DOMIRISK: A User-Friendly Domino Effect Decision Support System

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Abstract. The continuous development of modern industry has potential hazard, of which domino effect is a major threat that could result in catastrophe. Moreover, domino accidents will endanger the environment and human health. Some decision support systems for preventing the domino effect have been developed, while most of them are too theoretical and have obvious limitations, such as ignoring the influence of personnel, operational, and other real factors in the actual industrial production process. This paper emphasizes the causes of potential domino accidents and the construction of the accident chain. A system called DOMIRISK is designed which can: 1) quantify the domino effect of the entire plant; 2) identify the root cause of potential domino accidents; 3) build the accident chain of domino effect; 4) assess the environmental risk of the domino accident. A chemical plant is used as an example to illustrate how the system provides practical decision support for controlling the occurrence and spread of domino accidents and protecting environment.

1. Introduction
Hidden behind the prosperity of modern industry is the huge potential hazard. The awareness of industrial process safety is constantly improving. High-impact low-probability (HILP) accident scenarios, which are called “domino effect”, have gradually attracted people's attention[1]. There is still no widely accepted definition of domino events in the literature. Referring to previous studies, the domino effect is defined in this paper as: an accident in which a primary event propagates to nearby equipment, triggering one or more secondary events resulting in overall consequences more severe than those of the primary event[2]. Severe accidents involving “domino effect” have adverse effects on the individual and the social level, leading to casualties, property and environmental damage.

In the past 50 years, the occurrence of domino accidents was frequently reported around the world. In 1966, at the Feyzin refinery (France), a large fire started in the tank storage, causing a series of fires and explosions in other tanks. In 1984, the worst domino accident ever recorded happened in Mexico [3]. The leakage of LPG led to a fireball, BLEVE, which eventually caused about 650 deaths and more than 6,400 injuries. In addition, the accident leaked a lot of toxic and harmful chemicals, causing serious environmental pollution. Recently, in 2019, a severe fire and explosion accident occurred at a chemical plant in China, which involved 16 surrounding plants, and caused 78 deaths and more than 600 injuries.

The complexity of the domino effect aroused widespread concern in the academic field. In the past 25 years, the research on the domino effect mainly focuses on the following three aspects: 1) past accident analysis; 2) vulnerability models for equipment damage; 3) quantitative risk assessment
Previous studies systematically explored the mechanism and characteristics of the occurrence and propagation of domino effect, and proposed the overall framework of domino quantitative risk assessment [2, 4]. However, the domino effect involves a lot of scenarios with interacting parameters due to inherent complexity [5]. During the QRA of domino effect, numerous data needed to be dealt with, which makes prevention of the domino effect more difficult. To solve this problem, some domino effect risk assessment systems based on the previous scientific research have been developed [2, 4, 6, 7]. But these software have some common limitations.

Most of available software emphasize on accident risk assessment and consequence assessment. Equipment damage models and accident frequency simulation techniques used in the software are constantly being updated [7]. However, these systems seldom analyse the root causes of potential domino accidents in reality. The calculations in the software rely on information of the environment, equipment, and materials. But the influence of personnel, operations, and other factors in the actual industrial production process are ignored. These software are more theoretical and less suitable for practical industrial application. Besides, these software ignore the assessment of environmental risk. The users of the software do not have enough knowledge of the overall domino effect risk of the factory. Another limitation of these systems is that they lack the part of identifying and constructing the accident chain. Most software can only simulate the primary domino scenario. Software users are not able to have a relatively complete view of domino accident chain.

Based on the previous studies, this paper presents a decision support system called DOMIRISK, which has great application prospect in quantifying and preventing domino effect, as well as protecting environment.

2. The DOMIRISK system
Overall, the DOMIRISK software is a Chrome browser-based web application for PC users in the chemical industry. It provides users with more practical help in the identification and construction of domino effect chain and studying the potential causes of accidents. The software includes seven modules: domino effect risk pre-evaluation (Module 1), domino scene simulation (Module 2), domino effect environmental impact assessment (Module 3), image manager (Module 4), user control (Module 5), project documents (Module 6), and data system management (Module 7). The software system architecture diagram is shown in Figure 1.

As mentioned above, the cause of domino effect is complex in the actual chemical industry production. In addition to equipment and materials, there are some potential causes of domino accidents, which are ignored in the most of the existing software. For example, weak safety awareness and improper operation of employee, as well as inadequate emergency measures are also potential risks. Module 1 analyses the root causes of domino accidents in six aspects: process equipment, raw and auxiliary materials, safety equipment, staff, environmental management, and emergency rescue. Module 1 designs a domino accident risk index for the chemical industry to rate the risk of the chemical factory by “high”, “medium” and “low”. If the domino accident risk rating is “medium” or “high”, the software will advise users to complete the domino scenario simulation. Moreover, by using built-in accidental consequences models such as fires and explosions, users can identify and establish a domino accident chain. For those devices with severe risk, users can take targeted measures. After inputting all the required data, the above modules can be operated. The process of running the software is shown in Figure 2.

