Gis-Based Fire Risk Spatial Assessment for Semiconductor Plant

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Abstract. Traditional fire risk assessment of semiconductor plant mainly relies on engineer experience from fields of fire control, chemistry, construction, semiconductor and insurance, and lacks a collaborative tool to integrate different design blueprints and locate high risk regions. In this paper, we introduce GIS into fire risk research for semiconductor industry, and propose a GIS-based spatial and quantitative method of fire risk assessment. Based on semiconductor plant spatial database extracted from diversified indoor maps, we set up a fire risk index system and integrate factors of potential fire source, operation risks of fabrication process, fire proof design and fire management to identify the high fire risk regions by using analytic hierarchy process. The proposed method improves spatial analysis capabilities of fire risk assessment for more and more complex semiconductor factories.

1. Introduction
With the rapid growth of semiconductor consumption, semiconductor investments become more expensive. In the insurance field, semiconductor manufacturing enterprises can be summarized as three high, that is, high risk, high vulnerability and high insurance amount. On the one hand, lots of flammable, explosive, corrosive and toxic chemical materials are widely applied in the chip manufacturing process. On the other hand, clip equipment is sensitive to smoke and fire, and manufacturing needs to be done in a clean room.

Particularly for semiconductor industry, as pointed out by historical statistics [1][2], fire and explosion are the major disasters and will cause great damage. For example, on September 4th of 2013, a fire, which followed a chemical explosion during the installation of new manufacturing equipment at a SK Hynix plant in Wuxi, China, began at 3:30 p.m. and burned until nearly 6 p.m. The regions damaged by fire are not large, but it leaded to huge economic losses. The smoke damaged the DRAM fabrication (FAB)’s clean-room facilities and broke more than 800 sets of equipment. Finally, insurance companies paid US $860 million in total for equipment damage, building reconstruction, interrupted operation and indemnities.

Various traditional fire risk assessment methods have been developed to address the physical situation and seek to measure/predict and assess the acceptability of risk in a particular place and situation [3]. As outlined by Watts and Hall [4][5], the fire risk analysis may be classified into four categories: checklists, narratives, indexing and probabilistic methods. Alternatively, the types of assessments that are currently available for the purposes of fire hazard assessments can typically be
defined into three categories such as Qualitative, Semi-Qualitative and Quantitative methods as recognized by Ramachandran [6].

Existing assessment methods are based on Fire Service Act and the Building Standards Act, and mainly focus on architectural structure. Thus, high-standard fire prevention evaluation regulations such as National Fire Prevention Association (NFPA), Factory Mutual (FM), and Semiconductor Equipment and Materials International (SEMI) [7] are important supplement for assessment.

However, until now, special studies and assessment method of fire potential risks available for semiconductor factory are still scarce. Besides short of evaluation tools for semiconductor modern factories, the main reason is lack of tools for integrating a great diversity of indoor and outdoor maps, such as factory layout, architectural design, structural construction, production equipment, fire protection and pipelines, and lack of fire risk spatial analysis capabilities to locate risks in the more and more complex semiconductor factories.

Thus, in this paper, we introduce GIS database and analysis into fire risk assessment research for semiconductor industry, and propose a GIS-based fire risk spatial assessment. Combined with the information of architecture, structure, equipment, pipelines and fire services, the semiconductor plant spatial database is constructed after the steps of data transforming, extracting and cleaning. And then we establish a new fire risk spatial assessment method, which integrated potential fire source, operation risks of fabrication process, fire proof design, fire management, to identify and locate high risk regions.

2. Study Area and Data
Yangtze Memory Technologies Co., Ltd., established in Wuhan, China in July 2016, is an IDM memory company with a focus on the design, production and sales of 3D NAND flash memory chips for mobile devices, computing, and consumer electronics. The semiconductor fabrication plant has four floors. The building and facility are provided with fire detection system, automatic sprinkler system, indoor & outdoor hydrant systems and portable fire extinguishers throughout the buildings. The occupancies of semiconductor fabrication plant are summarized as following:

| Floor | Occupancies                                                      |
|-------|------------------------------------------------------------------|
| L10   | No cleanroom                                                     |
|       | Utility supporting area, chemical supply, waste chemical collection, power room, PCW, DI, HVAC, goods transporting etc. |
| L20   | cleanroom                                                        |
|       | Clean sub-fab, chemical booster room                             |
| L30   | cleanroom                                                        |
|       | Fabrication Plant (FAB)                                          |
| L40   | cleanroom                                                        |
|       | Truss, HVAC, power rooms, MAU                                    |

