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A SMART INDOOR AIR QUALITY SENSOR NETWORK – MODELING AND DESIGN

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ABSTRACT

Many new biological and chemical sensors have been or are continuously being developed for infrastructure and environmental protection, such as for protecting the quality of water and indoor and outdoor air. However, there is still a lack of fundamental system-level research leading to the development of sensor networks that both maximize protection and minimize the system cost for indoor air protection. Four key parameters are usually used to evaluate sensor performance: sensor sensitivity, probability of correct detection, false positive rate, and response time. The optimal design of a sensor system are affected by the values for the above sensor performance parameters. This paper describes a preliminary study to: 1) identify simplified simulation and optimization strategies that can be used for sensor system design; 2) examine the relationships between sensor location, sensitivity, and quantity, and; 3) use both detection time and total occupant exposure as optimization objective functions for sensor system design. Common building attack scenarios, using a typical CBW agent, are simulated for a small commercial building. Genetic Algorithm is then applied to optimize the sensor sensitivity, location, and quantity, thus achieving the best system behavior while also reducing the total system cost. Assuming that each attack scenario has the same probability for occurrence, optimal system designs that account for the simulated possible attack scenarios are obtained.

Keywords: indoor air quality, chemical and biological warfare (CBW) agent, sensor system design

INTRODUCTION

During the last few decades, significant effort has been made to ensure that buildings become safer, more energy efficient, and more cost effective than in the past. However, the public now expects the built environment to provide even more protection, especially against natural or man-made extraordinary incidents since the tragic events of September 11th and the subsequent anthrax attacks. Buildings are especially vulnerable to chemical and biological warfare (CBW) agent contamination because the central air conditioning and ventilation system serves as a natural carrier for spreading the released agent from a single release location to the entire indoor environment and within a short period of time. Most CBW agents are highly lethal. For example, a person may suffer mild injury, serious injury, or even death, respectively, if as little as 0.9, 10, or 15 mg VX gas (a nerve agent) is inhaled (Zhai et. al., 2003). Moreover, airborne CBW agents are usually colorless and odorless, exhibiting surprisingly rapid dispersion rates. Therefore, early detection and warning of airborne CBW agents play important roles in protecting the occupants and in minimizing the consequences of such extraordinary incidents. However, current built environments generally lack the ability to detect hazardous chemical and biological components in the indoor air (NRCa, 2004).

Rapid advancements in sensing technology are making a variety of sensors that are able to detect indoor pollutants available, including those that can detect chemical and biological agents. It is

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envisioned that a baseline detect-to-warn system will be available in the next one to two years, and a distributed low-cost sensor system will be available in the next ten years (NRCa, 2004).

In order to realize such visions, system-level analysis is needed along with developing sensing technology. Different sensing mechanisms offer different sensor characteristics. For example, structure-based detection (such as immunoassays) offers the greatest potential for identification in less than two minutes with very low false alarm rates. On the other hand, nucleic acid sequence-based assays (such as polymerase chain reaction based sensors) provide definitive confirmation of a specific agent. In general, sensors with a high detection threshold (i.e., low sensitivity) have lower false alarm rates, while sensors with a high sensitivity have higher false alarm rates. There is an opportunity to design a distributed sensor system which is composed of sensors with different characteristics in order to achieve the best system-level protection.

To achieve maximum protection, sensor locations also need to be carefully selected. It is not desirable to place sensors in locations where contaminant concentration is normally low at the beginning of an attack. For locations where a contaminant generally disperses rapidly, a fast response sensor is needed. Indoor air flow patters and contaminant movement are nonlinear and complicated; therefore, predicting the contaminant dispersion path is not a trivial task, especially when different attack scenarios and interior arrangement of partitions and furniture exist.

Sensor types, locations, quantities, and characteristics affect system costs, system-level detection probabilities, and system-level false positive rates. It is hypothesized that an optimized sensor system design does exist for a specific building. The focus of this project is to determine how to optimally design such a sensor system to ensure the safety of an indoor environment.

Many characteristics can be used to evaluate a CBW sensor, among which sensitivity, probability of correct detection, false positive rate, and response time are four key parameters. Moreover, these parameters are interrelated. For example, when the sensor sensitivity is increased, the false positive rate is increased as well. The "Receiver Operating Characteristics" curve can be used to describe the inter-relationship among the four key characteristics. A graphical technique called the spider chart (Fig. 1) includes twelve characteristics and is the recommended method to capture the overall performance of a CBW sensor (Carrano, 2004).

