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A chemical industry area-wide layout design methodology for piping implementation

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ABSTRACT

Chemical industry area-wide layout design is a significant section for enterprises management. Its main aim is to improve production efficiency and operational safety. At current stage, relative location of plants in an industrial area is determined by expertise based on material flow for shortening material transportation distance. However, few systematic methodology has been proposed to guide the material flow based area-wide layout design. Moreover, heat flow, such as steam, is often ignored in area-wide layout design, leading to a longer piping of heat and a higher energy loss. In this paper, a systematical area-wide layout design methodology is proposed considering both material flow piping and steam piping. A genetic algorithm based methodology is proposed to optimize the area-wide layout according to piping implementation. Different from one-to-one connection for material piping, steam piping configuration is an optimization with multi-branches pipe network and the calculation is difficult. To solve the problem, improved Kruskal algorithm is used in proposed method. In addition, some safety and environmental issues are considered in the model. A case study consisting of three scenarios is constructed to prove the effectiveness of the proposed methodology.

1. Introduction

The placement of the equipment in a single plant (plant layout design) or the plants in an industrial area (area-wide layout design) is known to be a comprehensive task, which has a great impact upon manufacturing costs, energy losses, performance of enterprise and safety.

Plant layout design problem is an essential stage of both new plant installation and existing plants retrofit. It aims to obtain the most effective facility arrangement and minimize the material handling costs (Tarkesh et al., 2009). It was estimated that effective facility planning can reduce the material handling costs by 10%–30% (Tompkins et al., 2010). Since Koopmans and Beckmann (1957) put forward plant layout design problem, especially with the development of computer science in the last three decades, a lot of achievements have been published in service and manufacturing industry, such as hospital (Feyzollahi et al., 2009; Lin et al., 2015), ship cabin (Luo et al., 2015), mobile robot or automated guided vehicle (Tubaileh, 2014), etc.

Plant layout is generally considered to be very complex and is an NP-hard problem (Garey and Johnson, 1979) of engineering optimization. Because it is an interdisciplinary field which involves in graph theory, artificial intelligence, operation research, computer science and engineering practical experience and so on. And the objective function is multiple, including minimum land costs, minimum handling costs (pipeline cost and pumping cost), safety costs (Caputo et al., 2015), etc. Additionally, there are a wide range of plant layout design factors, including material handling systems, location of facility, shape of facility, the safety and environmental issues, the pick-up and drop-off locations, the number of floors, space allocated, no-overlapping, budget constraints (Drira et al., 2007), etc. Sometimes these constraints are conflicting when they are taken into consideration comprehensively. So the designer needs to balance the different constraints in their layout schemes. Furthermore, because of the complexity of practical factors, the academics usually choose different constrains depending on different priorities in solving the problem.

In earlier researches, the design of plant layout is finished by humans based on the practical experiences and related national standards, and these achievements set up the basis on later research. For example, Kern (1977) published a number of works to consider imple-

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Nomenclature

Indices

i, j	Equipment items
x_i, y_i	Coordinates of geometrical centre of item i
x_j, y_j	Coordinates of geometrical centre of item j
x^I_β, y^I_β	Coordinates of the process materials supplier plant
x^o_β, y^o_β	Coordinates of the process materials user plant
G	A connected weighted graph without direction
V	A set of vertexes
E	A set of sides
W	A set of weights
N	A set of natural numbers
V	Matrix of the conditions of steam usage of plants

Parameters

a^S_β	Unit prices of different levels of steam piping
a^M_β	Unit prices of different process material piping

Binary variables

$v_{i,j}$	1 if the plant use or produce a kind of steam; 0 otherwise

Continuous variables

C	Total piping cost

Integer variables

$\omega_{i,j}$	The weights between each two vertexes; 1 if the two plants are adjacent; 0 if the two plants are overlapped; ∞ if the two plants are not adjacent
n	Number of steam levels
m	Number of material flows
L^M_β	Length of each process material piping
L^S_β	Length of each level of steam piping
N_p	Number of the plants which generate or use the same level of steam
L	Number of connections

mentation of different equipment in a plant. Additionally, some related standards also provide some guiding principles of plant layout design (Wang, 2015). These rules are qualitative and fuzzy, and they can't analyze layout plan systematically. Muther (1973) proposed a method of procedural approach named systematic layout planning (SLP), which is a logical plant layout design method combining the connections between material flow and the relationships between the production units. It is a classical approach of manual plant layout and has been used in many industrial fields. However, the final layout quality mainly depends on the knowledge level of the designer. Many steps may be coordinated according to their importance in the process of plant layout design using SLP. Besides, in order to evaluate the various solutions, a lot of calculations are repeated manually. Hence, it is difficult to obtain optimal results using artificial method to solve the large scale problem.