The specific design of the software modules includes four parts as following.
Figure 1. Software system architecture diagram

Figure 2. Software flow chart
2.1. Data system management design
Considering that a lot of data is involved in module operation, a corresponding basic information database is established in the software. By analysing the relationship between the data, the basic information database is divided into five sub-databases: materials, devices (units), environment, factory, and domino risk assessment information. For example, the material database includes basic chemical information, daily maximum storage, explosion heat, liquid pool area, substance name, combustion heat, reaction type and other basic information. The relationship of first four sub-databases is progressive. Domino risk assessment information can be calculated based on these data. The entity relationship among the sub-databases is illustrated in Figure 3. Most of the contents of the database in DOMIRISK software need to be input by the users.

2.2. Domino effect risk pre-evaluation module design
The design of this module is mainly based on the fishbone diagram analysis method[8]. In the past, C. C. Zeng et al. used the fishbone diagram analysis method to identify the main sources of domino accident risk in the chemical industry[9]. On this basis, an index system for calculating the risk of domino accidents was established and the relevant weight coefficients were determined. This paper has made some corrections to the domino accident risk calculation index system, so that it can be better programmed.

This module is divided into six parts: process equipment, raw and auxiliary materials, safety management, staff, environmental management and emergency rescue. Each part has corresponding sub-indicators. For example, when evaluating the domino risk brought by process equipment, it mainly involves multiple parameters such as temperature, pressure, equipment type, and frequency of inspection. Each sub-indicator is split into specific option questions. The operation for each question has a corresponding score. According to the weight coefficient of the indicator system, the final total score of the domino effect risk index can be obtained. After completing the basic database configuration, with a few simple operations, the users can view the overall plant's domino accident risk score and understand the key causes of potential Domino accidents.

When the overall domino risk value score of the enterprise belongs to [0, 2], the domino risk is low; when the score belongs to (2, 5], the domino risk is medium; when the score belongs to (5, 10], the domino risk is high. Plants with a Domino accident risk rating greater than medium will be advised to use the scenario simulation module to further identify sources of Domino accident risk.

![Figure 3. E-R diagram of database](image-url)
2.3. Domino scenario simulation module design

The scenario simulation module identifies and establishes the domino chain of accidents by: 1) identifying potential initial domino accidents; 2) using the accident consequence model to calculate the physical effects of the initial accidental heat radiation, overpressure, etc.[10]; 3) using the domino effect threshold to screen potential secondary accident target devices[11]; 4) use equipment vulnerability model to calculate the escalation probability of potential secondary accidents caused by initial accidents[2]; 5) identify secondary accidents compared with default accident probability; 6) use the same method to identify higher order accidents.

The criteria for initial accidents in DOMIRISK are: 1) the material in the device is a significant hazardous substance; 2) the mass of the device is greater than the critical mass. A device that satisfies both conditions is a potential initial accident device. After all the required data are input, the software can identify a list of potential initial accidents. Using a large number of fires, explosion accident consequences models and accident escalation probability models built into the software, DOMIRISK can calculate the physical effects of current accidents on potential secondary devices, the probability of accident escalation, and identify and establish a complete domino accident chain. Users can view a complete list of primary, secondary, and higher order accidents separately.

2.4. Domino effect environmental risk assessment module design

This module mainly involves atmospheric and water environmental risks. The system indirectly evaluates atmospheric environmental risks by assessing the impact of atmospheric particulates on human health. Due to various restrictions, the atmospheric environmental risk considered in this module is mainly atmospheric particulate pollution. According to previous studies, users only need to provide the added value of $PM_{10}$ concentration at a certain point and the added value of the incidence of respiratory system, cardiovascular disease and other diseases in this case, and the atmospheric risk value at that point can be calculated.

Since water pollution accidents do not directly affect people, this system mainly evaluates the environmental risks of water pollution by calculating the property losses of water pollution. According to previous studies, there is a certain ratio relationship between the water value loss caused by some pollutants and the total value of water. Users need to fill in water resource quantity, basic price of water resource, concentration of water pollution and other relevant parameters, and the software can calculate the water value loss caused by water pollution.