It is difficult to establish a certain sensitivity threshold because an extremely large uncertainty exists when attempting to relate an inhalation exposure level to the agent concentration in the air (Carrano, 2004). The ambiguity in the threat also suggests that the sensors have different modes of operation with different sensitivities/false positive rates for different threat probabilities. It is anticipated that a well-designed CBW sensor system, which is composed of sensors having different characteristics and operating modes, can reduce the system-level false positive rate and thus increase the system-level detection confidence, leading to better system-level protection. However, very few studies exist in the open literature that examine indoor air sensor system design issues for protecting a building against CBW agent dispersion.

Arvelo et al (2002) studied the possibility of using an enhanced multi-zone flow model, CONTAM (NIST, 2003), for CBW sensor location design. Only average mass flow and contaminant concentration are provided by CONTAM for each building zone, which limits its stand-alone application in CBW sensor design. Hence, the authors adopted a computational fluid dynamics (CFD) model to provide contaminant concentration information inside a zone, which is based on the average mass flow and contaminant concentration supplied by CONTAM. The authors simulated a Sarin attack for one floor of a two-floor office building. Multiple releasing locations, each associated with an attacking probability, were generated. Genetic Algorithm with a dynamic objective function, which accounts for varying releasing locations, was adopted. The optimal locations for two sensors that minimized detection time were selected. Although no internal partitions or furniture were considered in the building zones or the hallway, the study demonstrated the effect of the opening of office doors on the contamination concentration.

Zhai et al (2003) adopted commercial CFD software to predict a gas-phase CBW agent dispersion in a section of a typical office building, which consisted of two identical offices separated by a corridor. Three agent releasing locations were considered. The CBW agent dispersion information was then used to evaluate different sensor locations. This study demonstrated that the spreading rate of a CBW agent is very fast and will affect the occupants in five to 10 minutes. No methodology on how to optimally select sensor locations was provided.

The studies above demonstrate: 1) the effect that different sensor locations have on protecting the building against CBW terrorism; and 2) the feasibility of using fluid simulation software, especially CFD models, to select the indoor air sensor location(s). However, to design an indoor air sensor system for a real building, the following challenges need to be overcome: 1) modeling a real building using CFD or other fluid simulation software is not an easy task; it requires detailed information about the building as well as requires a user with adequate knowledge of fluid physics and numerical techniques; 2) the computing time for a CFD model is very high, especially when the building is complex; 3) besides minimizing the time of detection, other design objectives, such as minimizing the population exposed, the air volume contaminated, and the total sensor system cost, need to be considered concurrently; 4) identifying the effect of different internal objects, such as furniture, partitions, appliances, and occupants, on the CBW agent dispersion and sensor system design is not a trivial task; 5) the impact of indoor pollutant type on sensor system design needs further investigation; 6) a methodology to combine sensors of different characteristics into a single system in order to achieve optimal system-level protection is still lacking; and 7) a methodology to evaluate a sensor system as a whole is also lacking.

The objectives of this project, which is to respond to some of the challenges above, are to: 1) identify simplified simulation and optimization strategies that can be used for sensor system design; 2) examine the relationships between sensor location, sensitivity, and quantity, and; 3) use both detection time and total occupant exposure as optimization objective functions for sensor system design.

2. SIMULATION MODEL

The air flow pattern and pollutant dispersion for a typical small office building after the release of a chemical weapon agent is modeled in this project using a multi-zone model, CONTAM (NIST, 2003). Genetic Algorithm (GA) is then adopted as the optimization approach for sensor system design (introduced in Sec. 3.1). CONTAM is introduced first in Sec. 2.1 and Sec. 2.3 introduces the office building that is modeled in this study.

2.1 Simulation Software

To design an indoor air sensor system, information about indoor pollutant distribution needs to be available. Various numerical models have been developed, and reported in the literature, to simulate the indoor pollutant dispersion in a built environment. Sohn et al (2004) identified and reviewed currently available simulation models for determining the dispersion of CBW agents in and around buildings and serves as the basis for this discussion. For indoor air simulation, there are three categories of simulation models: CFD, multi-zone, and zonal models.

CFD modeling has been continually validated ever since the early 1970s. However, the degree of accuracy of a CFD model depends on the correct representation of boundary conditions, the solution grid, and the level of transient characteristics. One of the biggest obstacles of using a CFD model is its high computational overhead. It would take an estimated eight to 10 work weeks to completely model and analyze the air flow within a 60,000 sq. ft. four-story office building using a commercial CFD package (Sohn, et. al., 2004).