To solve the complex problem of plant layout, many researches proposed varieties of mathematical models. Mixed integer programming (MIP) model based on material flow was presented by Montreuil (1991). Kim and Kim (2000) then used a mix integer linear programming (MILP) model to solve the plant layout where each equipment has a predetermined shape. Then Xu and Papageorgiou (2009) presented an improvement-type algorithm to solve the large-scale, single-floor process plant layout problem. Additionally, Penteado and Ciric (1996) developed a mixed integer nonlinear programming (MINLP) model that identifies attractive layouts by minimizing overall costs for equipment layout.

The algorithms for solving above models have proposed a lot with the development of computer and information technology. Initially, branch and bound algorithms (Kettani and Oral, 1993) and graph partitioning algorithm (Jayakumar and Reklaitis, 1994) were used to solve quadratic assignment problem. A tabu search (TA) of global search method was proposed to solve dynamic plant layout problem by applying data envelopment analysis (DEA) (Bozorgi et al., 2015). Şahin et al. (2010) presented a simulated annealing (SA) algorithm in 2001, which is a stochastic neighborhood search technique to solve the dynamic layout problem (DLP). Genetic algorithm (GA) (Kaveh et al., 2013) is one of the evolutionary approaches, which is a commonly used method in solving equipment or plant layout problem. Nasab et al. (2012) solved a dynamic facility layout problem that the material flow is considered as fuzzy numbers with different membership functions using GA. Caputo et al. (2015) presented a method based on GA for optimizing safety-based process plant layout. Precisely, the solved problem is a plant layout problem.

Up to now, most of works are based on layout design of equipment in a single plant. Few considerations have been paid on the layout design of plants in an industrial area. When problem is extended from plant level to the area-wide level, the main constrains of models are no longer the pick-up and drop-off locations, sizes of the equipment, the number of floors, non-overlapping, etc. Material handling cost and safety issues may become the main considerations. For example, Patsiatzis et al. (2004) studied the MILP model considering simultaneously process plant layout and safety. The Dow Fire and Explosion Harzard Index (1994) is used to quantify the fire or explosion damage. At present, for area-wide layout design, most of works are based on safety factors. But the researches based on connection cost are not deep enough, and even most of their values are fixed. Jung et al. (2011) proposed a method to demonstrate a systematic technique to integrate quantitative risk analysis (QRA) in the optimization of plant layout. The proposed approach was formulated as an MINLP model that determines safe locations of plants by minimizing the overall cost. The cost consists of land cost, interconnection cost and probability of structural damage cost with weighting factors. Specially, the interconnection cost only includes material piping which is assumed by the authors. Similarly, Han et al. (2013) studied the optimal of a chemical plant layout to minimize the risk to humans. The proposed objective function consists of pipeline connection cost, land cost and installation cost of the additional protective devices. But it is applied by plant layout. Additionally, a disjunctive model is proposed to avoid overlapping problems in the layout configuration. Xu et al. (2013) proposed a new method based on MINLP model for plant layout including an improved non-overlapping and safety constraints. In the paper, the constraints about safety include minimum distance and toxic gas dispersion. Land cost and pipe length are included in the objective function. The paper presented an improved GA based on an infeasible solution fix technique to improve the globe search ability. Martinez-Gomez et al. (2015) published a similar work. In their paper, the two parts of objective function are safety cost and interconnection cost. However, all these works did not involve pipe cost into optimization.

Both safety issue and pipe implementation are very important factors in area-wide layout design. The design of piping directly decides the material handling, the cost of production operation and energy loss. However, for the conventional area-wide layout design methodologies, only safety issues are emphasized, but the pipe implementation is not involved in optimization.

Some chemical industry area-wide pipeline design principles can be found in the related international standards or layout design handbooks. In the standard or handbook (Wang, 2015), the presented principles are experience based rules that require expert users. Moreover, design is mainly based on material flow, and heat flow is not fully addressed. The piping of heat flow, for example, steam pipelines, is an important part of area-wide pipe network. Reasonable piping of heat flow can reduce construction investment and heat loss effectively, especially for the implementation of high pressure pipelines. Therefore, the optimal pipeline network cannot be obtained by using standard and handbook, as well as the optimal area-wide layout.