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Assessment of Low-Cost Manufacturing Process Sequences*

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Robert G. Chamberlain
Operations Research Group
Systems Analysis Section
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91103 USA

Abstract

The Low-Cost Solar Array Project, sponsored by the U.S. Department of Energy, is managing an extensive research and development activity to reduce the cost of manufacturing photovoltaic solar arrays by a factor of approximately one hundred. This management objective implies the need for a capability to relate proposed and actual manufacturing process descriptions to manufacturing costs.

The Solar Array Manufacturing Industry Costing Standards (SAMICS) methodology was developed to meet this need. An overview of this methodology is presented. Since the solar array manufacturing industry is expected to increase in capacity by several orders of magnitude when the price is reduced to a competitive level, it would be inappropriate to assume that indirect costs will be the same multiple of direct costs as is presently observed in the industry. Furthermore, identification of some other industry as "similar" would be highly questionable. Consequently, SAMICS contains a "factory construction and staffing algorithm," which infers indirect requirements from the specified direct requirements and implicitly builds a hypothetical, dedicated factory for performing the specified manufacturing processes.

SAMICS has been implemented by a computer program (SAMIS III). It has been applied to the assessment of Low-Cost Solar Array Project progress, and it has been used as a tool in the selection of research and development priorities.

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OBJECTIVES

The objective of the U.S. Solar Photovoltaic Conversion (PV) Program is to establish the direct conversion of solar energy to electricity (that is, *photovoltaics*) as a technologically and economically viable option for the generation of energy.

The U.S. Department of Energy is sponsoring the Low-Cost Solar Array (LSA) Project at the Jet Propulsion Laboratory as a part of the PV Program to initiate a major effort toward the development of low-cost solar arrays. The LSA Project objective is to manage the research and development, being carried out by over 80 companies and universities under JPL contracts, needed to reduce the costs of manufacturing by approximately a factor of one hundred (from about $50 per peak watt in 1975 to $0.50 — expressed in 1975 dollars — per peak watt by 1986).

The Solar Array Manufacturing Industry Costing Standards (SAMICS) were developed to provide the LSA Project with an accurate means of assessing the costs of purportedly low-cost manufacturing processes and process sequences proposed by its actual and prospective contractors in a fair, consistent fashion. As the price of solar arrays is brought down by a factor of a hundred, the size of the industry is expected to increase by several orders of magnitude, and the technology used is expected to evolve from being labor-intensive to being capital-intensive. Thus, to meet its objectives, the SAMICS methodology must be very versatile.

SAMICS OVERVIEW

A complete description of the SAMICS methodology is contained in reference [2]. The reader is directed to that document for a more complete bibliography as well as for detailed exposition of the derivations and algorithms of SAMICS.

The cost of manufacturing a product depends more on the manufacturing processes used than on the functional — or even the physical — description of the product. Consequently, any accurate estimate of manufacturing costs must start with detailed descriptions of the economically important characteristics of those processes.

Indirect costs — those that result from operating a company to support the performance of the manufacturing processes — are also very important, and usually account for 30% to 70% of the final product price. Comparison of competing processes to perform the same function requires that indirect costs be estimated in the same way for all processes to ensure that it is indeed the processes, and not the indirect cost assumptions, that are compared.

SAMICS requires that the direct requirements (floor space and other facilities, machine operating and servicing personnel, utilities and plant services, and materials and supplies) of each manufacturing process step be specified. New process steps are placed in the context of complete manufacturing sequences.

The annual production of the industry is specified as input, then a hypothetical industry containing those complete manufacturing sequences is created and its operation is simulated.

Industry Simulation

The hypothetical industry is constructed as a sequence of companies in a *generalized tree* (or *restricted network*) structure, with plant capacities consistent with the annual industry production and all process yields taken into account. Thus, alternative industry structures can be

readily compared in terms of their effects on product cost. The industry simulation is composed of a sequence of company simulations.