In contrast, multi-zone models represent a building as a network of well-mixed zones (i.e., conditions such as temperature, humidity, air velocity, and pollutant concentration are uniform within one zone), which are connected by discrete flow paths such as doors, windows, wall cracks, ducts, and hallways. The model then predicts the flow parameters based on mass conservation and component interaction. The major shortcomings of multi-zone models include: 1) they cannot determine detailed air flow within a zone; and 2) they cannot model bi-directional floor-to-floor flows, duct junctions, and transport delays. However, the most recent release of CONTAMW, version 2.4 (NIST, 2003), is able to account for transport delays using a "One-Dimensional Convection/Diffusion" model. This model creates contaminant concentration gradients along a specified axis in a zone and through an entire duct system. Despite the shortcomings in multi-zone models, compared with CFD modeling, multi-zone models are computational efficient and are able to consider numerous transient effects such as occupants coming and going, air handling units turning on and off, and wind directions etc.

When physical zones are large, the well-mixed condition assumed by multi-zone models would be unrealistic and inaccurate. A modeling approach called "zonal model", which aims at overcoming the simplicity of multi-zone model and the calculation complexity of CFD, has also been developed in the literature. In a zonal model, each physical zone is further divided into a small number of sub-zones. Sub-zones can be further divided into standard flow zones and specific flow zones (including jets, plumes, heaters, and boundary layer zones) (Mora et al, 2003). A challenge for a zonal model approach is to model the airflow pattern between zones. Many studies in the open literature have validated the use of zonal models to simulate indoor air flow and contaminant dispersion. A study by Mora et al (2003) compared zonal and CFD models to experimental measurements. The results showed that the CFD model was able to model air flow much more accurately than the zonal models employed.

As a preliminary study, the authors have chosen to utilize the multi-zone model, CONTAMW2.4 (NIST, 2003) developed by the National Institute of Standards and Technology, in simulating the building air flow and contaminant dispersion process. However, the size of zones in this study is much smaller than the physical rooms to overcome the short-comings by the well-mixed assumption.

2.2 Building Model

A small office building, which is similar to Iowa Energy Center Energy Resource Station (Price and Smith, 2000), is selected as the prototype building for this study. A schematic floor plan is shown in Fig. 2. The building is divided into three major areas: the common area and two sets of zones, designated A and B. Each set of zones is comprised of an east, south, west, and interior zone. The common areas consist of office space, a display room, a computer center, two classrooms (not simulated), service rooms, a media center, a reception space, and a mechanical room. The actual building is served by three small air handling units. In this study, however, only one larger air handling unit is assumed to serve the entire building. The mechanical room is not air conditioned and is thus not included in the simulation model. Detailed dimensions of the floor area, doors, and windows are also included in Fig. 2.

If each physically enclosed space in the building described above is considered as one zone, the building can be modeled in CONTAM as shown in Fig. 3a. To overcome the shortcomings of the well-mixed condition assumed by CONTAM, each enclosed space is further divided into smaller sub-zones in order to take into account the partially mixed conditions in a larger zone. The sub-zone model (Fig. 3b) increases the total number of zones from 13 to 77. The average zone size in the sub-zone model is about 6.5 m^2 × 2.6 m high. For brevity, the sub-zones created and shown in Fig. 3b will be further referred to as simply "zones".

Air flow between zones is modeled by a one-way power-law relationship (Mora et al, 2003),

$$\dot{m}_{i,j} ldz = C\rho S\left(\Delta P_{i,j}\right)^n ldz \tag{1}$$

where $\dot{m}_{i,j}$ is the mass flow rate from zone i to zone j, l is the interface width, dz is the interface height, C is a constant with units m/sPa^{-n}, ρ is the air density, and $\Delta P_{i,j}$ is the pressure difference between zones i and j. The values for C of 0.83 m/s-Pa^{-n} and n of 0.5 are commonly used (Mora et al, 2003). The average size of the interface between zones is 2.7 m × 3 m.

In the simulation model, the doors are modeled using the two-way air flow model (large single opening, discharge coefficient 0.78, and minimum temperature difference 0.01^{o}C) provided by CONTAM with dimensions of 2.1 m × 0.9 m for interior doors and 2.2 m × 1.5 m for exterior doors. The windows are modeled using the WNI06AA-CAV model supplied by the CONTAM library (typical inoperable window for building AA (Persily and Ivy, 2001)). Seven occupant exposure models are placed in the building model (Fig. 3a). Each is modeled as a person weighing 70 kg and inhaling at a peak rate of 12 s L/min. Steady state weather conditions (20 ^{o}C, 1 atm, 0 m/s wind speed) are used to simplify the simulation. The air handling unit that serves the building is the "Simple Air

Handling Unit" model (Persily and Ivy, 2001) with 4.7 m^3/s supply air flow rate and 0.47 m^3/s outdoor air flow rate. A transient air flow simulation model is chosen.

