of the manufacturing process train equipment and the production rate of that equipment. From this information, a machine rate can be calculated. The machine rate (R_M) can be defined as the cost per unit time ($/minute) of operating the machinery to make a certain quantity of parts within a specific time period. The manufacturing cost (C_{Man}) is the product of the machine rate and the sum of the operating and setup time

$$C_{Man} = R_M * (T_R + T_S) \quad (2)$$

where T_R is the total annual runtime and T_S is the total annual setup time. An expression for R_M is as follows:

$$R_M = C_{Cap}\frac{(F_{Inst} * F_{Cap} + F_{Maint} + F_{Misc})}{T_R + T_S} + C_P * P + C_L * L \quad (3)$$

whereby C_{Cap} is the total capital cost of the machinery; F_{Cap} is the annual capital recovery factor; F_{Inst} is the multiplicative factor applied to the total capital cost to account for installation and delivery of the machinery onto the factory floor; F_{Maint} is the annual maintenance cost factor as a fraction of capital cost; F_{Misc} is the annual miscellaneous expense cost factor as a fraction of capital cost; C_P is the electrical utility energy cost per unit of electric energy; P is the process power usage; C_L is the fully loaded labor cost per laborer, and L is the number of simultaneous laborers required for the process train. The annual capital recovery payment is the annual funding needed to pay for the capital cost of the equipment; it considers the cost of repaying of the initial purchase price, the time value of money, and the tax rate. The annual capital recovery factor (F_{Cap}) is based on the net present value [11] formula applied over the equipment's lifetime (T_L) using a discount rate (R_I) and a corporate income tax rate (R_{Tax})

$$F_{Cap} = \left[\frac{R_I(1+R_I)^{T_L}}{(1+R_I)^{T_L}-1} - \frac{R_{Tax}}{T_L}\right] \Big/ [1 - R_{Tax}] \quad (4)$$

Annual maintenance cost is defined as the annual cost of maintaining the equipment including labor time and providing spare parts for the machinery. It is expressed as a percentage of the total capital cost. Annual miscellaneous expenses encompass different

Table 2 BOM for a PEM fuel cell stack

Fuel cell stack component	Quantity per stack	Predominant feedstock materials	Feedstock material basic form	Finished product basic form	Make or buy decision	Part thickness	Primary formation process
Bipolar Plates	740	316 Stainless Steel	sheet metal coil	sheet	Make	76 microns (pre- stamping)	Progressive die stamping from coil
Anti-corrosion Bipolar Plate Coating	740	Proprietary	Proprietary	thin-film coating	Make	< 10 microns	Proprietary TreadStone Technologies Inc. Process
Membrane Electrode Assemblies (MEAs)	369	NA	NA	NA	NA	NA	NA
PEM Membranes	369	Nafion on ePTFE	roll	sheet	Buy	25 microns	Roll-to-Roll processing
Anode Catalyst Layers	369	Platinum/PR149	sputtering target block	high surface area thin-film	Buy	~5 microns	Sublimination of PR 149 followed by annealing and vacuum sputtering
Cathode Catalyst Layers	369	Platinum/Cobalt/ Manganese/PR149	sputtering target block	high surface area thin-film	Buy	~15 microns	Sublimination of PR149 followed by annealing and vacuum sputtering
Gas Diffusion Layers	738	Unwoven carbon fibers	roll	sheet	Buy	~150 microns	Slurry pressing fibers, micro porous layer spray, hydrophobic treatment
MEA Gaskets	369	Polyethylene terephthalate (PET)	roll	sheet	Make	2 layers of ~100 microns	Roll-to-Roll processing of PET roll goods
Coolant cells	370	NA	NA	NA	Make	twice the bipolar plate thickness	Laser welding of bipolar plates to form cooling cells
End Gaskets	2	Acrylate Resin	ink	thin-film coating	Make	~100 microns	Screen printing followed by ultraviolet cure
End Plates	2	Epoxy with glass fiber reinforcement	powder	molded shape	Make	~30 millimeters (mm)	Compression molding
Current Collectors	2	Copper	sheet metal coil	sheet	Make	~1 mm	Stamping
Compression Bands	4	Stainless Steel	sheet metal coil	sheet	Buy	~2 mm	Stamping/Slitting
Stack Insulation Housing	1	Polypropylene	powder	formed shell	Make	~0.5 cm	Vacuum thermoforming