3. Illustrative example

The illustrative enterprise selected in this paper is a large state-owned enterprise managed by China National Chemical Corporation. The main product are methionine, which are widely used in medicine, food, feed and cosmetics. The company occupies an area of 426,000 square meters and employs 344 people. It operates on a continuous working system and operates 24 hours a day. The annual operating hours are 8,000 hours. The company currently has a 140,000 tons/year liquid methionine (AT88) project. The main raw materials are sulfur, methanol, propylene, liquid ammonia, methane, etc. The products mainly include carbon disulfide, methyl mercaptan and ammonium sulfate. Production processes include carbon disulfide synthesis, MSH synthesis, MMP refining, and AT88 synthesis.

The storage tank of this enterprise is not involved in dust explosion, and the risk sources are all equipped with protective ponds. Few pollutants will enter the water body, and the pollution concentration is less than the critical concentration, so the environmental risk is not considered.

3.1. Domino effect risk pre-evaluation

Taking the process equipment risk assessment as an example, the factory production line includes 9 sections, of which the equipment pressure is mostly at 0-20 MPa, and the working temperature is lower than 1000°C. The equipment unit with a large risk value is above 100m$^3$. There is a moderate exothermic reaction during production. The production line is advanced in technology and uses custom imported equipment with a high degree of automation. The annual maintenance frequency of
the equipment is about 1 time. Through software running, the risk index of process equipment part is: 7.26.

Questions in other aspects of the domino risk pre-evaluation module can also be answered by field visits and viewing of corporate documents. It can be seen from Figure 4 that the overall corporate domino accident risk value is 6.95, which is a major domino risk. The risk indices of safety management, environmental management, raw and auxiliary materials, staff and emergency rescue parts are: 7.38, 6.68, 6.52, 6.67, and 7.34. By comparing the scores of each part indicator, the safety management risk is the main cause of the potential domino accident. The factory should use the scenario simulation module to further identify specific device risk sources.

![Figure 4. Result of domino effect risk pre-evaluation](https://example.com/figure4)

3.2. Domino scenario simulation
DOMIRISK identified a total of 14 potential primary accidents of the factory. Taking the device R74410 as an example, its potential accident type is PF and BLEVE. The software can query all potential secondary accidents corresponding to the device, as shown in Table 1. At the same time, the heat radiation, the overpressure value and the corresponding escalation probability can also be queried. The total escalation probability of the device R74600 is 1. Set it as a secondary device, the heat radiation value is 418.49 kJ/m², and the overpressure value is 15002 179.89 Pa. The software can also show other higher order accidents corresponding to the potential secondary accident and export the complete accident chain documentation.

4. Conclusion
The new decision support system “DOMIRISK” is a Chrome browser-based web application for PC users in the chemical industry. This user-friendly software is able to: 1) quantify the domino effect of the entire plant; 2) identify the root cause of potential domino accidents; 3) build an accident chain of domino effect; 4) assess the environmental risk of the domino accident.

The results of the illustrative example evidenced that many factors led to potential domino accidents in the plant. Domino accidents are not only related to the loopholes in the equipment, but also the shortage of emergency rescue, insufficient safety management and so on. Unlike most existing system, DOMIRISK combines the production process of the plant with the domino effect quantitative risk assessment theory. Using this software, decision makers can better understand the overall domino risk of the plant and find out the potential source that may lead to domino accidents. The software can provide decision support for controlling the occurrence and spread of domino accidents and protecting environment.
Table 1. Potential secondary accidents of R74410

|            | Heat radiation (kw/m²) | Overpressure (Pa) | Heat radiation escalation probability | Overpressure escalation probability | Total escalation probability |
|------------|------------------------|-------------------|---------------------------------------|-----------------------------------|-----------------------------|
| R74700     | 27.52                  | 37052.25          | 6.005E-8                              | 1                                 | 1                           |
| R95960     | 1.78                   | 24013.87          | 0                                     | 0.82                              | 0.82                        |
| R74400     | 418.49                 | 15002179.75       | 0.99                                  | 1                                 | 1                           |
| R96300     | 1.68                   | 22892.96          | 0                                     | 0.77                              | 0.77                        |
| R74600     | 418.49                 | 15002179.89       | 0.99                                  | 1                                 | 1                           |
| R95700     | 2.38                   | 30380.05          | 0                                     | 0.96                              | 0.96                        |
| R74610     | 104.62                 | 2193900.69        | 0.076                                 | 1                                 | 1                           |
| R95710     | 2.18                   | 28296.21          | 0                                     | 0.93                              | 0.93                        |
| R96200     | 2.16                   | 28067.30          | 0                                     | 0.92                              | 0.92                        |
| R74510     | 16.87                  | 208937.84         | 8.16E-12                              | 1                                 | 1                           |
| R74500     | 40.17                  | 589028.47         | 1.5E-6                                | 1                                 | 1                           |

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