2.3 Contaminant Releasing Scenarios

Sarin gas, a highly toxic nerve agent of high volatility, is selected as a typical chemical weapon agent to be simulated in this study. The source release rate is simulated using the cutoff concentration model (Arvelo et al, 2002),

$$S = G(1 - \frac{C}{C_{cut}}) \tag{2}$$

where S is the source strength, C is the current ambient Sarin concentration inside the zone where the source is located, G is the generation rate coefficient (5 mg/s), and C_{cut} is the cutoff concentration (0.1 kg/kg-air). Six releasing scenarios, including release around doorways, in the open office, and in enclosed offices, are assumed and simulated in this study (Fig. 3a). Each releasing location is given the same probability for occurrence.

3. SENSOR SYSTEM OPTIMIZATION

3.1 Optimization Approach

The contaminant dispersion process is a complicated nonlinear process. Hence GA, a stochastic search algorithm (Goldberg, 1989), is selected as the optimization approach because of its ability to handle complicated nonlinear problems. Compared with other stochastic search methods, GA has the following features (Goldberg, 1989): 1) GA works with a coding of the parameter set, not the parameters themselves; 2) GA searches for the optimized value from a population of points (multiple points) to another population instead of from a single point to another single point; 3) GA uses the objective function information rather than the derivatives or other auxiliary knowledge; and 4) GA uses probabilistic transition rules, not deterministic rules.
Figure 4 shows the basic process of a GA optimization. The user supplies n initial guesses for the design variables, which serves as the initial population. For each vector of n initial guesses, the objective function is calculated and compared. The vector that generates the optimal value of the objective function, whether the minimum or the maximum value depending on the definition of the problem, is called a best "parent". A second population is generated based on the information of the objective functions corresponding to each design variable. The goal is to generate a new population so that the "features" that make one vector yield better values of the objective function remain in the new population. Once a new population is generated, the values of the objective function are calculated and compared again. Thus, the third population is generated mainly by the best "parents" that yielded better values of the objective function in previous generations. This process is repeated until certain optimization criteria are satisfied. The terms "reproduction" and "crossover" (Fig. 4) represent processes that generate a new population from a previous population, guided by the information of the objective function for each vector. To prevent premature converging to a local optimal solution, a process called "mutation", which generates a new vector randomly, is involved in the process.

3.2 Objective Functions

Two objectives, to minimize detection time and to minimize occupant exposure, are considered in this study. The detection time of one sensor is defined as the earliest time when the sub-zone contaminant concentration, where a sensor is placed, is higher than the sensor sensitivity. The detection time of the kth releasing scenario, $t_{det\text{-}k}$, is defined as the shortest detection time among all the distributed sensors during the kth scenario. For all six releasing scenarios, the objective function based on detection time, $Jdet$, is thus defined as

$$J_{det} = \sum_{k=1}^{6} p_k \times t_{det-k} \tag{3}$$

where p_k is the probability for the kth releasing scenario to occur. Besides detection time, total exposure for an occupant, which is also related to detection time, is another design criterion. The total exposure of all seven occupants, E_k, for the kth releasing scenario is defined as

$$E_k = \sum_{m=1}^{7} \sum_{t=0}^{t_{det-k}} Exp(m,t) \tag{4}$$

where *Exp(m, t)* is the occupant exposure for the mth occupant at time *t*, which is obtained by the CONTAM simulation. Thus, for all six releasing scenarios, the objective function based on total occupant exposure, J_{exp}, is defined as

$$J_{exp} = \sum_{k=1}^{6} p_k \times E_k \tag{5}$$

Cost is a constraint in this study because of the high expense of CBW sensors. The total cost of the sensor system, *M*, is determined by the single sensor price and total sensor quantity. Since the sensors chosen for this study have the same characteristics and thus the same unit price, the constraint, *M*, will be discussed based on sensor quantity alone.