Company Simulation

Companies are constructed to contain the specified processes in a generalized tree structure, therefy providing a great deal of flexibility in defining the manufacturing sequences. Within each company, the annual direct process requirements for all processes in that company are collected in order to allow for economies of scale in the construction and staffing of the standardized hypothetical factory.

The procedure for building and staffing the standardized hypothetical factory depends upon the observation that the indirect requirements of a company (facilities, supervisors, air conditioning, etc.) depend on the direct requirements (floor space, welders, process power requirements, etc.) and on construction and staffing traditions, but not on any other characteristics of the processes. A major part of SAMICS is a collection of *indirect requirement relationships* that express those traditions as standardized submodels:

$$N_i = \Sigma_j f_{ij}(T_j)$$

where

N_i = Indirect requirement for expense item i,

T_j = Total requirement for expense item j,

f_{ij} = Standardized submodel for the amount of item i required indirectly to support an amount T_j of item j.

The functions $f_{ij}(T_j)$ are expressed as piece-wise continuous power functions, which permits a great deal of flexibility. Since these

functions represent construction and staffing traditions, they depend upon the economic environment — the functions currently in the SAMICS data base represent the U.S. electronics manufacturing industry, and will probably be changed as the differences between solar array manufacturing and electronics manufacturing, if any, gradually become apparent.

The total requirement for any expense item is simply the sum of the direct and indirect requirements:

$$T_j = D_j + N_j$$

where

D_j = Direct requirement for expense item j.

Since the D_j are known and the f_{ij} are standardized submodels, the indirect and total requirements vectors can be determined by recursive solution* of these two equations. It may be noted that the analytical problem is similar to that for which Leontief introduced input-output matrices [3-6].

After all of the quantities in a company have been determined, the associated prices (which are allowed to depend upon annual quantities purchased) can be determined. Of course, since some of the things purchased by a company may be manufactured by other companies in the modeled industry, their prices must be determined first, by starting the price calculations at the raw materials end of the industry. Conversely, since companies are sized to produce the specified annual industry production quantity, the quantity calculations had to start at the finished goods

*The author intends to present several algorithms for obtaining solutions at the XXIV International Meeting of The Institute of Management Sciences in Honolulu, Hawaii, in June 1979.

end. Calculation of quantities throughout the industry before calculation of prices allows those price calculations to incorporate economies of scale, and is a very important characteristic of SAMICS.

Required Revenue Condition

Normative product prices are determined by specifying a required rate of return on equity, treating profit (defined as the *return on equity*) as a cost, and applying the required revenue condition:

The *normative product price shall be chosen so that the present value of all revenues is exactly equal to the present value of all costs.*

The SAMICS *financial model of the firm* is based on the required revenue condition. If it is assumed that the company is operating in a *steady-state* condition (that is, producing the same quantity every year, and replacing equipment that wears out with identical — but new — equipment), then revenues must equal costs each year, not just in present value, even in the presence of inflation, provided that a cost term to account for the amortization of one-time costs is added. Thus,

Revenues = Product Price * Quantity + Byproduct Income

and

Costs = The sum of the following expenses:

- Annual purchased products expense,
- Annual cost of all expense items,
- Annual cost of replacing capital goods,
- Annual return on equity (profit),
- Annual interest on debt,

- Annual insurance premiums,
- Annual *ad valorem* (property) taxes,
- Annual income taxes,
- Annual miscellaneous expenses,
- Annual amortization of one-time costs,
- Annual value-added tax (not applicable -- yet -- in the U.S.; not now incorporated in SAMICS),
- Other annual expenses not now applicable in the U.S. that may be required for application of SAMICS in other countries.

Details of the submodels for each of these cost terms are given in reference [2]. Aside from differences in numerical values of parameters, the only cost term whose submodel may vary from country to country is the income tax:

TAX = tax (Taxable Income) - Tax Credits

with

Taxable Income = Revenues - Deductible Expenses

IMPLEMENTATION

SAMIS Computer Program

The generation of indirect requirements, even if the non-linearities that produce economies of scale were not allowed, is a formidable computational task. Allowing for non-linear price versus quantity functions and for differential inflation make the computational burden even worse. Consequently, a computer program, SAMIS III, has been prepared to facilitate application of SAMICS. SAMIS III is currently available on an international time-sharing service (NCSS, Inc.); contact Mr. Paul J. Firnett at JPL for details.

