Contam airflow models of three large buildings: Model descriptions and validation

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Overview

Airflow and pollutant transport models are useful for several reasons, including protection from or response to biological terrorism. In recent years they have been used for deciding how many biological agent samplers are needed in a given building to detect the release of an agent; to figure out where those samplers should be located; to predict the number of people at risk in the event of a release of a given size and location; to devise response strategies in the event of a release; to determine optimal trade-offs between sampler characteristics (such as detection limit and response time); and so on. For some of these purposes it is necessary to model a specific building of interest: if you are trying to determine optimal sampling locations, you must have a model of your building and not some different building. But for many purposes generic or "prototypical" building models would suffice. For example, for determining trade-offs between sampler characteristics, results from one building will carry over other, similar buildings. Prototypical building models are also useful for comparing or testing different algorithms or computational approaches: different researchers can use the same models, thus allowing direct comparison of results in a way that is not otherwise possible.

This document discusses prototypical building models developed by the Airflow and Pollutant Transport Group at Lawrence Berkeley National Laboratory. The models are implemented in the Contam v2.4c modeling program, available from the National Institutes for Standards and Technology. We present Contam airflow models of three virtual buildings: a convention center, an airport terminal, and a multi-story office building. All of the models are based to some extent on specific real buildings. Our goal is to produce models that are realistic, in terms of approximate magnitudes, directions, and speeds of airflow and pollutant transport.

The three models vary substantially in detail. The airport model is the simplest; the convention center model is more detailed; and the large office building model is quite complicated.

We give several simplified floor plans in this document, to explain basic features of the buildings. The actual models are somewhat more complicated; for instance, spaces that are represented as rectangles in this document sometimes have more complicated shapes in the models. (However, note that the shape of a zone is irrelevant in Contam). Consult the Contam models themselves for detailed floor plans.

Each building model is provided with three ventilation conditions, representing mechanical systems in which 20%, 50%, or 80% of the building air is recirculated and the rest is provided from outdoors. Please see the section on "Use of the models" for important information about issues to consider if you wish to modify the models to provide no mechanical ventilation or eliminate provision of outdoor air.

Use of the models

The convention center model and the office building model have both been adjusted to roughly match experimental data. They produce airflows and pollutant dispersion rates that are in line with what can be expected in buildings of their type. The airport model, though not checked against experimental data, was created using parameters and modeling methods known from the convention center model (and other experience) to also produce realistic airflow and pollutant transport. There are, however, some important issues to understand when exercising the models.

1. Modeling effort focused on the rooms, ducts, and other elements that we feel are of most interest to intended users of the models. Exercise caution if you wish to use model results that depend on unusual pollutant release locations, or rely on predictions of concentrations in unusual spaces. For example, some of the rooms in the basement of the large commercial building were not monitored experimentally, nor did we devote substantial modeling effort to making sure that the airflows into or out of all of those rooms are realistic. In short, there may be some rooms in which we have not achieved our goal of generating realistic predictions of air flow rates.
2. The building models have been adjusted and checked so that the air flow rates and pollutant dispersion rates are realistic – that is, in a range that could occur in a real-world building – in the three ventilation conditions that we provide for each building (with the possible exception of flows in some normally unoccupied rooms or mechanical spaces as discussed in item 1, above). If a user wishes to modify the ventilation conditions substantially then they should carefully check the results and the model. This is especially true if buildings are to be simulated with Heating, Ventilating, and Air Conditioning (HVAC) systems turned off: In the present models, the dominant drivers of transport are flows driven by the HVAC systems, whose effects we believe we have modeled adequately. We have also imposed some mixing (which will occur even if HVAC systems are modeled as being turned off) between some adjacent zones, but we do not expect the models to make predictions in the HVAC-off case that are as realistic as in the case of normal HVAC operation. A modeler who wishes to consider pollutant transport with the ventilation system turned off, or turned down to provide very low flow rates, should consider modifying the models to ensure that they generate realistic flow rates across doorways and between zones. This can be done by

either imposing mixing between zones --- as is done with the "virtual zones" discussed below --- or by imposing temperature differences (and therefore pressure differences) between zones. Also, external driving forces should be modeled with care, since the interaction of wind with the building will become much more important with the HVAC system off.

Simulating pollutant releases

By default, each model building assumes the release of two contaminants:

(1) Inert gas with molecular weight 146 (which matches sulfur hexafluoride), released at a rate of 50 grams per minute.
(2) Particles of 1 micron diameter, density of 1 kg/liter (which matches water), released at a rate of 50 milligrams per minute. This particle size was chosen to allow comparison of the Convention Center model to experimental data, since the experiments used 1-micron particles.

There is no loss mechanism for the inert gas, other than ventilation.

Particles are removed by ventilation, filtration, and a first-order decay rate (which simulates the effect of deposition). With respect to filtration, every air handler has a supply filter that has removal efficiency 0.3 for particles of 1-micron diameter. To simulate deposition, particles are subject to a first-order decay rate of 2×10^{-5} per second.

The default release location for the Convention Center is the center of the prefunction space / mezzanine.

The default release location for the large office building is the first floor lobby.

The default release location for the airport is the Terminal 1 baggage and ticketing area.

The gas and particle release each has its own release schedule. By default, the schedules are identical: each starts at t=0 of model run, and lasts for 20 minutes.

Convention Center model

The Convention Center model encompasses about 1 million square feet of floor area (93,000 square meters), including 800,000 square feet (74,000 square meters) in large rooms and exhibit halls. The model building has four large ground-floor halls that share a single multi-story mezzanine, as well as two additional floors with smaller meeting rooms, offices, and hallways. The model is based on a real building, in which tracer-gas experiments were performed. We first built a model of the real building and adjusted it to match the experimental data, and then modified the model, eliminating some unusual features of the convention center and thereby making it more generic.

Building Description
A simplified floor plan is shown in Figure 1.