4. RESULTS AND DISCUSSION

4.1 Simulation Results

The air flow rate through each air flow path after the contaminant is released is basically steady during our study and is not affected when changing the contaminant releasing location. Figure 5 shows the direction and magnitude of the simulated air flow rates for each air flow path by CONTAM under the procedure described in Sec. 2.2. The length of each line represents the magnitude and direction of the air flow. It is observed that the air flow rate through diffusers, returns, and exterior doors are generally larger than the air flow rates through interior doors and between zones. The latter is due to the modeling of free air movement between zones when a physical wall is not present.
The contaminant concentration for each zone varies with the contaminant releasing location.

a) Contaminant concentration in zones 18, 24, 29, 30, and 36 b) Occupant exposure for all occupants

Figure 6 shows the contaminant concentration in zones 18, 24, 29, 30, and 36 when the contaminant is released from location 1 (refer to Fig. 3 for release location and Fig. 7 for location of zones).

a) Contaminant concentration in zones 18, 24, 29, 30, and 36 b) Occupant exposure for all occupants

Figure 6a shows that the contaminant concentration in these zones peaks within 15 minutes and gradually reduces to zero due to the ventilation dilution effect. Both the rate of the concentration variation and the peak value of the concentration vary from zone to zone. Since contaminant concentration varies from zone to zone, this verifies the assumption that the sensor(s) location will affect the system-level detection time.

a) Contaminant concentration in zones 18, 24, 29, 30, and 36 b) Occupant exposure for all occupants

Figure 6b shows the occupant exposure when the contaminant is released at location 1. Contaminant concentration and occupant exposure under the other five releasing locations exhibit similar behaviors as those in Fig. 6 and are thus not provided.

4.2 System Design Results

The air flow rates, contaminant concentration, and occupant exposure are simulated for the six releasing scenarios. A sensor system is designed using the Matlab GA optimization toolkit (Mathworks, 2004) after the simulation. The selection of sensor quantities and location(s) for a fixed sensitivity are discussed in Sec. 4.2.1. For other sensitivities, sensor quantities and location(s) are discussed in Sec. 4.2.2.

4.2.1 Sensitivity = 0.03 mg/m^3

The first case discussed here is when the sensor sensitivity is a fixed value, such as 0.03 mg/m^3 (portable sensor, $7500 each (IMMRC, 1999). Because there are many locations where the contaminant concentration is higher than the sensitivity after one minute, the minimum detection time is one minute when the sensor quantity is large enough. The sensor quantity is originally set at six because six releasing scenarios are considered. When the sensor quantity is six, many sensor location design exist that will provide a minimum detection time of one minute for all six releasing scenarios. Table 1 summarizes some location combinations (refer to Fig. 7 for zone number). The total number of sensors can be reduced to two while still ensuring the detection time to be under one minute (Table 1). Using minimum detection time or minimum occupant exposure as the objective function yields similar results, when the total number of sensors is larger than one. When the sensor quantity is reduced to two, the sensor arrangement is unique in order to achieve a detection time of one minute. If the sensor quantity is further reduced to one, there would be at least one releasing scenario when the minimum detection time is two minutes, no matter which location is selected. However, at this time, using occupant exposure would yield a design that provides a minimum occupant total exposure. In order to maximize building protection, a specified detection time, such as two minutes, may be required. Therefore, in the case of only one sensor, using occupant exposure as the objective function yields the better sensor system design because it minimizes the total occupant exposure for all six releasing scenarios.

4.2.2 Other sensitivities

When the sensitivity of the sensor is lowered, i.e., the detection threshold is higher, not only does the false positive rate decrease but the cost of the sensor decreases as well. Therefore, sensors with lower sensitivities are examined in this study in order to observe the effect of this parameter on the design of the optimal sensor system. In general, lowering the sensitivity increases the minimum number of sensors that are needed to guarantee a specified detection time. Thus, in this study where there are a total of six possible releasing scenarios, a minimum of six sensors is needed to guarantee a detection time of one minute, when the sensor sensitivity is lower than 0.03 mg/m^3. The sensor location design using a total of six sensors is not unique. However, as sensor sensitivity decreases further, the possible locations where the sensors can be optimally located are also reduced until an extreme case is met when the sensor sensitivity is the same as the initial contaminant releasing strength. For this extreme case, the sensor has to be placed in the same zone as the releasing location. Hence, six would be the maximum sensor quantity for this study since six releasing scenarios are simulated.
Both sensor quantity and sensitivity affect detection time and occupant exposure. Likewise, the relationship between these design parameters, sensor quantity and sensitivity, and the cost of a sensor system is most likely non-linear and is thus currently not well defined. If this relationship were known, the sensor system which both maximizes protection and minimizes the system cost could be chosen.

