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An industrial area layout design methodology considering piping and safety using genetic algorithm

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ABSTRACT

The industrial area layout can influence the economic benefit, safety and surrounding environment of an industrial area to a large extent, especially the length of piping and safety. Every year, the construction of new industrial areas requires thousands of tons of steel pipes, resulting in a high consumption of natural resource of iron and high emission of carbon dioxide. Additionally, the long pipeline will increase the energy consumption for material transportation. Meanwhile, accidents in industrial areas can usually result in serious damage to the local environment. So the optimization of industrial area layout holds great significance for natural resource, energy saving, and environment protection. But up to now, very few papers have been reported to consider the use of pipes and safety simultaneously to optimize the layout in industrial area level. Most works only focus on safety aspects, and the impact of connection is ignored. Accordingly, this paper proposes a methodology to optimize the relative position of each plant, whose objective function consists of piping cost and safety cost. In this paper, despite conventional consideration of material piping, steam piping, which features multiple-branches connected pipeline network, is also considered. For safety issues, it is firstly analyzed by qualitative principles to limit position for some specified plants. Then quantitative analysis, including explosion and toxic release, are optimized simultaneously with connection cost. A genetic algorithm is used to solve the proposed model. Kruskal algorithm and Arrangement & Combination are used to calculate the length of steam piping. Finally, a case study illustrates the effectiveness and applicability of the proposed methodology.

1. Introduction

Industrial area layout design is to determine the relative position of each plant. It is a significant design stage of an industrial area that can improve the rationality of the engineering design, especially in economic benefit, safe production, management efficiency and environmental impact. Usually, an industrial area includes several plants, and a plant includes several devices. So far, most works have focused on the device layout in a single plant. They study the influence of different arrangements of devices on investment and safety issues. But few papers research the plant layout from the view of the whole industrial area.

After expanding the research boundary to the industrial area, the long pipes connecting plants should be noticed. China's crude steel production accounts for 49.5% of world production in 2014. And the production of steel tubes and tube fittings reached 89 million tons, which accounts for 10.8% of the total production of China's crude steel (World Steel Association, 2017). It is a huge consumption. At the same time, China consumes lots of energy and released lots of carbon dioxide in steelmaking process every year (Xu et al., 2016). In United Nations Framework Convention on Climate Change (UNFCCC), the goal of “Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels” (UNFCCC, 2015) has been set. But Meinshausen et al. (2009) indicated that if we keep the CO_2 emission level of 2000–2006, the probability of exceeding 2 °C in 2039 is 50%. Kang and Lee (2016) examined the positive contribution of energy and resources efficiency to the growth of final output, using the method of Malmquist Efficiency Analysis (MEA), and they suggested that industries should make efforts to improve the use of energy. So a scientific and reasonable layout of an industrial area is important to reduce the usage of pipes and pipe fitting. On the other hand, a shorter pipeline can reduce energy consumption for material transportation.

The layout of an industrial area cannot only influence the length

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and cost of pipeline, but also influence safety. Industrial accidents can cause the release of toxic and harmful substance and destruction of high energy or high value-added substance. And this will seriously damage the local environment. So industrial area layout has a great impact on reducing the possibility of accidents and relieving the consequence of accidents. Industrial area layout problem involves many aspects and requires comprehensive consideration.

The pipe connection is one of the most important considerations in the process of layout optimization. And the pipe cost is used to quantify the usage of pipes usually. Up to now, most works focus on the device layout in plant level. Caputo et al. (2015). proposed a method to take pipe cost, pump cost, land cost, and safety cost into consideration. And the case study of the production of nitric acid illustrates the good performance of this method and a better layout is obtained.

Whether in the level of plant or industrial area, only one-to-one connection structure is considered in most works. But in practice, a number of connections contain branches (for example, steam pipe network). This complex structure cannot be described by simple one-to-one connection model. Especially when expanding the layout to industrial area level, the length of steam pipeline network is hard to calculate. In addition, in some works, piping length is calculated as the linear distance between two devices, but in practice, the pipeline should follow pipe rack. Wu et al. (2016) developed an algorithm to work out the shortest path of steam pipe network based on Kruskal algorithm. This method effectively reduces the length of steam pipeline network and the cost of pipes in an industrial area. Wu et al. (2016). took qualitative analysis, material pipeline and steam pipeline network into account when optimized the area layout, contributing to a shorter pipeline length. Three heuristic methods were proposed according to different objectives. The case study illustrated that simultaneously optimizing material and steam piping can obtain a shorter pipeline length. However, these two works mentioned above lack detailed consideration of safety.