The model includes four first-level Exhibit Halls: 670,000 square feet total (62,000 square meters), divided as follows:

- One large hall, 220,000 square feet (20,500 square meters)
- Three smaller halls, each 150,000 square feet (14,000 square meters)

All have ceiling height 23 ft (7 meters).

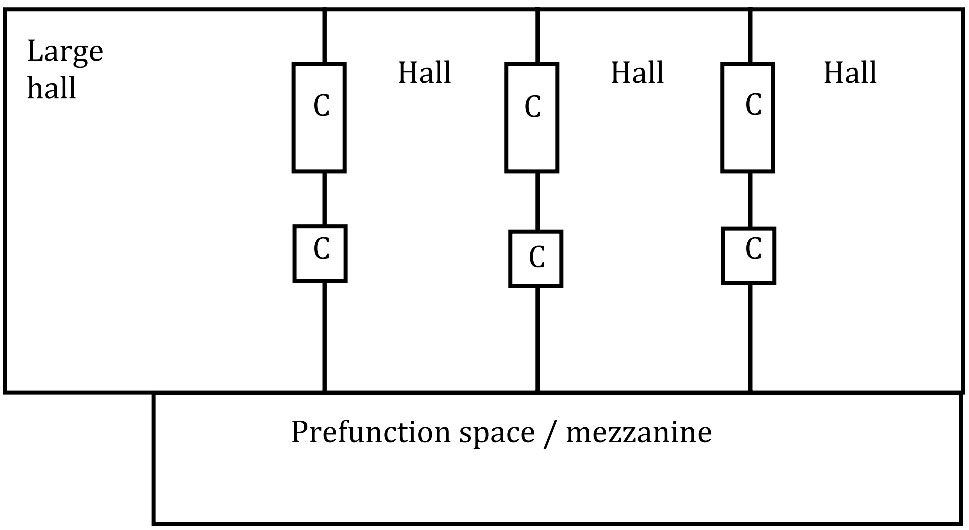

Figure 1: Stylized view of the first floor of the convention center model. Between each pair of halls are a large and a small courtyard, labeled “C”.

Outside the exhibit halls is a tall, wide mezzanine known as “prefunction space.” The prefunction space covers 72,000 square feet (6700 square meters).
The ceiling height is 50 feet (15 meters).

There are several second-floor meeting rooms, totaling 65,600 square feet (6,100 square meters).
Hallways and other prefunction space on the second floor total 51,000 square feet (4,700 square meters).
Second-story ceiling height is 10 ft (3 m).

Third-level meeting rooms total 54,000 square feet 5,000 square meters).
Third-level prefunction space totals 30,000 square feet (2,800 square meters).
Third-floor ceiling height is 10 feet (3 meters).

There are courtyards between the exhibit halls: there is one large courtyard and one small courtyard between each pair of adjacent halls (for a total of three large courtyards and three small).

HVAC systems
All of the dozens of model zones that are connected to the HVAC system are served by "simple" air handlers – a Contam model element that does not require specifying ductwork to convey air between the air handling unit and the zones that it serves. Each air handler has a supply filter, with 0.3 filtration efficiency for particles of 1 micron diameter (see the section that discusses default pollutant releases).

The largest exhibit hall has ceiling-level supply and return registers.

The three smaller exhibit halls have large return grilles on the walls, immediately at the return fan inlet. The supply and return system works differently in the portions of the exhibit halls nearest the mezzanine: in those areas, there are ceiling-level supplies and returns. This HVAC configuration matches the real building on which the model is based.

The second and third floors have plenum returns.

The mezzanine has supply and return at each occupied floor.

Doors
All doors are modeled as closed, which matched the experimental conditions. There is assumed to be 100 square centimeters leakage area around each door.

Airflow modeling of large interior spaces
All of the large spaces (> 10,000 square feet) are subdivided into virtual zones. For instance, each of the exhibit halls is divided into 22 to 24 zones. These zones have no real-world counterpart: there are no walls or dividers. Each zone has at least one supply register, but not all zones have returns. The virtual zones are necessary because, under the fully-mixed assumptions of the model, using a single extremely large zone would lead to instantaneous mixing of tracer gases or pollutants through the entire exhibit hall, which is obviously unrealistic and would lead to predicted transport times much shorter (faster) than occur in reality.

Hallways and the mezzanine are also broken into virtual zones for the same reason.

The mezzanine is divided into virtual zones both horizontally and vertically. Horizontal divisions are such that there is a zone at the height of each occupied level, as well as one at the height of each plenum. Thus the mezzanine has five layers of virtual zones, with the bottom of the zones corresponding to the floor of Level 1, floor of Level 2, bottom of the plenum of Level 2, floor of Level 3, and the bottom of the plenum of Level 3).

Each virtual zone is coupled to all of the adjacent zones using two “fan and forced flow” elements, one blowing in and one blowing out of the zone, to simulate the natural mixing of flow within the room. Additionally, an “orifice” element connects all pairs of adjacent virtual zones, allowing one-way flow with a power-law relationship between pressure and flow rate. The orifices allow the model to adjust for unbalanced supply and return flows. Orifice flows turned out to be small compared to the mixing flows in almost all cases.

Operating Conditions
The convention center model is provided with three different HVAC operating conditions.

1. Mild weather (cool outdoor temperatures); Exhibit halls provided with 20% outdoor air, 80% recirculation.; The rest of the building provided with 80% outdoor air, 20% recirculation (economizer mode). This was the situation in which the real-world experiments were conducted, and for which model-measurement comparisons are discussed below.
2. Entire building provided with 20% outdoor air, 80% recirculation.
3. Entire building provided with 80% outdoor air, 20% recirculation.

The model assumes zero wind speed, and both indoor and outdoor temperature of 20 C.

