Costing models for capacity optimization in Industry 4.0: Trade-off between used capacity and operational efficiency

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Abstract

Under the concept of "Industry 4.0", production processes will be pushed to be increasingly interconnected, information based on a real time basis and, necessarily, much more efficient. In this context, capacity optimization goes beyond the traditional aim of capacity maximization, contributing also for organization’s profitability and value. Indeed, lean management and continuous improvement approaches suggest capacity optimization instead of maximization. The study of capacity optimization and costing models is an important research topic that deserves contributions from both the practical and theoretical perspectives. This paper presents and discusses a mathematical model for capacity management based on different costing models (ABC and TDABC). A generic model has been developed and it was used to analyze idle capacity and to design strategies towards the maximization of organization’s value. The trade-off capacity maximization vs operational efficiency is highlighted and it is shown that capacity optimization might hide operational inefficiency.

Keywords: Cost Models; ABC; TDABC; Capacity Management; Idle Capacity; Operational Efficiency

1. Introduction

The cost of idle capacity is a fundamental information for companies and their management of extreme importance in modern production systems. In general, it is defined as unused capacity or production potential and can be measured in several ways: tons of production, available hours of manufacturing, etc. The management of the idle capacity

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requires cost models that translate and incorporate adequately production processes and market conditions from both operational and financial perspectives. Therefore, it is important to know and compare the different cost models and the different approaches that can be used to manage used and idle capacity.

Furthermore, the concept of "Industry 4.0", originated from a high technology strategic project of the German Government and German leading companies, has been promoting a new wave of change in industry. The first industrial revolution mobilized the mechanization of production using water and steam energy. The second industrial revolution focused on mass production with the help of electric power. Then came the digital revolution and the use of information and communication technologies that increased the level of automation of production in several industries. Industry 4.0 intends to integrate a number of very recent technological innovations, connecting automation and production control with information and communication technologies improving and changing manufacturing processes (e.g. the Internet of Things and the Internet of Services).

In this context, production processes will tend to be increasingly efficient, more autonomous and easily adaptable and customizable. This new approach will have a huge impact on capacity optimization and will require new ways of managing such capacity. Capacity management is a central problem in operations and production systems.

Traditionally, cost models do not meet precisely the information that managers need to make decisions, i.e., in many cases occurs an inappropriate or even arbitrary distribution of resources consumed by different cost objects. Indeed, full cost systems allocate all manufacturing costs to products using apportionments criteria, and therein the existence of measurement and allocation errors may compromise them as effective control instruments.

Because of the problems and limitations of traditional costing systems, the Activity Based Costing (ABC) emerged in the 1980's. Furthermore, these last years, ABC models evolved from the initial ABC approach to the more recent Time-Driven ABC (TDABC) - [1]. TDABC is supported on two key parameters, the capacity cost per unit time and the time required to complete an activity. Thus, time is usually considered the measure of capacity. The model distributes costs using the capacity cost rate and the estimated needs of resources by each cost object [2]. In a complementary or combined basis, these two methods can be a very valuable framework to deal with the problem of unused capacity and capacity optimization considering both operational and financial dimensions. Nevertheless, these methods are characterized by some differences both in terms of assumptions and procedures.

In this context, the use of Ideal or Rational Absorption Costing instead of a full costing approach can be preferable. In this case, waste and factory idleness should not be incorporated into the cost of the products, acting differently as in the case of Integral Absorption Costing (Full Costing). Also [3] who focused their research work on the cost of idle capacity in the definition of economic lots in the purchasing process opted to not use any particular or specific costing method. Furthermore, in [4] a hypothetical model was presented to show the conversion of ABC to Time-driven Activity Based Costing (TDABC) and Resource Consumption Accounting (RCA) models and showed the results in terms of cost allocation and cost of idle capacity. Alternatively, [5] proposes the adoption of a linear programming method to estimate the value of the unused capacity cost, using a ABC model - but any numerical example or real case is presented. Finally, [6] do not to mention a specific costing method, but based on data from 2002 to 2008 of the US automaker GM, stressed the importance of a good knowledge and understanding of idle capacity as relevant information for internal and external users.