5. CONCLUSION

Indoor contaminant sensor system design to protect a building from CBW attack is discussed in this study. Contaminant concentration and occupant exposure are simulated using a multi-zone air flow model, for six contaminant releasing scenarios. GA is used to optimize the sensor system using either minimum detection time or minimum occupant exposure as the objective function. Sensor sensitivity, quantity, and location are considered when optimizing the sensor system with cost constrictions. In this study, six sensors guarantee a detection of one minute under six releasing scenarios. However, the sensor quantity could also be lowered to two while still maintaining a detection time of one minute, when sensor sensitivity is 0.03 mg/m^3. For any given sensitivity, a minimum sensor quantity that achieves the same minimum detection as using more sensors does in fact exist. Lowering the sensor sensitivity increases the minimum number of sensors needed throughout the building. If the total sensor quantity chosen is less than this minimum sensor quantity, the desired detection time cannot be guaranteed because lowering the sensitivity raises the threshold at which the sensor begins to detect. It is also found that occupant exposure is a better objective function used to identify the locations which will minimize both detection time and total occupant exposure.

6. FUTURE WORK

The selection of sensor quantity and location in this study were based on the air flow and contaminant dispersion results from a multi-zone model. It is desired to compare the sensor system designs when using multi-zone model, zonal model, and CFD model approaches.

Design of a sensor system in this study was comprised of sensors that exhibited identical characteristics, such as type and sensor sensitivity. The possible benefit of incorporating sensors with varying characteristics into a single sensor system is another area for future research. Furthermore, the overall performance of a CBW sensor, as mentioned in "Introduction", includes twelve characteristics, and all of them should be considered when embarking on sensor system design.

While the authors chose two objectives for the sensor system design, to minimize detection and occupant exposure, other objectives for other building types exist, such as after CBW agent release, at what point is the building safe to allow occupants to re-enter. Establishing design objectives leads to future work in developing strategies to evaluate the performance of sensor systems.

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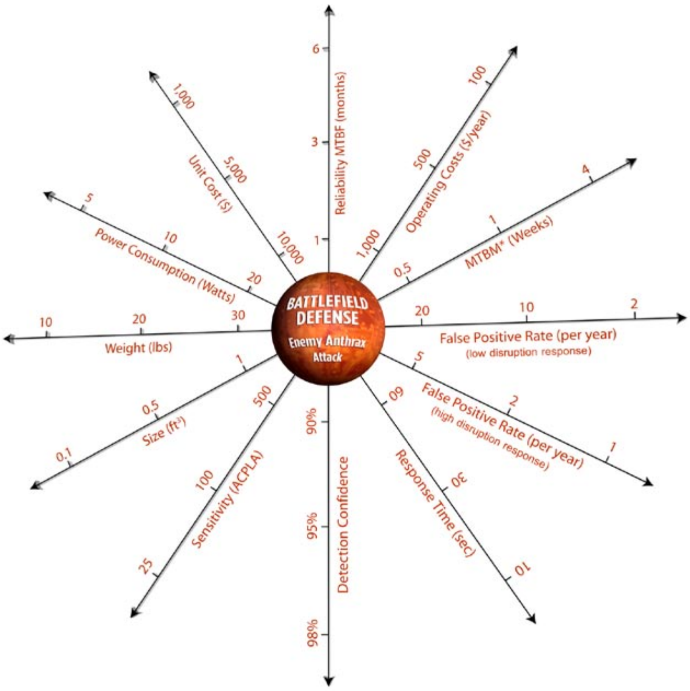
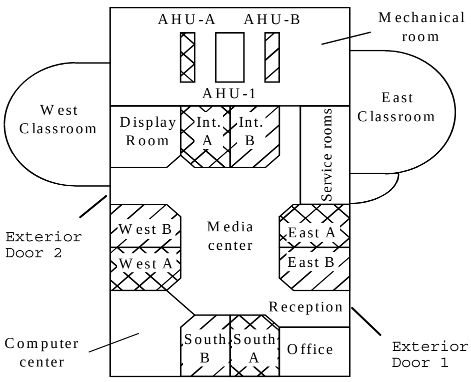


Figure 1 Overall performance of a CBW sensor (Carrano, 2004)