Model-Measurement Comparison
A series of experiments was conducted in the building on which the model is based. Tracer gases were released simultaneously at several locations, and the tracer gas concentrations were measured as a function of the time elapsed since the release, at multiple measurement sites. Each pair of (release location, sampler location) generates a series of measurements of concentration versus time. Each of these can be compared to time series predicted by the model for the same release location and sampler location.

A subset of the data is presented in Figures 2 - 4. Each figure shows data from a different experiment. Each small plot shows concentration versus time, with time measured from the start of the tracer gas release. Measured data are shown with solid dots, and predictions are shown with smooth curves. Each row shows the concentration of a tracer gas that was released at a different location (i.e., row 1 shows the concentration of the gas that was released at location 1, row 2 shows the concentration of the gas that was released at location 2, and so on). Within a row, each plot shows the concentration at a different sampling location. In each row, the first column shows the concentration observed and predicted at a sampling point close to the release; other columns in the row show results from other sampling locations throughout the building.

For security reasons, we do not identify the zones represented in each plot, nor do we reveal the release concentration. Doing so would allow people to easily determine, quantitatively, how quickly and in what concentrations the release of a chemical or biological agent would spread to different areas of the building on which the model is based, should they be able to identify the building from its description.

Even without the zones being identified, though, the plots are useful inasmuch as they allow both qualitative and quantitative evaluation of the degree of model fit, and the ways in which the model fails to fit. In most (but not all) zones, the amount of time between the start of the release and the peak concentration in the zone is predicted within 50%; the peak concentration is predicted within a factor of three or better; and the time for the concentration to fall from its peak to 10% of the peak value is predicted within 30%.

This level of agreement is entirely satisfactory: the intent of the model is to provide predictions of behavior that are realistic enough that they can be used to test or compare algorithms for sampler placement, risk evaluation, and so on. To serve these purposes, a highly accurate model of a specific building is not required.

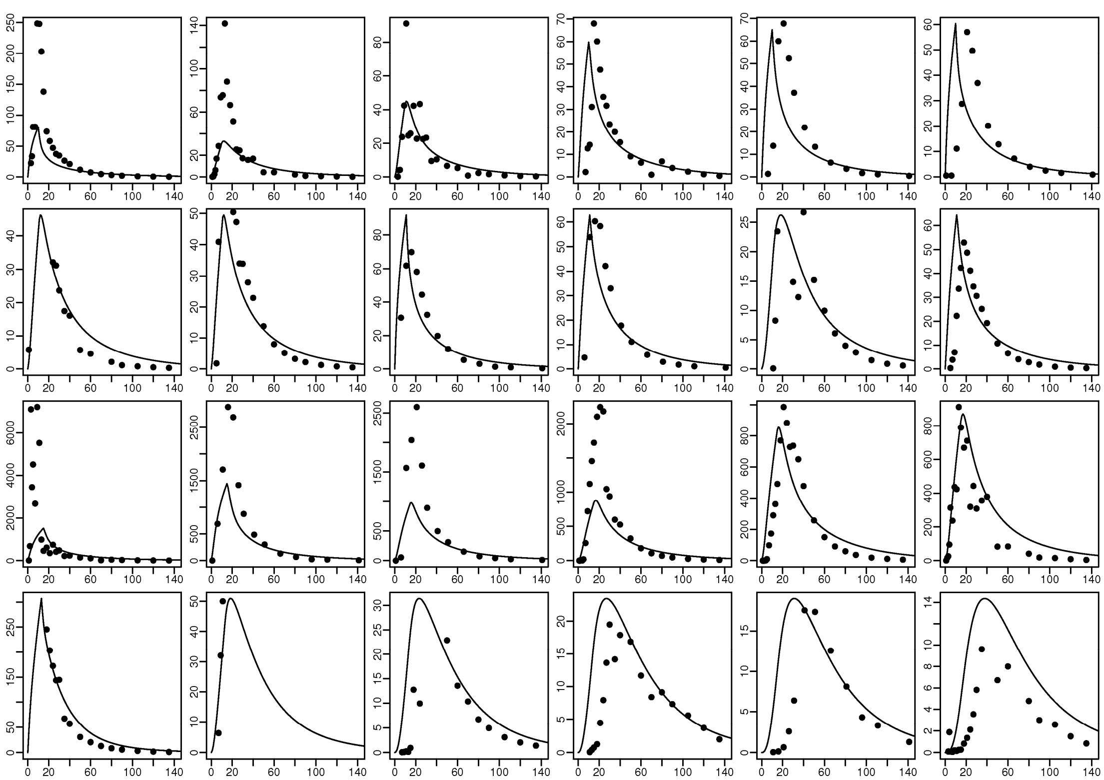

Figure 2: Predicted (lines) and measured (dots) tracer gas concentration vs. time. Each plot shows data from a different room. Each row shows data from a different tracer gas release location. All of these plots show data from a single experiment in which multiple tracer gases were simultaneously released from different locations.

