Computers and Chemical Engineering 83 (2015) 72–78

Contents lists available at ScienceDirect

Computers and Chemical Engineering

journal homepage: www.elsevier.com/locate/compchemeng

Optimum sizing of supply equipment for time varying demand

G.S. Krishna Priya, Santanu Bandyopadhyay*

Department of Energy Science and Engineering, Indian Institute of Technology Bombay, Powai, Mumbai 400076, India

ARTICLE INFO

Article history:
Received 16 October 2014
Received in revised form 26 April 2015
Accepted 4 May 2015
Available online 12 May 2015

Keywords:
Screening curve
Optimisation
Time varying demand
System planning
Expansion planning

ABSTRACT

The sizing of supply equipment to meet a time varying demand is an important engineering problem. Optimal sizing of various supply equipment can reduce the overall cost of the supply system significantly. In this paper, the screening curve methodology, originally proposed for planning electrical power system, is extended to address various process system related problems: cost optimal sizing of various pumps to satisfy time varying water demand, ideal mix of various lighting options for a given lighting load, etc. These examples illustrate that the proposed methodology is a simple, versatile, and powerful tool for appropriately sizing various equipment to satisfy time varying demands during grassroots design. During debottlenecking, supply system is expanded; new supply equipment are installed along with appropriate utilisation of existing supply equipment. A methodology is proposed to address expansion planning of various supply equipment during debottlenecking and demonstrated using an example of debottlenecking an air conditioning system.

1. Introduction

In many process system applications, a large number of demands are time varying in nature. Requirements of electric power, cooling load, water pumping, etc. are common examples of such time varying demands. Typically, single supply equipment with the capability of satisfying the maximum demand is selected to meet the time varying demand. This results in part load operation of the supply equipment for predominant period. Most equipment operate with significantly lower efficiency at part load condition and hence, an oversized supply equipment typically operates at much higher operating cost. There may also be significant capital investment related to high capacity of the supply equipment. For a demand of short time duration, capital cost of the supply equipment is most important. On the other hand, for a demand of large duration, operating cost of the supply equipment is most important. It is, therefore, important to identify an optimum mix of various supply equipment for meeting the time varying demand to reduce the overall cost of the system.

Many studies have been conducted at optimising process supply equipment. Garcia and Wozny (2009) used chance constrained programming to study nonlinear systems. Martin et al. (2014) used mixed integer linear programming (MILP) formulation to optimise the aeration profile in water treatment units. Jiménez-Gutiérrez et al. (2014) used a similar formulation to study simultaneous mass and energy integration in water networks. Um et al. (2014) studied energy efficient factory planning in the light of recent advances in cloud computing. Similarly, overall impacts on the economics of the process industries are also studied. While these works focused on optimising common process industries, Troup and Goergakis (2013) studied the extent to which common process engineering techniques have been adopted by the pharmaceutical industry while Lim et al. (2013) used process engineering tools for the optimal design and planning of the product portfolio as well as processing route and applied to an integrated, resource-efficient rice mill complex. To incorporate time varying demands, multi-period optimisations are proposed in the literature. The problem of multi-period multi-objective optimisation, which is common in process industries, was addressed by Yeu and You (2013) using mixed integer nonlinear programming (MINLP) formulation. Kabra et al. (2013) studied the scheduling optimisation of a multi-stage multi-product pharmaceutical process. An MILP based model was used to optimise a multi-period multi-objective power system by Fazlollahi et al. (2014a,b). However, these approaches cannot be directly applicable to optimal sizing of various supply equipment to satisfy time varying demands.

It may be noted that a large number of engineering applications involve supplying time varying demands. Often, multiple competing supply equipment are also available. Most supply equipments have two types of investments associated with them; an initial capital investment and an ongoing operating cost. Operating cost is a linear function of demand supplied and thus, the overall cost

* Corresponding author. Tel.: +91 22 25767894; fax: +91 22 25726875.
E-mail address: santanub@iitb.ac.in (S. Bandyopadhyay).

http://dx.doi.org/10.1016/j.compchemeng.2015.05.004
0098-1354/

List of symbols

C_{tot}	total annualised cost
CF	capacity factor
d(t)	time varying demand
D	discretised demand
D_{max}	Maximum demand
e	cumulative demand
$f(y)$	duration as a function of demand
F	fixed annualised cost component
i	index for supply equipment
j	index for existing equipment
k	index for time interval
n	number of new supply equipment
m	number of existing supply equipment
R	rating of existing equipment
S	savings
t	time
T	time interval
T	technology option
TS	total savings
V	variable cost component
X	flow from a source to a demand
y	demand as represented in the demand duration curve

function is affine in nature. The objective is to minimise the overall cost of the system by appropriately selecting various supply equipment while meeting the demand requirements.