3. The Proposed Method
Our main process of fire risk spatial assessment can be summarized in four parts: indoor fire application mapping and spatial database, fire risk spatial assessment index analysis, determination of indicator weight and fire risk spatial assessment (Figure 1).
3.1. Indoor fire application mapping and spatial database
Unlike the tradition indoor map which is applied for navigation in large-scale commercial buildings, the content of indoor map is focus on industrial process and building fire safety [8]. Therefore, the production steps are as follows:

1. Obtain semiconductor plant data. The main data source includes the architectural and structure, semiconductor equipment assembly blueprint, pipeline design and fire protection design map. Because the production process is often adjusted, equipment and position need to be verified on site.

2. Meanwhile, attribute data can be obtained from building design, equipment test and assembly reports.

3. Design semiconductor plant indoor map. Because the above data involves a lot of other content, data need to be transformed, extracted and cleaned according to fire application. The fire application data is expressed with map graphical symbols (points, lines, faces) and annotation symbols.

4. Establish spatial database for fire risk assessment. The database includes two group spatial layers, outdoor maps for recording function divisions and buildings in the industrial park, such as fabrication, hazardous chemical warehouse, pipe racks/bridges, H2 generation station, special gas station, silane station and so on. Meanwhile, indoor maps provide a detailed expression of the complex structure, different fire services and diverse equipment of each workshop for each floor.

3.2. Fire risk spatial assessment index
Fire risk (FR) is defined as the product of the probability of fire occurrence and damage to be expected on the occurrence of fire (severity).

\[ FR = \sum_{i=1}^{n} P_i \times C_i \]  

Where FR is the fire risk, i is different part of workshop, \( P_i \) is the probability of fire occurrence, \( C_i \) is consequences damage value, and \( n \) represents the total part number of workshop. Probability of fire can be used to forecast the probability of a fire disaster, whereas fire severity represents the degree of damage from a disaster.
Besides traditional fire risk assessment index of public buildings such as structure, fire management and social fire safety prevention, potential chemicals ignition and fabrication process for semiconductor factory are considered and added into assessment index system. Thus, in this paper, the fire risk assessment index is composed of 5 categories as follows.

### Table 2. Fire risk assessment index for semiconductor plant.

| C1. Potential chemicals ignition risk index | C2. Fabrication process hazard risk index |
|-------------------------------------------|----------------------------------------|
| **1.1 Usage amount of hazardous chemicals** | **Production process**                 |
| Flammable/ Explosive gas types            | Type, such as diffusion, etching       |
| Corrosive chemicals                      | Workshop area                          |
| Organic solvent                          | Machine interval distance              |
| Storage capacity of hazardous chemicals   |                                        |
| Flammable/ Explosive gas                  | Machine usage age                      |
| Corrosive chemicals                       | Machine maintenance                    |
| Organic solvent                          | Process temperature                    |
| **Delivery of hazardous chemicals**       |                                        |
| Pipe usage age                            | Process voltage                        |
| Pipe material                             | Process pressure                       |
| Pipe length and radius                    | Machine abnormal alarm                 |
| Scrubbers                                 | Valve Manifold Box                     |
| **Monitoring and protection**             | **Personnel operation**                |
| Fume Exhaust Systems                      | Operator quality                       |
| Explosion venting protection              | CCTV Monitor                           |
| Operation valve interlock                 | Safety guards’ checks                  |
| **C3. Building structure risk index**     |                                        |
| **C4. Fire safety management**            |                                        |
| **C5. Social safety prevention**          |                                        |
| Risk of spreading                         |                                        |
| Internal or Exterior fire wall            | Fire management                        |
| Internal or Exterior fire door            | Equipment maintenance                  |
| Fire compartment area                     | Emergency Responses                    |
| Fire resistance rating                    | Fire emergency plan                    |
| Columns & Beams                          | Fire training and drills                |
| Floor height                             | Organization management                |
| Heating Ventilation and Air Conditioning  | Inspection potential safety hazard    |
| **Combustion materials**                 |                                        |
| Machine material                         | Production safety monitoring           |
| Roof material                            | Firefighting equipment                 |
| Floor material                           | Communication ability                  |
| Pipe valve material                       |                                        |
| Door material                            | Fire brigade                           |
| Window material                          |                                        |
| Link Bridges & pipe racks                | Fire Fighting Command System           |
| AMHS                                     | Fire brigade Arrival time              |
| **Fire protection system**               |                                        |
| Fire Detection Systems                    | Municipal facilities population density|
| Fire pump system                         | Road network                           |
| Sprinkler systems                        | Social safety control                  |
| Gaseous suppression systems              | Public fire safety awareness           |
| Evacuation passage                       | Guarantee cooperation                  |