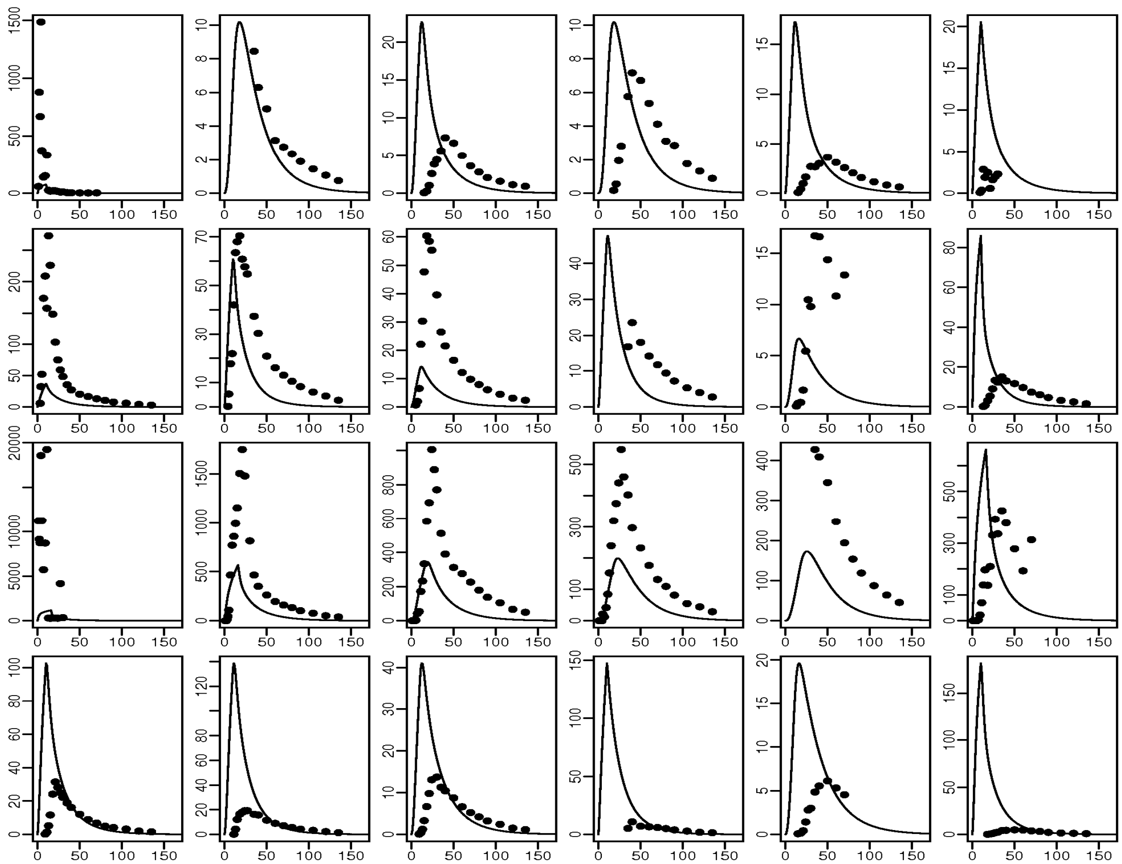

Figure 3: This figure is similar to the previous one, but data are from a different experiment and the plot shows results from sampler locations that differ from those in the previous figure. Predicted (lines) and measured (dots) tracer gas concentration vs. time. Each plot shows data from a different room. Each row shows data from a different tracer gas release location.

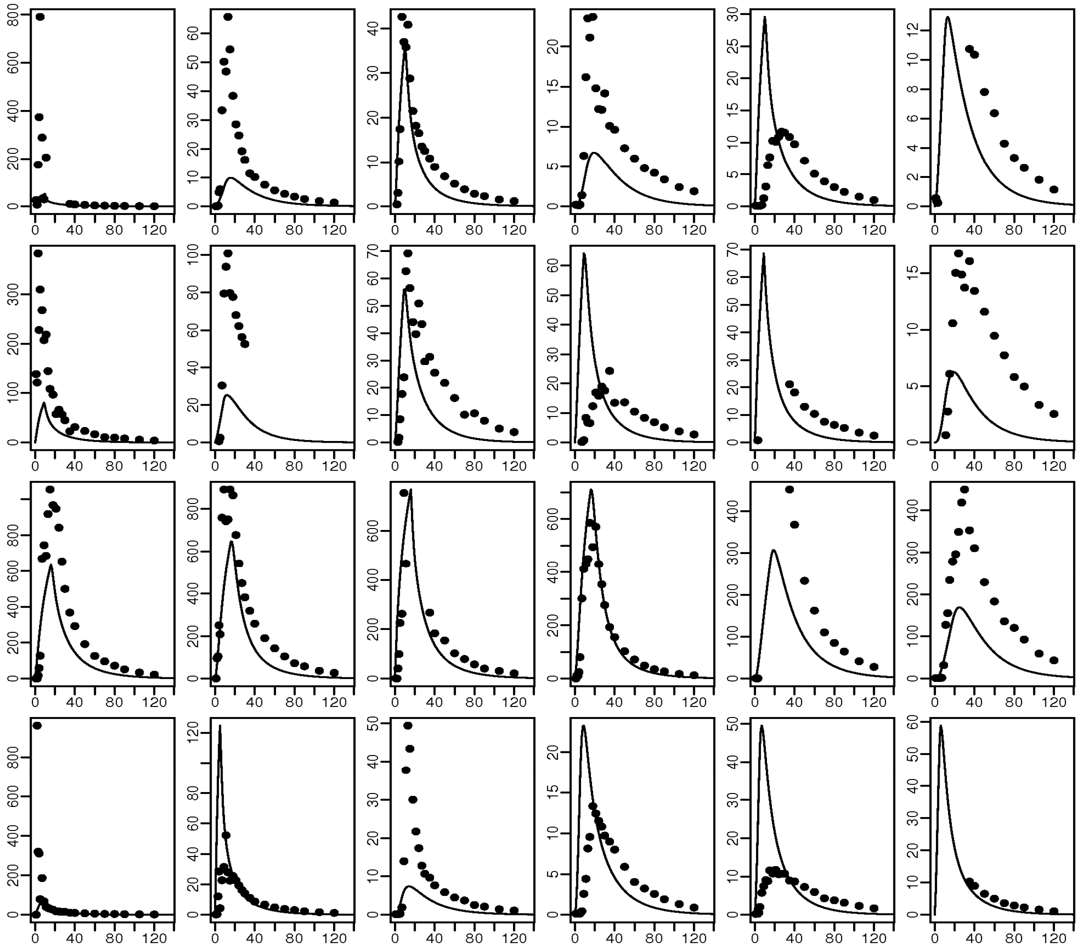

Figure 4: This figure is similar to the previous one, but data are from a different experiment and the plot shows results from sampler locations that differ from those in the previous figure. Predicted (lines) and measured (dots) tracer gas concentration vs. time. Each plot shows data from a different room. Each row shows data from a different tracer gas release location.