In the electrical power sector, the screening curve methodology is used to solve problems of a similar structure. The screening curve methodology uses the concept of load–duration curve to find a cost optimum generation mix (i.e., optimum sizes of various power plants). Fitzpatrick and Gallagerr (1962) introduced the concept of finding the most ideal generator for each region of the load–duration curve. Anderson (1972) described a linear programming model, similar to screening curve analysis, to obtain the ideal generation mix. In this work, the load–duration curve is segregated into peak, intermediate, and base loads and available power plants are prioritised for each load based on incremental cost. Though screening curves are not plotted in this case, the theory is essentially equivalent. Lee and Dechamps (1978) used the screening curve methodology to study the effectiveness of a tidal power plant. While mathematical optimisation is used to study the case with a tidal power plant, the screening curve methodology is used to identify the optimum energy mix in the case without tidal power plant. In this paper, the concept of screening curve methodology is extended to minimise overall cost of the system by optimally sizing various supply equipment to satisfy time varying demands. In this paper the applicability of the screening curve method is extended to optimal sizing of process equipment and demonstrated through diverse engineering applications.

During debottlenecking, new supply equipment are installed, along with existing equipment, to meet enhanced requirement. Such debottlenecking or expansion problems are of practical importance. Stoughton et al. (1980) and Levin and Zahavi (1984) applied the screening curve methodology for expansion planning problem. The basic theory used is that an existing unit can be considered to have a fictitious fixed cost, such that the installed capacity is used to the maximum. Koomey et al. (1990) modified the screening curve methodology to introduce a quantity named conservation load factor. This methodology helps in studying the peak load savings in each region of the load–duration curve. Sevilgen et al. (2005) used the method to study the effect of economic parameters like annualised levelised cost on the generation mix for the Turkish energy sector. Jonghe et al. (2011) used the screening curve methodology to analyse the effect of high wind penetration, considering the wind generation as a negative load and altering the load curve accordingly. Hirth and Ueckerdt (2012) applied the method to carbon emission minimisation and Batlle and Rodilla (2013) applied it to thermal expansion planning. These methodologies are based on the principles of nonlinear optimisation problems and computationally intensive. Furthermore, it is difficult to guarantee the global optimality. Based on a discretised representation of demand, a linear programming formulation is also proposed in this paper to address expansion planning of various supply equipment during debottlenecking. Being a linear programming problem, global optimality can be guaranteed without scarifying accuracy. Furthermore, the proposed formulation is equivalent to transportation problem and hence, specific algorithms can be applied to solve a large problem efficiently.

The paper is organised as follows. Problem statement is provided in Section 2. In Section 3, screening curve-based methodology is proposed and the applicability of the proposed methodology is demonstrated in Section 4. In Section 5, linear programming formulation for the expansion planning during debottleneck is presented and demonstrated through an illustrative example. Finally the paper is concluded highlighting the main contribution.

2. Problem statement

Consider a time varying demand d(t) over a time interval $0 \leq t \leq T$. Consider availability of n supply equipment. Each supply equipment has a fixed annualised cost component F_i which depends on the rated capacity of the equipment and a variable cost component V_i. The objective is to minimise the overall cost of the system by appropriately sizing supply equipment while satisfying the time varying demand. Here, the demand can be any time varying quantity. For example, water demand in a process plant may be time varying and pumps are the supply equipment. Let us assume that many pumps are available with different capital and operating costs. The overall objective here is to meet the water demand at the minimum overall cost.

Variation of demand as function time is known as demand curve. Consider plotting the demand as a demand duration curve (DDC) given by depicting the demand as a function of its duration. DDC is obtained by arranging all demand levels in descending order of magnitude and plotting them against the duration for which they occur. In other words, it represents the percentage/fraction (or number) of hours of a given time frame at which the demand is at or above a given value. DDC may be represented as duration $f(y)$ as a function of demand, y. It may be noted that the numerical values of demand and the corresponding optimal sizing of the supply equipment do not change by representing the time varying demand as DDC.

Assume that the demand represented by the DDC is supplied by a collection of n supply equipment. Let each supply equipment supply a part of the load from the DDC, dividing it into n intervals. Let the supply equipment i satisfy the demand from y_{i-1} to y_i. The total cumulative demand (e_i) supplied by supply equipment i is given as:

$$e_i = \int_{y_{i-1}}^{y_i} f(y) \cdot \mathrm{d}(y) \quad (1)$$

The capital cost of each supply equipment is assumed to be a linear function of its capacity. The capital cost of the ith supply equipment may be expressed as $F_i * (y_i - y_{i-1})$. On the other hand, the operating cost of any supply equipment depends on the cumulative demand supplied and hence, the operating cost of the ith