3.3. Determination of indicator weight

Considering new materials and processes are adopted for semiconductor plants, moreover, the frequency of fires is lower, it is difficult for data collection and fire risk assessment is mainly based on expert experience [9][10]. Thus, in this paper, analytic hierarchy process (AHP) with expert experience, a regional fire risk assessment model, is applied to determination weight of above 68 indicators, 14 sub-categories and 5 categories.
Firstly, the relative importance of above indicators for fire risk is determined by one to one comparisons. A pairwise comparison matrix for all indicators is designed, and we gather statistics of the comparison matrix scored from experts in semiconductor field such fire, safety, architecture, equipment and manufacture. Finally, above comparison matrix results are synthesized to calculate the relative importance, i.e., weights for each indicator and category in the hierarchy, to identify the risk level of a certain workshop. The weight of main categories is illustrated in Table 3.

### Table 3. Weights of main fire risk assessment categories index.

| Category                        | Weight  |
|---------------------------------|---------|
| C1. Potential chemicals ignition risk index | 0.4503  |
| C2 Fabrication process hazard risk index | 0.2349  |
| C3 Building structure risk index  | 0.1731  |
| C4 Fire safety management        | 0.0750  |
| C5 Social safety prevention      | 0.0666  |

Generally, the priority ranking and consistency judgments are given by the eigenvector of each pairwise comparison matrix. The principal eigenvalue \((\lambda_{\text{max}})\) is 15.9062, and the consistency index \((CI)\) and consistency ratio \((CR)\) for sub-categories are calculated as follows. For \(CR\) is less than 0.1, the proposed assessment is considered as acceptable.

\[
CI = \frac{\lambda_{\text{max}} - n}{n - 1} = \frac{15.9062 - 14}{14} = 0.1466
\]

\[
CR = \frac{CI}{RI} = \frac{0.1466}{1.57} = 0.0934
\]

Where \(CI\) is consistency index, \(CR\) consistency ratio, \(n\) number of sub-categories and \(RI\) is random index.

### 3.4. Fire Risk Spatial Assessment

Every workshop in the plant is divided into different functional regions, and each functional region includes spatial boundary and above assessment indicators. These indicators in the list are scored by experts, and conducted spatial overlay analysis according to above indicator weights to derive serial fire risk maps for each floor. These maps include single indicator analysis, category risk analysis, and final fire risk map (Figure 2).
4. Result Analysis
According to the indicator weights, sub-categories of production process, usage amount of hazardous chemicals, storage capacity of hazardous chemicals, delivery of hazardous chemicals are mainly factors, which result high fire risk.

In the cleanroom for usage amount of hazardous chemicals, high temperature, voltage and pressure in the process with high price of machine, workshops of wet etch, chemical vapor deposition, diffusion, and Photolithography have highest risk. Meanwhile, in the first floor, the workshops of exhaust gas scrubbers, silane, H2 and ClF3 chemical supply are also high risk. Furthermore, in these workshops, as an exchange and control equipment which links different pipes, and dispenses flammable gas to machines and exhaust to scrubbers, valve manifold box has a high fire risk, and results some fire in history.

5. Conclusion
For the semiconductor factory involves a variety of drawings and information, the traditional fire risk assessment method lacks a collaborative integrated platform. In this paper, based on GIS indoor maps and spatial analysis, we propose a fire risk index system and spatial assessment method for semiconductor plant. After calibration and verification by factory and insurance experts, this method and fire risk assessment results have been applied to plant emergency response teams.

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