Office Building Model

Building Description

The model office building has 33 stories in addition to a basement, for a total of 1 million square feet (93,000 square meters) of floor area, of which 720,000 square feet (67,000 square meters) are usable, i.e. not occupied by mechanical systems, elevators, or stairwells. Each lower floor has an area of about 47,000 square feet (4,400 square meters); above the 9th floor, the floor area at each level is about 30,000 square feet (2,800 square meters); and each of floors 30-33 occupy about 19,000 square feet (1,800 square meters).

The 10th, 11th, 22nd, and 33rd floors are unoccupied (and unconditioned) mechanical spaces.

Each floor consists of a central core of elevator shafts, stairwells, bathrooms, and mechanical shafts, surrounded by open-plan offices. Figure 5 shows one example, for the second and third floor. However, the details vary from one set of floors to the next. For instance, although the second and third floors have the same floor plan, the fourth floor differs from them.

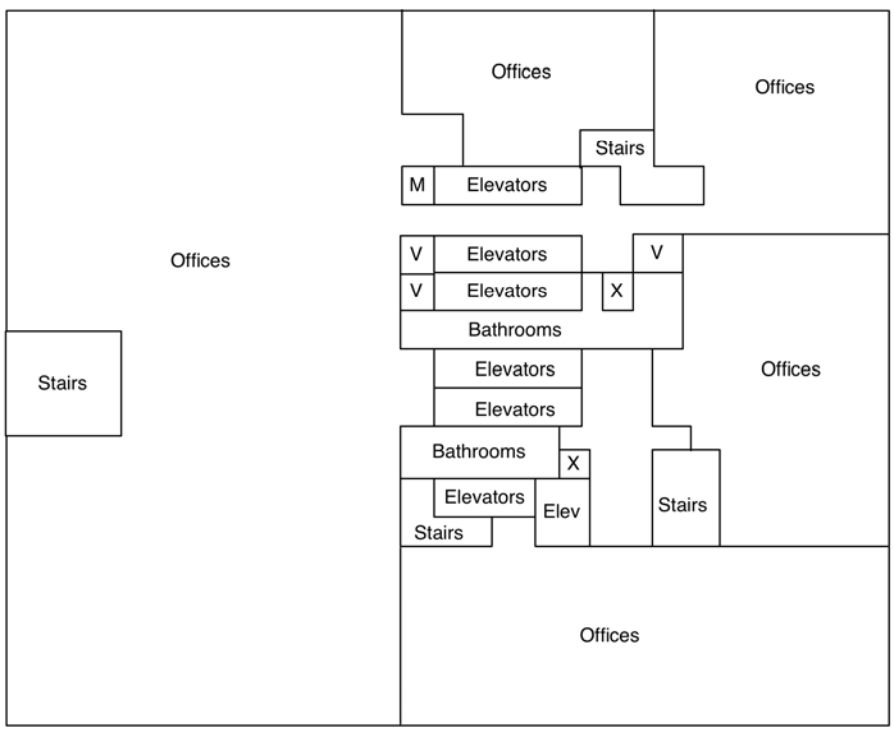

Figure 5: Floor plan (not to scale) of the second and third floor of the office building model. M represents a “mechanical” shaft (cables, pipes, etc.); V represents a ventilation shaft; X represents a bathroom exhaust shaft.

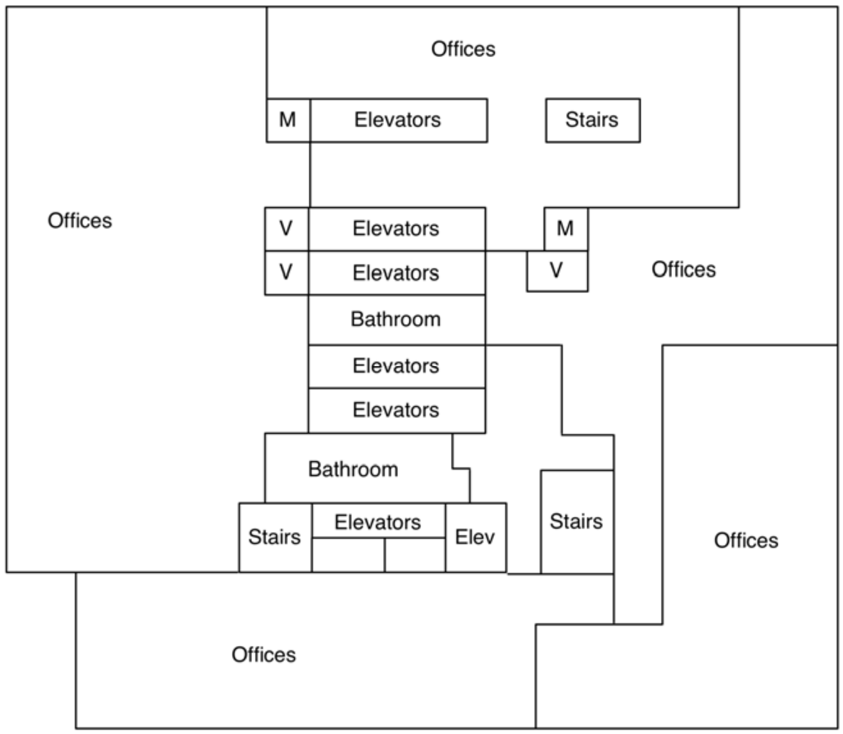

Figure 6: Floor plan (not to scale) of the 8th through 22nd floor of the office building model. M represents a "mechanical" shaft (cables, pipes, etc.); V represents a ventilation shaft. Unlabeled space is divided by walls differently on the 8th through 22nd floors, this figure shows the situation for one of the floors.