This paper presents and discusses a mathematical model for the capacity management using two different cost models (ABC and TDABC) which have been applied in several real cases. The general model is explained and some results and implications of its application are discussed in this paper; improvements, applications and opportunities for the development of the model are also suggested.

2. Activity based mathematical cost models

Currently, organizations seek new solutions to efficiently and effectively manage their costs. Therefore, it is necessary the development and implementation of effective strategic cost management tools to provide support for more consistent decision making. Nowadays, cost models in the context of strategic cost management are evolving from traditional models to ABC and more recently to TDABC. TDABC models are supported and translated into time equations. Furthermore, some authors claim that the next stage of evolution of activity based cost models will withstand up on the concept of cost equations and the use of cost optimization and cost equations systems [7].
The modeling of the costs of an organization through cost equations opens new perspectives for cost analysis and optimization that deserve thorough research work and application in practical. Thus, such contribution may contribute to solve business problems and provide solutions that can mitigate the uncertainties of decisions that need to be taken in day-to-day life and also those of strategic dimension and long term impact.

Through TDABC, it is possible to study the effectiveness of the processes at the level of available capacity versus used capacity. Several works have demonstrated how the quality of the decisions can be improved when the production process is considered and modelled in an integrated way. For example, [8] carried out a study applying a cost-estimation model considering the determination of activity times. [9] has shown how to compute optimal solutions to price and capacity problems. [17] examine the product mix and capacity expansion decisions when economies of scope are presented and [12] developed a mathematical cost model using cost-based activity information to determine optimal orders to suppliers depending when the different costs associated with the purchase decision are considered.

Thus, mathematical cost models may represent a powerful tool for decision making and strategic management particularly, in organizations characterized by complex production and business processes and those operating in very dynamic, competitive and uncertain markets, as well as public companies and large companies where cost management is critical for planning and budgeting processes.

3. Model development

A generic model has been developed to accommodate the alternative cost models which can be used to capacity optimization and to design strategies towards the mitigation of unused capacity [13]. This, is only possible with a better use of resources and through a real orientation to the market. Thus, there is a need for appropriate mathematical models that can represent production and market conditions and so, offer a good basis for capacity optimization. The model presented here turns possible to use the assumptions of traditional cost models, ABC and TDABC (see [14]).

The mathematical model relies on the two-stage approach of an ABC system. First, activity costs are calculated, according to the distribution of resources to the various activities using the selected resource drivers. In the second stage, the activity costs are allocated to cost objects (typically products). Time equations and other TDABC assumptions can be also introduced in this model. Particularly, if fictitious activities and products are introduced in order to receive the information on idle costs. Furthermore, direct costs can be also included using additional or fictitious resources and activities.

The calculation of the activity costs considers a Resource matrix of \( n \) lines (number of resources), where the element \( r_{ij} \) is the total amount of resource \( n \). On the other hand, in the matrix for the activities, the \( a_{ij} \) element represents the amount of the costs attributed to the activity \( i \); \( r_{ij} \) represents the technical relation between resources and activities, i.e. the cost driver. In this model, cost drivers are normalized, i.e. de sum of each column in the coefficient matrix equals 1.

The same logic for the allocation of activity costs, to the cost objects (e.g. products) resulting in \( p_k \) and using the activity-product coefficient matrix of \( a_{ik} \) elements (Equations 1 and 2).

\[
\begin{bmatrix}
 r_{11} & \cdots & r_{1j} \\
 \vdots & \ddots & \vdots \\
 r_{i1} & \cdots & r_{ij}
\end{bmatrix}
\begin{bmatrix}
 a_{1i} \\
 \vdots \\
 a_{ji}
\end{bmatrix}
= \begin{bmatrix}
 a_i \\
 \vdots \\
 a_i
\end{bmatrix}
\]  

(1)

\[
\begin{bmatrix}
 a_{11} & \cdots & a_{1i} \\
 \vdots & \ddots & \vdots \\
 a_{K1} & \cdots & a_{Ki}
\end{bmatrix}
\begin{bmatrix}
 a_{1i} \\
 \vdots \\
 a_{ji}
\end{bmatrix}
= \begin{bmatrix}
 p_k \\
 \vdots \\
 p_k
\end{bmatrix}
\]  