Table 3 Table of input assumptions for cost modeling calculations

Financial variables	Example values	Comments
Annual Discount Rate (R_I)	10%	The annual interest rate is used to determine the annual amount for repayment of capital.
Corporate Income Tax Rate (R_{Tax})	38.90%	Tax rates are assumed to be 35% for federal taxes and 6% for state taxes.
Electrical Utility Energy Cost (C_P)	$0.08/kWh$_e$	The electrical utility energy cost per unit of electric power for an industrial facility.
Equipment Lifetime (T_L)	15 years	Equipment lifetime varies with equipment type.
Setup Time per Batch (T_S)	3 hours	Setup time is the time to prepare equipment on the manufacturing line for production.
Installation Cost Factor (F_{Inst})	1.4	This value is a multiplier applied to the equipment capital cost to include the cost of delivery and installation of machinery onto the factory floor.
Annual Maintenance Cost Factor (F_{Maint})	6% of capital costs	This value is a multiplier applied to the equipment capital cost to include the cost of equipment maintenance.
Annual Miscellaneous Expense Cost Factor (F_{Misc})	12% of capital costs	This value is a multiplier applied to the equipment capital cost to include the cost of miscellaneous expenses.

added contingent expenses. It is also modeled as a percentage of total capital cost. Table 3 delineates example values used in this modeling work for these variables.

At lower production rates, the manufacturing process train utilization is lower, the machine rate is higher, and manufacturing costs are higher. As a result, at low production rates, external machine shops may make parts at a lower cost, by pooling orders, even considering machine shop markups. This methodological approach also estimates the manufacturing cost by an external machine shop, based on an industry standard for nominal process train utilization of 37%.[2] The chosen method is the lower cost option.

The cost of expendable tooling per manufactured part (C_{Tool}) is calculated as the capital cost of the tool, divided by the number of parts made by that tool over its lifetime. Expendable tools include dies and molds. This modeling effort limits the maximum tool lifetime to 3 years, even though some tools are expected to outlast the production horizon, particularly at low annual production rates. In general, the tooling lifetime is determined at high manufacturing rates by cycle life[3] (or hours of continuous use) or at low manufacturing rates by the design lifetime of the part the tool is making.

The cost of assembly of the system per manufactured system (C_{Assy}) encompasses the cost of assembling nonstandard components (such as the fuel cell stack) as well as the cost of combining both standard and nonstandard components in a single system assembly. C_{Assy} can be represented as follows:

$$C_{Assy} = R_{Assy} * \sum T_{Assy} \tag{5}$$

whereby R_{Assy} is the machine rate for the assembly train and can be defined as the cost per unit time ($/min) of assembling components within a certain time period and T_{Assy} is the assembly time for various parts. R_{Assy} is analogous to R_M and is calculated according to

$$R_{Assy} = C_{Cap} \frac{(F_{Inst} * F_{Cap} + F_{Maint} + F_{Misc})}{\sum T_{Assy}} + C_P * P + C_L * L \tag{6}$$

using similar variable definitions as above, but for the assembly process, and based on the capital cost of the installation workstation (C_{Cap}).

