Journal of Loss Prevention in the Process Industries 40 (2016) 603–614

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

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

A new concept of adjacency for concurrent consideration of economic and safety aspects in design of facility layout problems

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ARTICLE INFO

Article history:
Received 11 May 2015
Received in revised form
17 December 2015
Accepted 11 February 2016
Available online 18 February 2016

Keywords:
Mixed integer programming
Economic and safety aspect
Facility layout
Unequal department

ABSTRACT

In this manuscript a new phenomenon of adjacency and closeness rating is proposed for constructing the optimal facility layout design. In the proposed approach, the closeness rating is applied to every pair of neighboring departments in a range of their attached point up to a predefined distance between them. Also, while in the traditional approach the closeness rating is applied for determining either the proximity or farness of two departments, the proposed approach considers both the degree of closeness as the economical purposes, and farness as the safety purposes concurrently. A mathematical model is proposed for constructing the optimal layout design. For evaluating the efficiency and flexibility of the proposed model, a computational experiment is conducted. Through the results of this experiment, three major novelties of the proposed model such as its flexibility for concurrent consideration of the economic and the safety aspects of the layout design, its ability for constructing varieties of the layout designs, and a better implementation of adjacency among the neighboring department's pairs during the designing processes are demonstrated.

1. Introduction

Facility layout is an important problem in the early stage of system design and plays a key role in modern manufacturing systems. An efficient facility layout design means to arrange the physical equipment within a workshop to help the facility work in a productive way. The arrangement of process equipment and buildings can have a large impact on plant economics. A good facility layout contributes to overall efficiency of operations and can reduce up to 50% of the total operating costs (Xie and Sahinidis, 2008). In effort to maximize plant efficiency, the design of plant layout should facilitate the production process, minimize material handling and operating cost, and promote ease of the related activities. The overall layout development should incorporate safety considerations in conjunction with the cost and efficiency issues.

Facility layout problem (FLP) may arise in many contexts. Considering a manufacturing plant, it consists of a number of diverse activities interacting with each other. These activities, from a dock for receiving of the raw materials through several processing units, and ending to the finished products shipping dock, all take place in different areas, called departments or facilities. FLPs are classified as, product or assembly line, process or functional layout, and fixed position layout (Muther, 1973). Among these, the process or functional layout is widely used in manufacturing systems to organize cost-effective working environments. In this type of layout, machines and equipment are grouped together by their functions.

The facility layout approaches, especially for the process or functional layout, can generally be classified into two groups, constructive approaches and improvement approaches (Liggett, 2000). The improvement approaches start with an initial solution and attempt to incrementally improve it, while the constructive approaches built a solution by the use of activity relation. Furthermore, two tools are widely used for the analysis of a process layout, namely “from-to chart” (FTC), and “activity relationship chart” (ARC). The ARC usually is utilized for the constructive layout design, while FTC is applied for the improving layout design (Francis and White, 1974). ARC is a qualitative tool for determining which departments have a need for proximity/farness due to effectiveness/safety considerations. In ARC, a closeness rating is assigned to a pair of departments based on several factors and quantified by the “ordinal scale” for denoting the desired proximity/farness of departments (Steven, 1946). In process of assigning the proper closeness rating, one may be faced with the problem of

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http://dx.doi.org/10.1016/j.jlp.2016.02.010
0950-4230/

conflicting factors. To explore this fact, consider two departments in which there are two factors of a) high materials follow; and b) safety factor of fire and explosion. For assigning the closeness rating, we actually need to decide on one as the primary factor. In the effort to maximize plant efficiency, these two departments may be eligible of acquiring “A” closeness rating. In contrast, for the safety consideration, they may be eligible of obtaining “X” closeness rating. As another example, consider a case in which two departments with high materials follow, which may imply having “A” closeness rating, but due to a noise factor, it is desired to locate them apart. Obviously, by placing them apart, the noise factor is fulfilled but the layout efficiency may be reduced. In contrast, by placing them adjacent, the noise factor may become unfulfilled but the layout efficiency is increased. These conflicting factors appear in many practical scenarios. However, usually most of the traditional approaches dealing with the construction of layout design consider only one aspect of the closeness rating, either the efficiency or safety aspect. To resolve this problem, we proposed a new concept of closeness rating by which the concurrent consideration of efficiency and safety can be applied. In addition, traditionally, the closeness rating is applied only to a pair of adjacent department which are attached to each other, while in the proposed approach, the closeness rating is applied to every pair of adjacent departments in a range of their attached point up to a predefined distance between them. Also, in the traditional approaches the closeness rating is applied for determining either the proximity or farness of two departments, but the proposed approach simultaneously considers both the proximity and the farness as the economical and safety purposes respectively. A mathematical model is proposed for constructing the optimal layout design with the objective function of maximizing the total utility which defined by sum product of the closeness rating and adjacency rating. As the results of these new concepts, varieties of layout designs can be constructed which overcome the limitations imposed by the use of the ordinal scale for evaluating the final designs.