Elevators

There are three sets of elevator shafts:

1. "Low-rise" elevators stop at all floors from the basement through then 9th floor.
2. "Mid-rise" elevators stop at the 1st through 17th floors, but not at the unoccupied tenth floor.
3. "High-rise" elevators stop at the 1st, 9th, and 18th through 32nd floors, but not at the unoccupied 22nd floor.

Each shaft has doors only onto the floors at which it stops.

The elevator shafts are modeled with one zone per floor per bank of elevators, with forced vertical two-way air flow of 5,000 cubic feet per minute (cfm) between adjacent zones in the shaft, and forced airflow of 1,000 cfm between the shaft and the adjacent hallway on each floor. This mixing is applied in order to crudely model two real-world effects: (1) the elevator shafts allow transport of air between floors, driven by motion of the elevators and by the stack effect; and (2) the elevators themselves carry air between floors.

HVAC system
AHUs in the basement supply air to the basement and first floor. AHUs on the 10th floor supply air to the 2nd through 9th floors (inclusive). AHUs on the 22nd floor supply air to the 10th through 32nd floor. Each air handler has a supply filter, with 0.3 filtration efficiency for particles of 1 micron diameter (see the section that discusses default pollutant releases).

On each level, ducts carry return air to vertical return shafts. These shafts lead to one of the equipment floors, where the air handling units (AHUs) are located. Ducts then connect the shafts to the AHUs. Ducts carry air from the AHUs to vertical supply ducts, which feed the individual floors. Dampers control the amount of exhaust, intake of outside air, and mixing of outside air with return air. A schematic of an air handling unit is shown in Figure 7. A fan cannot be directly connected to a duct in Contam, so the model implements a slightly different scheme, shown in Figure 8.

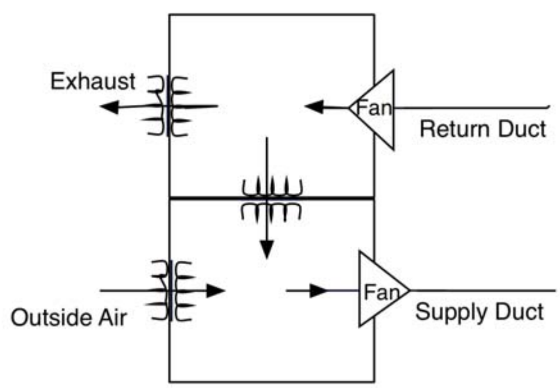

Figure 7: Schematic diagram of an air handling unit, showing exhaust, supply, and mixing dampers.

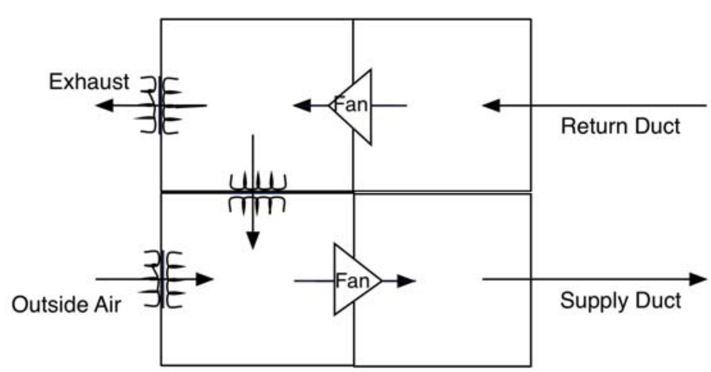

Figure 8: Diagram showing how an air handling unit is represented in the model.

Doors and Other Connections
All doors were modeled as closed, which matched the experimental conditions. We assume that all doors except stairwell doors allow two-way flow of 50 cubic feet per minute in each direction, in addition to pressure-driven flows through a crack of 500 square centimeters for double doors, or 125 square centimeters for single doors. The two-way flow is intended to represent flows caused by people occasionally opening and passing through the doors, as well as flows caused by temporary pressure changes within spaces due to factors that are not or cannot be included in the model (e.g. due to motion of people in rooms).

Connections between large zones, such as adjacent open-plan offices, are modeled as openings that provide 1000 cubic feet per minute (equivalent to a velocity of ~0.2 feet per second) of two-way flow, in addition to pressure-driven flows.

Operating Conditions

As with the convention center model, the office building model is provided with three sets of operating conditions:

1. Entire building provided with 50% outdoor air, 50% recirculation.
2. Entire building provided with 20% outdoor air, 80% recirculation.
3. Entire building provided with 80% outdoor air, 20% recirculation

There is no wind.

Unlike the convention center model, there is an indoor-outdoor temperature difference: the indoor temperature is 70 F (21 C), and the outdoor temperature is 95 F (35 C), to approximately match conditions during the experiments.

Model-Measurement Comparison
As with the Convention Center model discussed previously, we show how tracer gas transport predictions from the model compare with data from the building on which it is based, but we do not identify the locations of the samplers because this would allow someone to figure out the rate and concentration at which a chemical or biological agent would spread into specific parts of the building.

Figures 9 and 10 show predicted concentrations (curves) and measured concentrations (points) of tracer gases. Figure 9 shows concentrations resulting from one release location, and Figure 10 shows concentrations resulting from a different release location. In each case, measurements were made in many different sampling locations, including some on floors of the building far from the release point.