(B) Standardized Components: Projections From Industry Quotes. When standard components are needed, costs are derived from industry quotations. Mathematically reasonable projections of these quotations are made to higher or lower manufacturing rates. (A full manufacturing process train need not be specified). Industry quotes are obtained for materials and devices that meet performance criteria specified in the first two steps. Where possible, quotations at different production quantities are obtained. To apply this industry data over a larger range of manufacturing rates, a learning curve formula is applied

$$P_Q = P_I * F_{\mathrm{LC}}^{\left(\frac{\ln\left(\frac{Q}{Q_I}\right)}{\ln 2}\right)} \tag{7}$$

where P_Q is the price at a desired annual production quantity (Q) given the initial quotation price (P_I) at an initial quantity Q_I and an assumed learning curve reduction factor (F_{LC}). This relationship decreases the price by a fixed factor for every doubling of annual order quantity. This approach is based on standard experience curve theory but alters the base from "cumulative production quantity" to "annual order quantity." When two or more sets of industry quotations are available, F_{LC} is derived by applying the values provided in the second quotation to the numerical values for P_Q and Q and solving Eq. (7) for F_{LC}. When only one industry quotation is available, a standard value is applied to the variable F_{LC}.

Cost Model Scope. This cost analysis focuses on capital costs only and does not evaluate life cycle costs over the lifetime of the vehicles. This analysis also does not perform a life cycle assessment that typically includes an analysis of the financial value of avoided environmental externalities such as greenhouse gas emissions, air pollution emissions, and solid waste. Furthermore, in the

[2]Based upon 2010 median single shift utilization of 65% for machine shops converted to 14-h two-shift work days (0.65×8 h/14 h) http://www.mmsonline.com/articles/see-how-you-stack-up

[3]Cycle life is generally determined by the strength and/or abrasion resistance of the tool material and the strength and/or abrasiveness of the material the tool is processing.

analysis of capital costs, the following are not included: one-time costs such as nonrecurring research, design, and engineering costs; profit and markup costs; general and administrative (G&A) costs, warranty costs, marketing and advertising costs, and government tariffs (such as sales tax). By contrast, this capital cost analysis does include these common manufacturing expenses: machine maintenance costs; tooling amortization; fixed factory expenses such as equipment depreciation; electric, gas, water, and other utilities; materials for manufacture; and manufacturing and assembly labor time. As such, the projected costs should not be confused with "price," which typically will be a higher value (potentially much higher) and is heavily influenced by market conditions.

(4) Continuous Improvement to Reduce Cost. This design and costing methodology is highly iterative. In this approach, the benefits and drawbacks of alternative materials, technologies, manufacturing methods, and assembly methods are continually weighed, so as to progressively iterate towards lower cost designs and production methods. Changes are considered at all steps: system conceptual design, system physical design, and the selection of manufacturing and assembly methods. Literature reviews, patent searches, and discussions with industry drawn from a global pool continually inform this process. Thus, this research approach attempts to continually improve upon the first three steps of the methodology, with the aim of reducing capital costs.

Conclusions

A DFMA-style methodology can be applied to analyze the cost to manufacture emerging energy technologies not yet in mass-production. A case study is presented applying this methodology to automobile FCS designs. The methodology consists of four major steps: (1) System Conceptual Design, (2) System Physical Design, (3) Cost Modeling, and (4) Continuous Improvement to Reduce Cost.

A key goal of the system conceptual design step (1) is to validate a chemical engineering process plant or other physics-based model of an energy system. A crucial aspect of the system physical design step (2) is to identify an overall system BOM and BOMs for all key subsystems. In the cost modeling step (3), for each unique component, a detailed cost analysis is undertaken, in which all aspects of materials, manufacturing, tooling, and assembly costs are determined for a specific manufacturing process train. An important aim of the continuous improvement to reduce cost step (4) is to iterate on the conceptual designs and physical designs, as well as the manufacturing and assembly process trains to reduce costs.

The results of this DFMA-style analysis can elucidate key cost drivers at various annual production rates. Results can also be used to compare future, projected capital system costs in mass-production with current capital system costs of incumbent technologies already in mass-production.

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