(2)
The cost equations represented by these matrixes show the flexibility and the potential application range which can be used to calculate and relate product costs, margins, consumption patterns of resources and activities, among other. On the other hand, cost equations turn simpler the association between resources and cost objects.

\[ R = \sum_{j=1}^{J} R_j ; \quad A = \sum_{i=1}^{I} A_i ; \quad P = \sum_{k=1}^{K} P_k \]  
(3)

\[ A_i = \sum_{j=1}^{J} r_{ij} \times R_j \]  
(4)

\[ P_k = \sum_{j=1}^{J} \sum_{i=1}^{I} a_{ki} \times r_{ij} \times R_j \]  
(5)

If \( x_{ij} = \sum_{i=1}^{I} a_{ki} \times r_{ij} \)

Then

\[ P_k \sum_{j=1}^{J} x_{kj} \times R_j \]  
(7)

\[ \sum_{k=1}^{K} x_{ki} = 1, \forall i ; \]  
(8)

\[ \sum_{i=1}^{I} r_{ij} = 1, \forall j ; \sum_{k=1}^{K} a_{ki} = 1, \forall i \]  
(9)

This model can be used for several applications namely, product costing and product cost minimization, capacity management and target costing [15]. Capacity is modelled here through the use of fictitious activities and cost objects given us a powerful tool for simulating and optimizing used and unused capacity costs.

4. Application, results and discussion

4.1. Input data and assumptions

A general 2x2 matrix model was developed considering 2 types of resources (R1 and R2), 2 different activities (A1 and A2) and 2 products (P1 and P2). Fictitious or additional resources, activities and products were created to accommodate the inclusion of idle capacity and the use of ABC and TDABC. Idle capacity is associated to R2 which is a fixed cost, being R1 variable costs. Both A1 and A2 consume variable and fixed costs. Cost drivers are time thus, they can be used in both ABC and TDABC models. Resource 2 (fixed costs) has a capacity restriction but Resource 1 is unlimited; the first one was simulated using both (one) fixed cost and step costs (which are function of the activity level, i.e. units produced).

Product unitary prices, cost per hour of Resource 1, fixed costs, material costs per unit, etc. were previously defined for all simulations made. Nevertheless, it was realized that two of the most important independent variables are the number of units produced (and sold) and the production technical conditions which are presented in this model through the production time of each product in each activity. To reduce the number of independent variables without reduce the validity and usefulness of the model, market conditions (units produced and sold, unitary price) and production conditions of Product 2 were indexed to Product 1; i.e., P2 requires twice the time of P1 in A1 and 3 times in A2, also the price of P2 is 2.5 times P1 and units sold of P2 are always one third of P1. Additional assumptions were considered to turn de cost model more interdepend and manageable for the purpose of this research.

There were made several simulations and analysis with both the ABC and the TDABC model in order to establish relationships and compare capacity costs with profitability and value measures towards the discussion of capacity
optimization in demand-driven business and production environments. Thus, the model takes into consideration production (efficiency) assumptions, market conditions, capacity restrictions and economic objectives (product margins, overall profitability and return on investment). This framework allow us to analyze and discuss capacity not isolated from other relevant constraints and objectives.

4.2 Cost model: ABC and TDABC

The major difference between the two models is the inclusion of an additional activity and an additional product (respectively, A3 and P3) to highlight the information on idle costs. Resource-Activity and Activity-Product matrixes are different in ABC and TDABC models. Also the Resource-Product matrix is different but only in terms of the coefficients that establish the mathematical relationship between R2 (the fixed cost with capacity constraints) and the Products. Total cost by product (in this model presented in the P matrix) and average or unit total cost per product (ATC) are presented in Table 1.

R1 to R3 columns are coefficients of the Resource-Product (ABC and TDABC) matrixes. P and ATC are presented in monetary units. It is important to highlight that in the TDABC model, ATC are independent of the capacity used because additional use of or more unused capacity results in costs allocated to P3. Thus, in the TDABC model, capacity optimization strategies can be compared in terms of idle capacity costs and overall profitability but not product margins. For such propose, the ABC model was used. From several analysis, the following aspects deserve particular attention in the context of capacity optimization. Market conditions, production optimization and economic results must be all considered to reach an effective and sustainable capacity optimization.