The safety issue is another very important factor. A number of studies on plant layout considering safety factors are reported. Penteado and Ciric (1996) firstly put forward the idea of safety based on plant layout. They developed a mathematical programming approach to identify attractive process plant layouts by minimizing the costs of piping, land, protection device and financial risk. Park et al. (2011) took minimum safety distance as a constraint to ensure the security of the layout. Quantitative Risk Analysis (QRA) is an essential way to reduce the potential risk and acquire a better layout. Medina-Herrera et al. (2014) optimized the plant layout with the consideration of QRA. The paper researched non-wind direction dependent events and wind direction dependent scenario by QRA. And they used a developed bowtie analysis to identify the possible consequence. Alves et al. (2016) proposed a new approach to optimizing the layout of process units in a plant area, aiming at minimizing the risk to the general public. The works mentioned above just take one kind of possible accident into consideration. Rahman et al. (2014) took explosion and toxic release into consideration simultaneously. But only four plants are optimized in this work.

As one of the inherent safety assessment tools, index approach is used for plant layout designs in many published papers. Patsiatzis et al. (2004) proposed a mathematical programming methodology to determine protection devices and interconnection cost via Dow Fire and Explosion Index system, which is a useful tool to quantify the hazards of fire or explosion. The constraints of the model are device orientation, non-overlapping, distance and area of exposure. Tugnoli et al. (2008) developed an index for evaluation of the hazards related to the potential domino effects. Combined with I2SI index, that index was used in the work of Julio et al. (2014) to select the better layout with lower risk. This work developed a mathematical method to prevent domino chains by improving the inherent safety of device layout. Baalisampang et al. (2016) proposed a method to optimize the layout to achieve inherently safe, and the case study showed that, the economic loss due to domino effects is limited because of a better layout.

Some studies consider plant layout design by using mathematical programming. Quadratic Assignment Problem (QAP) was proposed firstly by Koopmans and Beckmann (1957) to formulate plant layout problem. Han et al. (2013) used a mix integer linear programming (MILP) model to formulate process layout optimization problem with risk zones. The objective function included pipeline connection cost, land cost and installation cost of the additional protective devices. The objective is to minimize economic and safety. Xu et al. (2013) developed a mixed integer nonlinear programming (MINLP) model to optimize plant layout with novel non-overlapping and toxic gas dispersion. Their work can effectively reduce the number of variables in the model and improve the computational efficiency.

For safety evaluation of industrial area, there are some works reported. Failure mode effect analysis, fault tree analysis, and event tree analysis are the most common methods, while some researchers evaluate the safety of an industrial area based on the consequence accidents may result in. Governments and organizations issued varieties of regulations and standards to evaluate and control the safety of an industrial area, like “Major Hazard Control: a practical manual” (ILO, 1988) issued by International Labour Organization and “Method of Comprehensive Evaluation of Petrochemical Enterprise Safety” (Sinopec, 1992) from China. But these methods are practical rules, and a certain layout cannot be directly obtained from them. In academia, Chen et al. (2012) proposed a comprehensive risk assessment method for the enterprises in chemical industrial parks based on catastrophe theory. And the method takes the inherent risk of sources, the effectiveness of prevention and control mechanism, and the vulnerability of receptor into consideration. Li et al. (2010) proposed a conceptual model of the human vulnerability of chemical accidents in a chemical industrial park. This model reveals the roots of human vulnerability and emphasizes its role in risk management. Li and Wang (2013) quantitatively assessed the risk of a chemical industry park using CASSTQRA software, and based on this, a safety planning was proposed to ensure the safety and long-term development of the park. Wang and Zheng (2010) proposed a new method to assess the safety of a chemical industrial park based on grid partition method and information diffusion theory. In their work, multi-danger source is taken into consideration and the risk of grid center is calculated by superposition principle. The works mentioned above just consider the safety of an industrial area, without the length of the pipeline.

For the problems mentioned above, this work focuses on the plant layout problem in industrial area level. Material pipelines, steam pipeline network and safety issues are taken into consideration. For the safety issues, qualitative and quantitative analysis are put together in safety optimization. The qualitative optimization of safety is implemented by limiting or fixing positions of some plants according to the geological and hydrological conditions of the area and the characteristics of the plants. For quantitative optimization, explosion and toxic release are optimized simultaneously. Extensive and comprehensive consideration of these complex factors makes it possible to obtain a better industrial area layout using the method we proposed. The usage of pipes can be reduced and the safety can be enhanced. Finally, the aim of iron natural resource saving, carbon emission reduction and damage relief of accident to nature and people can be achieved.