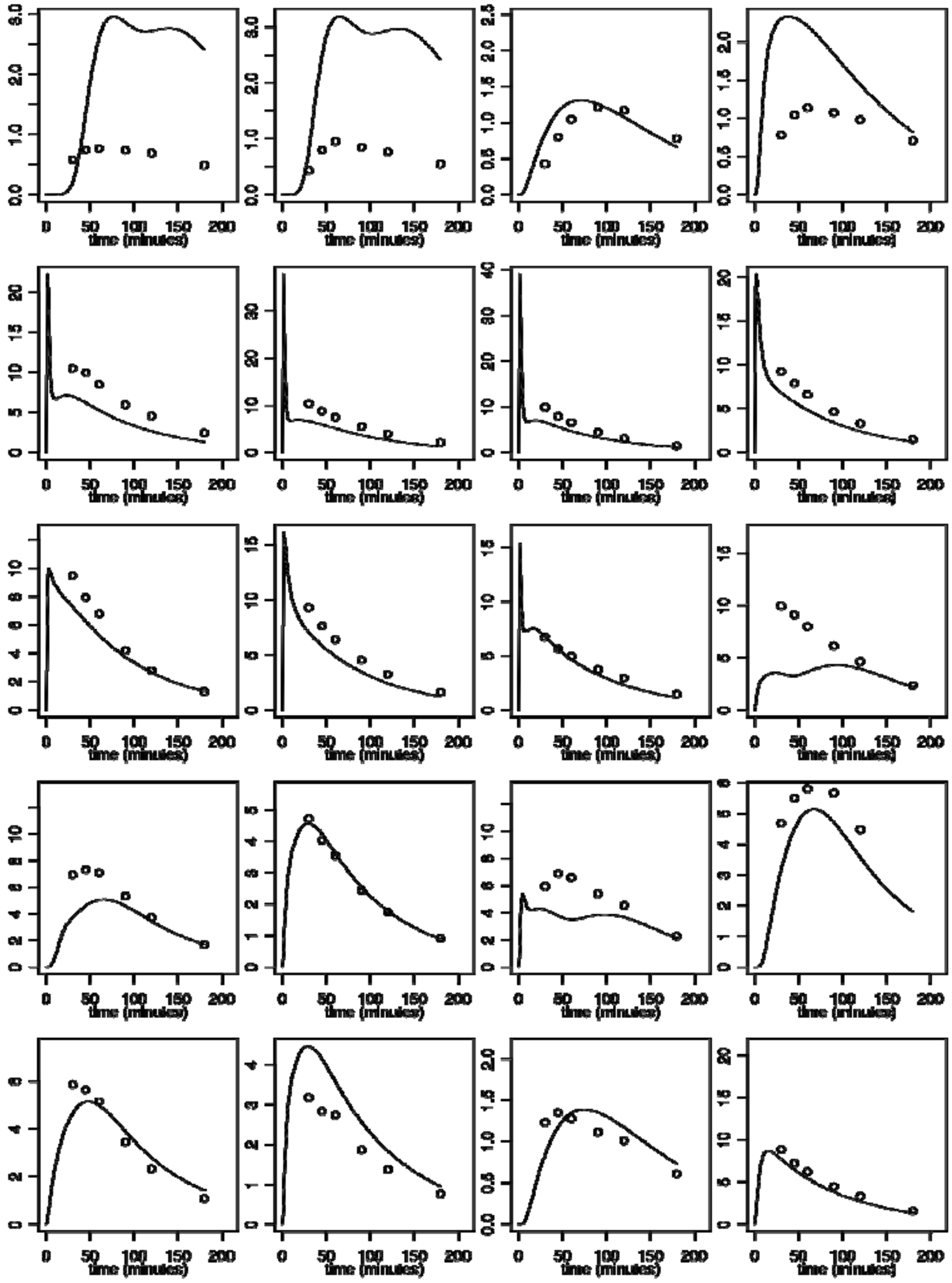

Figure 9: Predictions (lines) and measurements (points) of tracer gas concentration at different locations in the building, for a release from a single location.