4.3 Used capacity and (Hidden) operational inefficiency

An important aspect that should be taken into consideration when capacity costs are analyzed is to understand if capacity maximization is not the result of low operational efficiency. On the other hand, lower levels of used capacity can be provided by high levels of operational efficiency (see Fig. 1). The x-axis represents the time required in A2 to produce P1 thus, as higher, more inefficiency we have but that directly implies more use of the available R2 and idle costs are reduced. Product margins result lower because unitary costs are now higher (if the level of A2 increases, also the level of consumption of the variable resource, R1, increases).
Thus, capacity maximization strategies which do not consider the economic dimension may just apparently improve the company from the operational perspective but with a negative impact in the firm’s overall profitability. In this case, the average (of P1 and P2) unitary margin was reduced to less than ½ of the initial value and the capacity showed good usage levels - between 80% and 100%.

4.4 Used capacity versus operational efficiency

In general terms, we may propose two generic strategies to improve profitability and the return on investment (ROI). In this case we use ROI because it is a relative measure. This indicator was calculated dividing the overall profitability by the investment (which was considered equal to the level of fixed costs, i.e. R2). Those generic approaches are improving operational efficiency (thus, reducing production unit costs) or producing and selling more units (this one is directly related to capacity maximization). For simplification, the relative product mix is stable being the quantity of P1 always 3P2 – the results that will be presented considered a level of 600 units of P1. In fact, we will have combinations of these two strategies. Fig. 2 presents the simulated ROI for different combinations of P1 produced and sold (which is directly related to capacity use) and operational efficiency (expressed in terms of time required to produce one unit of P1 in A2).
Reduced production times per unit (x-axis) and high levels of sales (y-axis) have associated a higher ROI. It is possible to recognize that efficiency impacts more on ROI than units produced. Indeed, for high levels of inefficiency there is not possible to reach the higher levels of ROI even if with a great number of sales. Thus, methods and approaches that can improve operational efficiency (thus, reducing production unit costs) are more valuable from an economic perspective than capacity maximization.

4.5 Used capacity, costs and profitability

Capacity optimization must take into consideration, in an interrelated way, the different dimensions explained before. Separately, capacity maximization cannot result in an effective capacity optimization with a positive impact on organization’s overall profitability and value. Thus, costs, revenues, company’s value and idle costs or capacity costs must be viewed jointly. In this case, we opted to compute the product unitary margin (which reflects product price and costs), the level of used capacity and the ROI (that goes beyond just profitability and considers also the assets involved). Considering the same general assumptions presented before and a production mix of (600, 200) units of P1 and P2, respectively, these indicators were computed and compared. A synthesis is presented in Fig. 3.

![Fig. 3. ROI, Used capacity and product unit margins](image)

Indeed, as discussed before, we can observe that capacity maximization (from left to right) can be associated with reductions on margins and lower ROI. This asks for a set of propositions which should be tested when idle costs are reduced. Some of them are related with what is happening in terms of operational efficiency. On one hand, capacity maximization does not result in any capacity optimization but may just reflect poor levels of operational efficiency. On the other hand, capacity optimization always impacts positively in both operational and financial performance. Capacity optimization can be achieved producing more units, increased operational efficiency and by a combination of the two; if, and only if, a financial or economic benefit to the organization is also achieved.

5. Conclusions

Appropriate cost models play a key role in the process of measuring and understanding used and unused capacity, theoretical (or installed), actual and normal production capacities, since the knowledge of these is required to determine the cost to be attributed to the products stocked or sold and also to develop a correct performance measurement which needs to take into account the idle capacity. In this research, a general cost model architecture has been developed and applied to several real cases and the conditions of capacity use and optimization were analyzed and discussed.

They were considered some constraints that limit feasible solutions and that impose several challenges. The results obtained show that capacity issues, demand restrictions, technical limitations, cost and profitability conditions should be all considered to optimize instead of just maximize capacity. Such approach asks for more elaborated mathematical models like the one that is proposed here.
Particularly, a general trade-off exists between the level of reduction obtained in terms of resources’ costs versus the quantity of resources used (gains of efficiency). Furthermore, changes or the manipulation of external conditions (price, quantities, level of service and product mix) are also important and affect the return of the investment and the profitability of the system. In fact, both, internal and external aspects, are important and change simultaneously. Further research may develop these issues.

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