Room	Net floor area, ft²	Ceiling height, ft	Plenum height, ft	Exterior wall, ft²	Window area, ft²
Test Room A and B					
Interior	267	8.5	5.5	0	0
West	267	8.5	5.5	137	74
East	267	8.5	5.5	137	74
South	267	8.5	5.5	137	74
General Areas					
Mechanical	1764	14.0	0.0	1080	0
Storage	90	14.0	0.0	294	0
Communications	66	14.0	0.0	88	0
Electrical	110	14.0	0.0	119	0
Service rooms	390	8.0	6.0	499	0
Display room	316	8.5	5.5	0	0
East Classroom	769	9.0	1.0	762	70
West Classroom	769	9.0	1.0	762	70
Vestibule (west)	85	8.5	5.5	125	30
Vestibule (east)	36	8.5	5.5	33	30
Media center	1888	10.0	4.0	0	0
Reception area	178	8.5	5.5	75	40
Office	197	8.5	5.5	238	136
Computer center	415	8.5	5.5	383	197

Figure 2 Simulated building: Iowa Energy Center Energy Resource Station (Price and Smith, 2000)

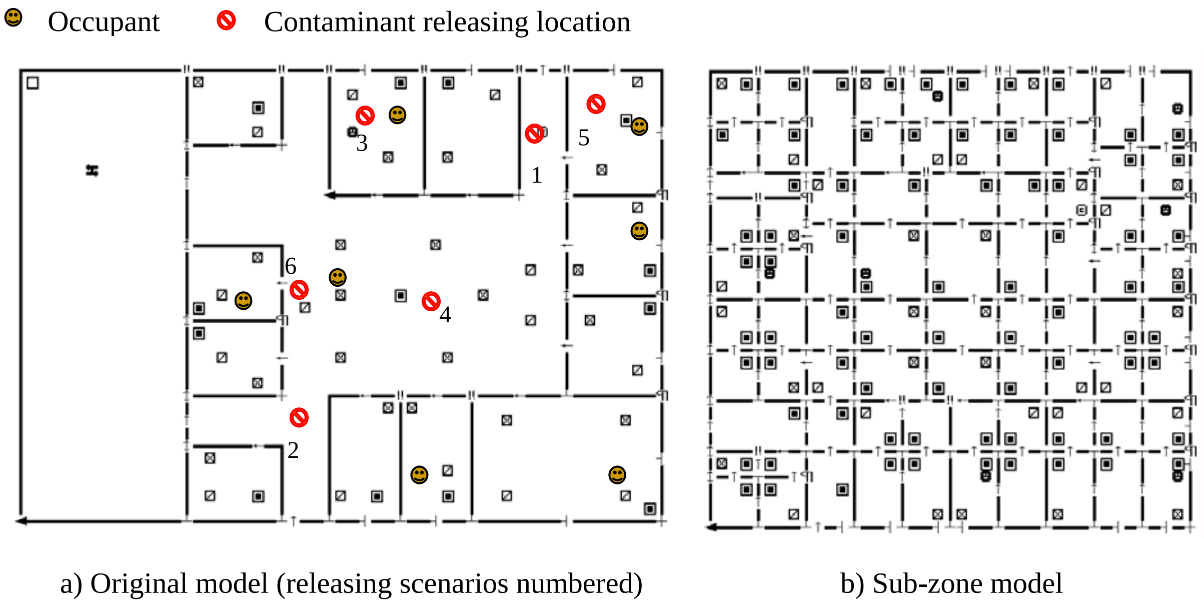


Figure 3 Building model in CONTAM