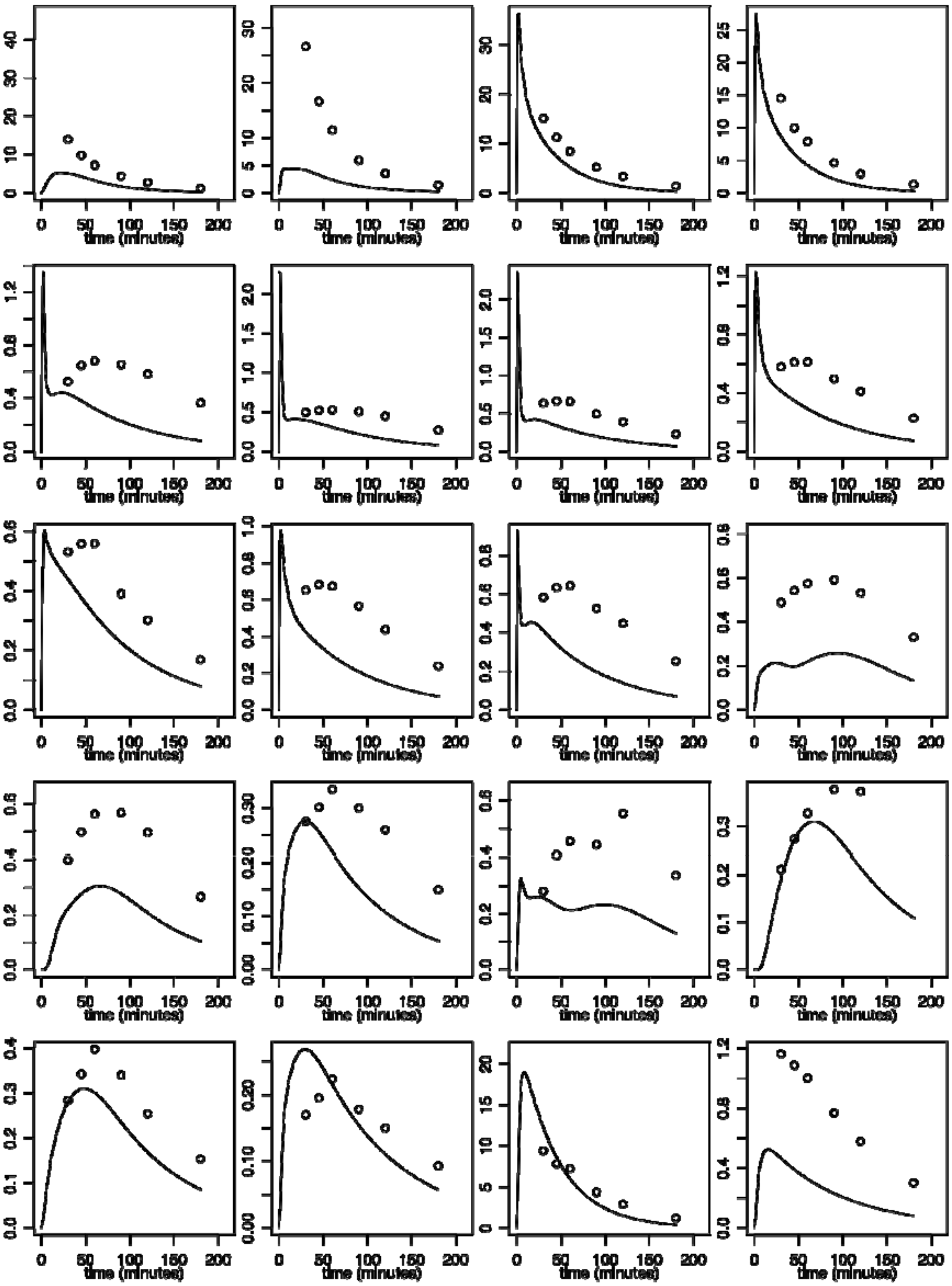

Figure 10: Predictions (lines) and measurements (points) of tracer gas concentration at different locations in the building, from a release from a single location. The release location is different from that in Figure 9.

As with the convention center model, predictions for the large office building are in reasonably good agreement with data: the predicted peak concentration in a zone is usually within a factor of three of the actual peak concentration, and the predicted time at which the peak will occur is generally within a factor of two of the time it actually took for the concentration to reach its peak.

Perfect agreement between experimental measurements and model predictions is neither expected nor necessary, since the point of the model is simply to provide a virtual building that behaves similarly to a real building.

Airport Model

Building Description

The airport model, which is based on a real airport, consists of two linked terminals as shown in Figure 11: an L-shaped terminal (Terminal 2) that is linked by a hallway to a linear terminal (Terminal 1). Each terminal has a large security area and baggage claim area; these total 50,000 square feet (4,600 square meters) in Terminal 1 and 77,000 square feet (7,200 square meters) in Terminal 2.

Each terminal has external doors that correspond to boarding gates: 13 doors in Terminal 1 and 15 in Terminal 2 (split between the two wings of that terminal).

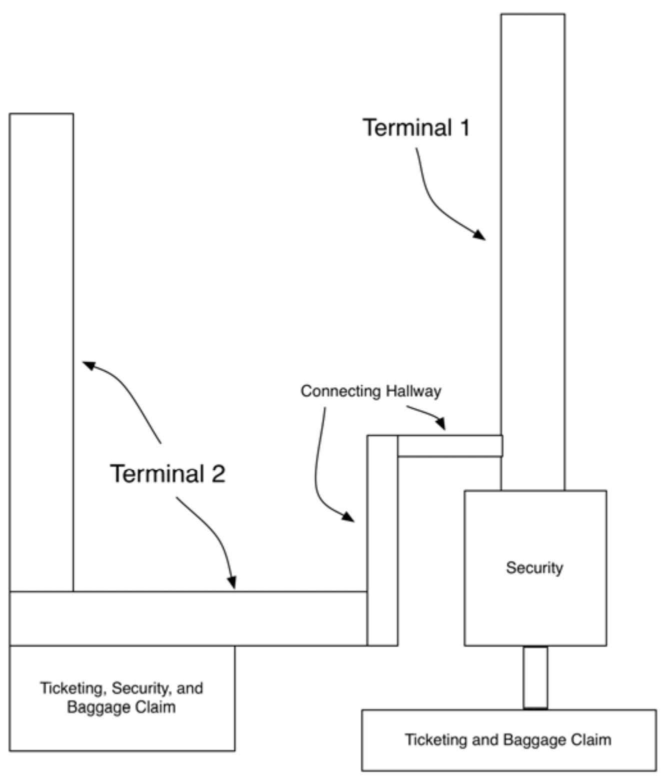

Figure 11: Simplified schematic (not to scale) of the model airport.

HVAC system
All model zones are served by "simple" air handlers – a Contam model element that does not require specifying ductwork to convey air between the air handling unit and the zones that it serves. There are 37 simple air handlers in the model; in a real airport, these could be either small roof-mounted units or mechanical room AHUs. Each air handler has a supply filter, with 0.3 filtration efficiency for particles of 1 micron diameter (see the section that discusses default pollutant releases).

Virtual Zones
Large connected spaces are divided into "virtual zones" and flows are specified between adjacent virtual zones, using the approach described in the Convention Center section.

Doors
The 37 boarding gate doors are scheduled in the model to alternate between open and closed, such that when one door is open the adjacent doors are closed. (I.e. first the odd-numbered gate doors are open, then the even-numbered). Doors switch from open to closed, or vice versa, every sixty minutes.

Operating Conditions
The indoor and outdoor temperatures are 20C. There is no wind.

Similarity to a Real Airport
The model is based on a real airport: the lengths and widths of the terminal hallways, the connectivity of the zones, the number of gates, and the operation of the HVAC systems all match the real buildings. However, the real airport (like most airports) has offices and other "backstage" spaces; these are not included in the model. In the real building, those backstage spaces are served by their own air handlers and are separated from the public spaces by doorways, so those spaces do not interact strongly with the public spaces that are included in the model. Such separation is present in some, but not all, other airports.

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