IPEG Manual Approximation

By making very stringent simplifying assumptions with regard to indirect requirements, it is possible to obtain a price equation [1] that can be used* without a computer:

Price = (0.49*EQPT + 97*SQFT + 2.1*DLAB + 1.3*MATS + 1.3*UTIL)/Quantity

where

EQPT = Cost of all the equipment,

SQFT = Floor space required by the equipment,

DLAB = Annual cost of all direct labor,

MATS = Annual cost of all direct materials and supplies,

UTIL = Annual cost of all direct utilities.

Under appropriate conditions, the above equation gives results within about 5% to 10% of the SAMIS computer program results. It is anticipated that econometric calibration of the coefficients will make an equation of this form very useful for sensitivity studies.

VALIDATION

Validation of the SAMICS methodology has been sought constantly throughout its development.

The methodology and numerical results have been given extensive exposure, albeit primarily among the LSA Project contractors. Since those contractors have often made their own estimates, and since they can be expected to be financially affected by the numerical results produced by

*Warning: The coefficients in this equation depend upon particular assumed values of a variety of financial parameters. See [1] for further information.

SAMICS, the fact that SAMICS is gaining wide acceptance is very encouraging. These contractors have made numerous detailed suggestions — mostly with regard to prices in the expense item data file; by and large, these suggestions have been accepted.

A major validation study [7] recently compared the results of SAMIS computations against the results of applying conventional manual methods to conceptual point designs, on a very detailed level. Price estimates were within about 5% over a 1000 to 1 size range.

Users of the methodology are urged to apply their experience, engineering judgment, and common sense to all details of results, and to pass along any discrepancies found.

SAMICS results have not yet been compared with costs observed in existing manufacturing plants. Such comparisons may be obtained within the next couple of years.

ASSESSMENT OF PROCESS SEQUENCES

SAMICS was developed primarily to facilitate comparison of alternative manufacturing processes. Analysis of 24 variations on manufacturing process sequences in the summer of 1978 gave the results shown in Table 1; the prices of all sequences were within the range $7-11/Wpk.

Proposed process "improvements" can be (and have been) similarly compared, with the interesting observation that anticipated savings are *not* strongly correlated with development risk.

Due to the extreme versatility that had to be built into SAMICS in order to meet its objectives, a wide variety of other questions can also be addressed.

Table 1. Comparisons of Current Process Options

Preferred	Savings	Not Preferred
Superstrate	$2.44/Wpk	Substrate
Silk screen printing of metal pattern	$0.83/Wpk	Plating of metal pattern
Simultaneous front and back junction formation	$0.33/Wpk	Back, then front
	$0.10/Wpk	Front, then back
Texturization etch	$0.17/Wpk	Damge removal etch

Different Economic Environments

Since prices of all expense items are supplied to SAMICS as data, it is possible to investigate the implications of differences in price structures (such as labor costs versus capital costs) on prices of products from particular process sequences, and to obtain preferred process sequences for particular environments. The effects of local factory construction and staffing traditions (such as working conditions and building designs) can also be investigated.

Changing Economic Conditions

Changes in industry structure and size, and long-run (but not short-run) company growth can be studied, as can the effects of differential inflation rates and of changes in interest rates, company fiscal structure (debt-to-equity ratio), and rates of return on equity.

Although SAMICS is designed to accept the *rate of return on equity* as an input and to produce *price* as output, the same relationships, once obtained, can be interpreted as if the input/output roles were reversed.

Government Policies

The effects of some governmental policies, particularly those that affect tax laws, can be assessed. Policies that affect economic parameters (such as loan guarantees which affect interest rates) can also be addressed.

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