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Optimization design of exhaust duct system in semiconductor factory using dynamic programming method

Huan-Ruei Shiu*, Feng-Chu Ou, Sih-Li Chen

Department of Mechanical Engineering, National Taiwan University, Rooseveit Road, Taipei, Taiwan

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Abstract

An exhaust duct system in semiconductor factory is designed using the dynamic programming method (DPM), which considers system pressure equilibrium and the least life-cycle cost to derive the duct size and fan capacity. An example of alkaline gas exhaust system is provided to understand the characteristics of DPM and to compare with the conventional duct design methods. Since DPM contains the concept of minimizing the life-cycle cost, the design results not only guarantee each path to share the same pressure, but also bear a smaller cost than other methods. The limit on duct diameter or flow velocity is added to the computation process. As a result, all the derived outcomes satisfy the requirements on the range of duct diameter or flow velocity. The differences between the design and simulation (actual operation) results under DPM are much lower than those of other methods. Thus, an exhaust duct system that best approximates the actual operation may be designed using DPM.

Keywords: Exhaust duct system; Dynamic programming method

1. Introduction

The semiconductor industry is on a continuous course of development and improvement in both product and process at Taiwan. The number and types of special gases used in the process rise, meaning more varieties of chemical fumes are released in the air, posing greater threat to the human health and the environment. Therefore, good process exhaust duct system design becomes all the more important. The main purpose of exhaust system is to discharge waste gases generated in the process outside the plant. Exhaust volume is the first factor to be considered in the design. In addition, the air velocity in each duct section must be constrained within an acceptable range. Other problems, such as noise, vibration, pressure balance, costs and space limitations during construction have to be factored in as well. These factors are mostly inter-containing. For example, increasing design velocity or reducing duct size can lower initial costs, but in this case fan pressure needs to be increased which might require bigger fan, resulting in higher operating cost or bringing about noise or vibration problem. Thus it is always a challenge for designers to come up with an optimum exhaust system while satisfying the individual constraints.

Most conventional HVAC duct designs use the equal friction method [1] or the velocity method. These methods may be simple, but they fail to achieve pressure equilibrium. Thus, the system designed does not meet the actual operations. On-site ventilation adjustment after project completion becomes a must. In some cases, overly large fans must be installed to make up for poor design, which add to the extra costs. Although the static regain method [1] takes pressure equilibrium into consideration, it does not contain the cost concept, like other conventional design methods, and thus cannot meet the optimization requirement. T-method [2,3] is the most comprehensive and the most powerful tool applied in duct design. This method is established on a scrupulous mathematical model. It uses iteration computation and cost optimization theory, which enable the designed system to have the lowest life-cycle cost and all paths to have the same pressure loss. There is no need to waste extra time or money to attain system pressure equilibrium. However, the computation procedure of T-method is extremely complex. There are at least 20 computation steps in one iteration for only one duct section. Besides, T-method offers poor control of flow velocity or duct diameter. In cases of relatively inexpensive initial cost, the flow velocity may be too high.

* Corresponding author.

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Nomenclature

E	Life-cycle cost (in NT$)
E_p	Operating energy cost for the first year (in NT$)
E_s	Initial cost (in NT$)
Q_{fan}	Fan ventilation volume (m^3/s)
P_{fan}	Fan static pressure (Pa)
η_f	Fan efficiency (%)
η_e	Efficiency of the drive motor (%)
E_c	Unit price of electricity (NT$/kW-h)
Y	Annual hours of system operation (h/yr)
Y_I^*	Minimum cost (in NT$)
S_d	Unit area cost of the ducts (NT$/$m^2$)
L	Duct length (m)
C	Local loss coefficient
D	Diameter of circular duct (m)
H	Height of square duct (m)
W	Width of square duct (m)

In contrast, for cases of relatively inexpensive energy cost, the duct size may be too big. Nevertheless, in actual duct design, considerations of the factors of space and noise often require a limit on the duct diameter or flow velocity during certain sections. When there are too many limitations, it is difficult to obtain the satisfactory and stable optimal solution from T-method, as discussed by Mathews and Claassen [4]. Thus, it is necessary to search for a design method that contains a simple computation procedure, considers the least life-cycle cost and pressure equilibrium under certain limits on space or flow velocity.

Dynamic programming method (DPM) is a type of mathematical technique first developed by Richard Bellman [5]. It is an optimization method extremely suitable for use in analyzing problems with a complex and multiple stage decision-making procedure and searching for the best strategy. Bellman believes that the optimal decision should possess the following characteristic: "Regardless of the initial conditions and initial decisions, the future condition and decision resulted from these initial conditions and decisions must be able to produce the best solution for the problem". In other words, if the current states and the devised decisions are known conditions, the best policy they produce in the future must be independent of the previous policy. Thus, the problems to be solved using dynamic programming are mostly decision-making problems with multiple stages that can be divided. In particular, dynamic programming is very suitable for solving the optimization problem whose objective function *cannot be differentiated*. The optimization design of a duct system happens to conform to such an application.

Problems that can be solved by dynamic programming must possess the following four characteristics [6]:

1. The problem must be able to be divided into several stages, in which a decision needs to be made in each stage. For instance, in solving the optimization problem of a duct system, the problem is divided into stages according to the duct nodes.
2. Each stage has a state vector, which consists of a set of state variables that describe the system conditions such as the pressure value of the duct.
3. A certain decision vector in each stage must be able to transform a certain state vector in that stage into a certain state vector in the next stage. The decision vector consists of a set of decision variables, which represent the decisions made in relation to the system during a certain stage. The effect of these decisions on the system can be expressed in an appropriate measurement. Usually, this effect is quantified through the objective function.
4. As far as each state of any one stage is concerned, the optimal decision made is unrelated to the decision made during the previous stage. This means that the state variables of the current stage already contain all impact on the system resulting from the decisions made during the previous stage.

To sum up the above, the optimization design problem of the duct system satisfies all of the above characteristics, and is thus very suitable for using DPM for solution. The objective of this paper is to apply the method in order to develop an optimal duct design method that better meets practical applications.

2. Objective function

The objective of an optimal HVAC duct system design is to search for the pipeline combination with the lowest total system pressure loss in order to optimize the total cost, given the known conditions of ventilation volume at each ventilation exit. Thus, it is necessary to use the life-cycle cost of the system as the objective function of optimization. The life-cycle cost can then be minimized through the selection of the optimal duct diameter and optimal fan pressure.

The life-cycle cost of a duct system includes the initial cost and operating energy cost. The initial cost includes the duct price and installation cost, while the operating energy cost includes energy charge and energy demand. The optimization method can derive the fan static pressure that minimizes costs. Since many of the costs mentioned above are constants and unrelated to optimization, only the initial cost and energy cost need to be included in the objective