In the following sections of this manuscript, the scope of the new FLP model as well as development of mathematical models will be more elaborated. More specifically after the review of the related literature in Section 2, the description of a new closeness rating concept will be presented in Section 3. In Section 4, the development of the mathematical model will be discussed. The computational experiment and its results are presented in Section 5. Finally the manuscript will be concluded in Section 6.

2. Literature review

Incorporating safety considerations in conjunction with the cost and efficiency aspects in optimization of facility layout has attracted the attention of researchers in the past two decades. Facility siting is a vital element in process safety. This is due to the consequences of the Pasadena, TX, incident (1989), Flixborough accident (1974), the Texas City refinery explosion on March 2005 incidents (Mannan et al., 2007, Baker et al., 2007). Inadequate separation distance between hazardous departments with the adjacent process units have been observed in most of these cases. The siting of a hazardous plant near a densely populated area has also resulted in fatal disasters, most notably in Seveso (1976) and Bhopal (1984). In the toxic gas released in Bhopal incident, major victims were not only workers within the plant but also residents who lived in the surrounding area (Joseph et al., 2005). This important issue has been focused by the Occupational Safety and Health Administration's (OSHA) process safety management regulation. To enforce this regulation, OSHA has issued tens of citations during 1992–2004 to process industries (Dreux, 2005). The major reason for issuing these citations is lack of adequate consideration to facility siting and buildings spacing.

Unfortunately, most of the studies dealing with the FLPs, have directed on the perimeter of efficiency and cost saving (Sharma et al., 2012; Rawinkhan-Srinon, 2014; Bukchin and Tzur, 2014; Neghabi and Ghassemi-Tari, 2015; Neghabi et al., 2014; Salmani et al., 2015). Few research efforts have implemented safety considerations in design of facility layouts. Penteado and Ciric (1996) developed a layout design assuming that the land occupied by each unit is characterized by a circular footprint. This model was then evaluated with a rectangular footprint (Patsiatzis and Papageorgiou, 2002) and incorporated the Dow Fire and Explosion Index as a risk analysis tool for evaluating new and existing layouts (AIChE, 1994). Other studies have concentrated on risk evaluation of FLP at the conceptual level (Paterson et al., 2000; Sanders, 2003; Cozzani et al., 2007).

In the layout literature, the mathematical models have frequently been used to solve the specific aspects of FLPs. Georgiadis et al. (1999) introduced a mathematical programming approach for process plant layout. Guirardello and Swaney (2005) incorporated the pipe routing in the plant layout optimization. Park et al. (2011) reported a mathematical model for the optimal multi-floor plant layout involving safety distances. They considered a short distance between dangerous units and the high number of workers that can be affected by an accident. In the last decade, more methodologies have been focused on the simultaneous consideration of economic and safety aspects of facility layouts, in this context, Patsiatzis et al. (2004) reported a mixed-integer linear programming model to safe process plant layout. Taylor (2007) incorporated safety considerations in modeling LNG facility siting. Safety assessment in plant layout design using indexing approach is due to the works conducted by Tugnoli et al., 2008a, 2008b. They reported a study for comparing deterministic versus stochastic approaches in facility layout, which was later incorporated by Diaz-Ovalle et al. (2010). They developed a new approach for determining the optimal arrangement of process facilities consisting of several toxic releasing facilities.

Jung (2010), and Jung et al. (2010a, 2010b) proposed a methodology for finding the optimal placement of a hazardous process unit and other facilities using optimization theory while considering a risk map in the plant area. Later, Jung et al. (2011) presented a new approach to optimizing facility siting and layout for flammable gas release scenarios to minimize the consequences of fire and explosion. They proposed a mixed integer nonlinear program (MINLP) that determines safe locations of facilities by minimizing the overall cost. Through their methodology they provided substantial guidance for designing of an optimal layout by which fire and explosion risks in the chemical process plant is managed.

Safety consideration in layout design of a chemical process plant, for preventing hazardous conditions, is another research conducted by Han et al. (2012, 2013). Lira-Flores et al. (2013), implemented a mixed-integer nonlinear programming model for layout designs based on the domino hazard index. Martinez-Gomez et al. (2014) presented a multi objective optimization approach for the optimal siting in industrial facilities. Medina-Herrera et al. (2014) reported a mathematical programming model for the optimal layout considering a quantitative risk analysis. In these methodologies, the risk was associated to the accidents for fire and explosion, as well as the accidents associated to toxic gas release scenarios. In fact, a domino effect is an issue where an accident in a given unit affects the adjacent facilities producing a more dangerous effect. Incorporating process safety in plant layout configuration of an ammonia plant is another research attempt conducted by Rahman et al. (2014). In this research, four critical process units were selected as the sources of overpressure and toxic release. Locations of four facilities including control room, two