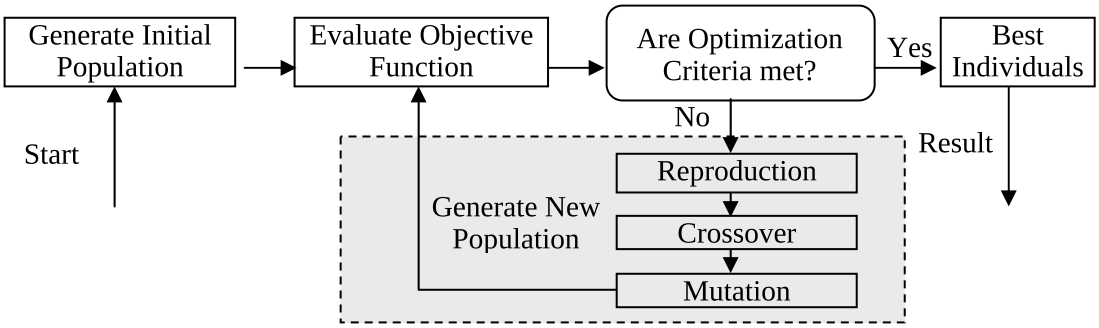


Figure 4 GA flow chart

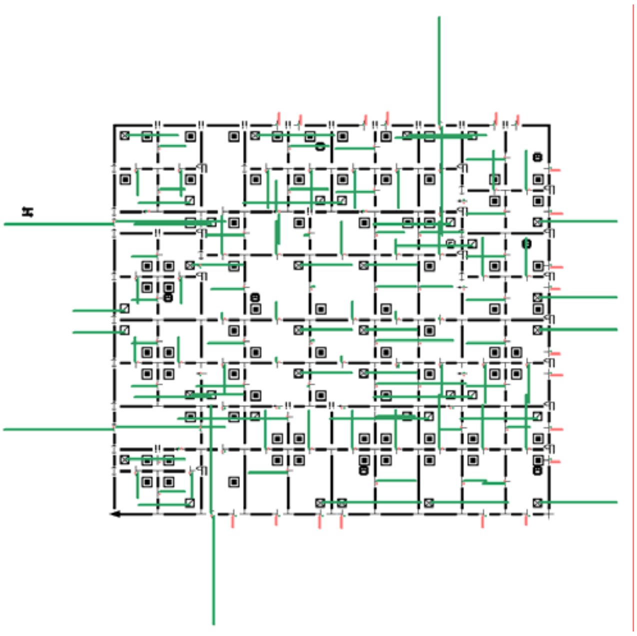
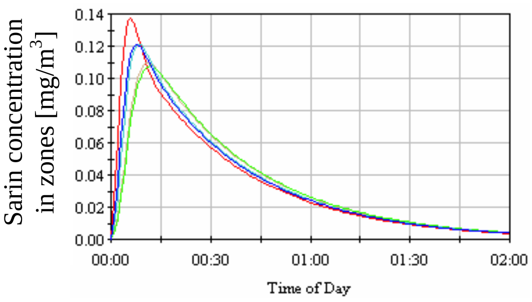
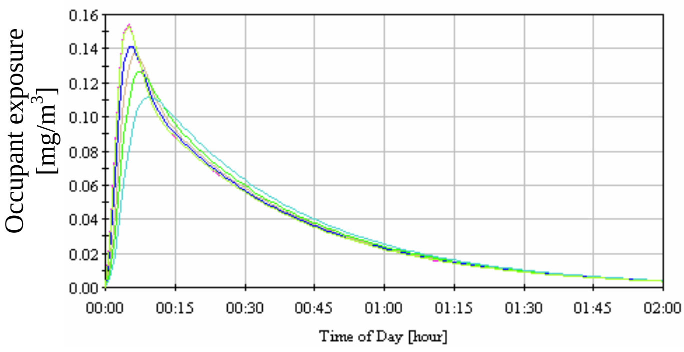


Figure 5 Air flow rates through airflow paths

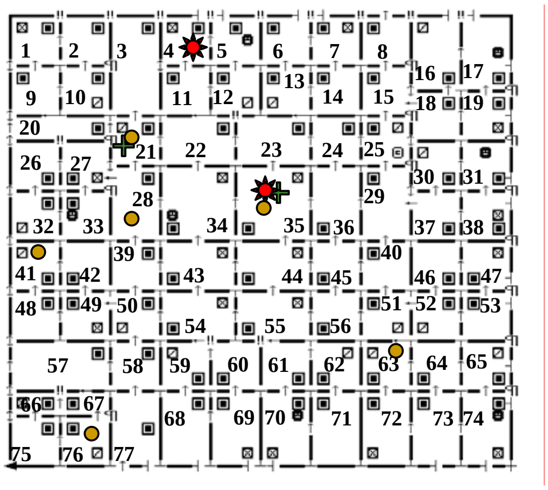


a) Contaminant concentration in zones 18, 24, 29, 30, and 36



b) Occupant exposure for all occupants

Figure 6 Contaminant concentration and occupant exposure for releasing location 1



Note: Symbols indicate sensor location for various sensor quantities

Figure 7 Sensor location design

Table 1 Sensor design for sensor with 0.03 mg/m^3 sensitivity

Quantity	Detection Time	Objective	Location
6	1 min	D or E	28, 21, 35, 41, 63, 76
6	1 min	D or E	1, 12, 21, 29, 42, 61
6	1 min	D or E	8, 22, 28, 52, 59, 62
2	1 min	D or E	21, 35
1	2 min	D	35
1	2 min	E	4

Note: "D" is detection time; "E" is occupant exposure