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A mathematical programming model for optimal layout considering quantitative risk analysis

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ABSTRACT

Safety and performance are important factors in the design and operation of chemical plants. This paper describes the formulation of a mixed integer nonlinear programming model for the optimization of plant layout with safety considerations. The model considers a quantitative risk analysis to take safety into account, and a bowtie analysis is used to identify possible catastrophic outcomes. These effects are quantified through consequence analyses and probit models. The model allows the location of facilities at any available point, an advantage over grid-based models. Two case studies are solved to show the applicability of the proposed approach.

1. Introduction

Chemical plants must not only be cost effective, but also avoid or minimize the risk of major hazards, which places safety as one of the major components in the operation of chemical plants.

A good facility siting and a proper layout contribute to an inherently safer plant and better risk management, and may even reduce occupied land and operation costs (Patsiatzis et al., 2004). The Center for Chemical Process Safety (CCPS) has published guidelines for facility siting and layout (AIChE, 2003). The CCPS guidelines, based on industry practice and standards, provide guidance for finding an optimal production site and for proper placing of units within the plant with safety considerations as a major consideration. However, the guidelines do not provide a systematic method for plant layout.

Mathematical programming has been applied to model layout problems. Guirardello and Swaney (2005) have decomposed the layout task into a sequence of subproblems using mixed integer linear programming models. They show two solution approaches, one using global optimization and another one using a short path-algorithm. Papageorgiou and Rotstein (1998) developed a MILP model for optimal process layout for a continuous dimension space. They used piping costs of the connected equipment as an objective function. Özyurt and Realff (1999) have proposed a MINLP approach coupled to a geographic information system (GIS). Several mathematical programming models have also been developed for special layout cases such as multi-floor plants (Patsiatzis and Papageorgiou, 2003; Park et al., 2011). These works have contributed in terms of modeling these types of systems, but safety considerations were not included in such models.

Facility siting and layout is an important item in risk management and safety (Crowl and Louvar, 2002). History supports this fact. The Texas City refinery explosion in 2005 and the Flixborough disaster in 1974, among others, are examples of lack of safety in chemical plants due to poor layouts and back-up systems (Crowl and Louvar, 2002). There are some interesting works on safe layout. Georgiadis et al. (1999) have proposed a general mathematical programming approach for plant layout under restrictions of fixed safety distances. Penteado and Ciric (1996) developed an MINLP model for safe process layout considering three possible hazardous incidents in an ethylene oxide plant. Addition of safety devices to decrease consequences in case of an incident was also taken into account. Vázquez-Román et al. (2010) proposed an MINLP model that considers atmospheric uncertainties under toxic releases using Monte Carlo simulation. Patsiatzis

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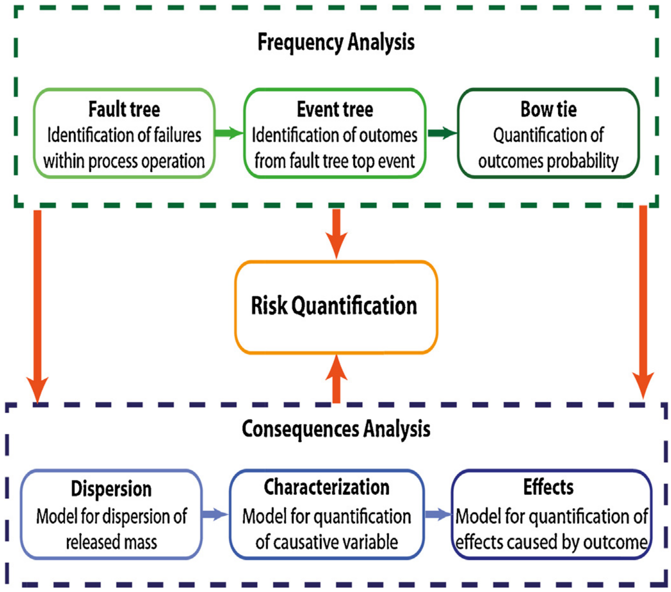

Fig. 1. Graphic representation of a quantitative risk analysis.

et al. (2004) proposed an MILP model to provide safe plant layouts. They included the Dow's fire and explosion index systems to account for safety in a continuous space. Jung et al. (2010a) developed a systematic approach for facility layout considering fire and explosion scenarios using a grid-based MILP model. In a second work, Jung et al. (2010b) reported a MINLP model for facility layout considering toxic releases using CFD software to validate the results. These works have particularly contributed to a better understanding and modeling of the relationship between layout and safety. However, most of them have focused on worst-case scenarios, which can be classified as a pessimistic view of the entire spectrum of risk sources, typically overestimating risk.

This work aims at providing a more realistic analysis of risk sources through the full application of a quantitative risk analysis (QRA). A QRA identifies common scenarios and quantifies their corresponding risk. In this way, a QRA finds possible outcomes, among them the most frequent one, and the scenario with highest consequences. We propose a mathematical model that yields a systematic algorithm for plant layout following CCPS guidelines for facility siting and layout. The proposed model requires a bowtie analysis, which identifies potential catastrophic outcomes given a failure within dangerous process equipment. Once the outcomes are identified, an MINLP model is formulated to find the optimal location for process units and equipment. The objective function considers risk of workers at the units, risk of damage to process equipment, and land and interconnection costs. The objective function is subject to geometry constraints, non-overlapping constraints, scenarios characterization constraints, and consequences quantification constraints considering economic data and wind direction uncertainty.

The outline of the paper is as follows. First, we introduce basic concepts and common risk management procedures. Next, we present the problem statement and state some assumptions for the formulation of the MINLP model. The general formulation of the model is explained and relevant constraints such as geometrical relations, disjunctions for non-overlapping, frequency analysis, consequences analysis, the objective function, and the reformulation of the disjunctions are addressed in detail. Two examples are then used to show the application of the proposed model.

2. Background

In dealing with safety, a common practice is to relate it with risk. Risk is defined as a function of probability of a loss and the loss itself. In chemical plants such a loss is a consequence of an abnormal event (loss of equipment, injured people, loss of material, etc.) Risk management is the identification, assessment and prioritization of risk. In industry, a well-accepted risk identification method is a hazard and operability study (HAZOP), which is developed through the contributions of experienced people to assess possible failures of equipment and operation. Venkatasubramanian et al. (2003a,b,c) have shown several fault identification methods and discussed their strengths and weaknesses. Qualitative and quantitative assessment can be performed; a risk matrix being the principal method for qualitative assessment (Ni et al., 2010), while a QRA is a more detailed method because it requires identification of failures, failure rates data, and a consequence analysis. Qualitative methods are simpler and represent a good starting point, while quantitative methods give more specific data and a better prioritization of risk. A disadvantage of a quantitative analysis is that failure rates and environmental conditions are uncertain. Some works have proved the importance of using plant-specific failures rates estimations rather than generic values within chemical plants (Meel and Seider, 2008; Meel et al., 2008).

In this work, a QRA is considered to optimize the facility layout of the plant. Fig. 1 shows a graphic representation of the risk quantification by means of a QRA, which requires the quantification of both frequency and consequences. The probability quantification can be performed using fault trees, which identify the possible failures that cause a release of material and event trees, which identify the outcomes caused by the material released. Both analyses are combined into one, yielding a bowtie analysis. Therefore, from a bowtie analysis the probability of all outcomes can be quantified based on historic plant-specific data and expert judgment (top part of Fig. 1.) After the outcomes are identified by the bow tie analysis, consequences are quantified by a consequence analysis. An outcome consequence analysis includes