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Full paper

ESTIMATING INDOOR AIR QUALITY USING INTEGRATED 3D CAD BUILDING MODELS

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ABSTRACT

The indoor air quality (IAQ) in buildings is currently assessed by measurement of pollutants during building operation for comparison with air quality standards. Current practice at the design stage tries to minimise potential indoor air quality impacts of new building materials and contents by selecting low-emission materials. However low-emission materials are not always available, and even when used the aggregated pollutant concentrations from such materials are generally overlooked. This paper presents an innovative tool for estimating indoor air pollutant concentrations at the design stage, based on emissions over time from large area building materials, furniture and office equipment. The estimator considers volatile organic compounds, formaldehyde and airborne particles from indoor materials and office equipment and the contribution of outdoor urban air pollutants affected by urban location and ventilation system filtration. The estimated pollutants are for a single, fully mixed and ventilated zone in an office building with acceptable levels derived from Australian and international health-based standards. The model acquires its dimensional data for the indoor spaces from a 3D CAD model via IFC files and the emission data from a building products/contents emissions database. This paper describes the underlying approach to estimating indoor air quality and discusses the benefits of such an approach for designers and the occupants of buildings.

Keywords: Indoor air quality, 3D CAD, pollutants, ventilation, material emissions

1. INTRODUCTION

Current assessment of indoor air quality in buildings focuses on the measurement of pollutants to assess their compliance with recommended guidelines. At the design stage, experience is the main source of information for deciding on choice of materials on the basis of indoor air quality. There does not exist any model or tool which is specifically aimed at predicting the indoor air quality of a building at the design stage, yet a method/tool for predicting pollutants would assist designers in creating optimum indoor air environments. A method for predicting optimised indoor air quality and the use of appropriate performance measures are key prerequisites for developing a building code for indoor air quality, and to provide estimates of indoor quality from which environmental and occupant health consequences can be minimised.

In the Indoor Air Quality (IAQ) Estimator (Tucker et al 2007), the pollutant emission properties of major pollutant sources in offices are used to predict their impacts on indoor air quality. This prediction is made using a software tool for building designers so that they can select materials and appliances that, in combination, are sufficiently low emitting to prevent goals for indoor air pollution from being exceeded.

The principal objectives for IAQ Estimator were:

- To create a database of air pollutant emission rates for common large-area building materials and contents, focussing on typical examples of paints, adhesives, floor coverings, plasterboard, reconstituted wood-based panels, office furniture and copiers/printers;
- To utilise this database to estimate the effects of different ventilation scenarios on indoor air quality for a single zone of an office building in a 3D CAD model;
- To estimate the submicrometre particle levels and urban air toxics in mechanically ventilated office buildings for different levels of urban air particle pollution, particle emissions from copiers/printers, and ventilation system filter efficiency; and
- To integrate the above three factors for estimating indoor air pollutant levels within a building zone directly from the materials information available in a 3D CAD model or from information introduced manually.

2. INDOOR AIR POLLUTION

The primary sources of indoor air pollution in office buildings, as illustrated in Figure 1, are considered to be:

- Emissions from large-area building products,
- Emissions from office furniture and equipment, and
- Pollutants from urban air introduced by ventilation.

Emissions from large-area building products are Volatile Organic Compounds (VOCs) and formaldehyde from paints, floor covering systems, wall-boards (plasterboard and wood-based panels), and fixed furniture materials (structure and surfaces).

Emissions from office equipment are VOCs and submicrometre particles from operating office equipment, linked to the frequencies of operation of such sources in office buildings. Emissions from office furniture are typical emissions of VOCs and formaldehyde from office furniture such as work-stations.

Pollutants in ventilation air in mechanically ventilated office buildings are from outdoor urban submicrometre particle and air toxics pollution and are dependent on the ventilation flows in the enclosed space and efficiency of HVAC filtration.

It was considered that the IAQ Estimator must utilise a methodology for estimating indoor air pollution from key materials and contents through:

- Identifying the dominant volatile organic compounds and airborne particles present in indoor air in office buildings,
- Loading the building space (volume) at quantifiable ratios with materials and contents,
- Interfacing with pollutants introduced from outdoor air and the effect of HVAC filtration,
- Estimating the changing profile of emissions over time after construction, and
- Comparing the estimated pollutant levels with health-based criteria.

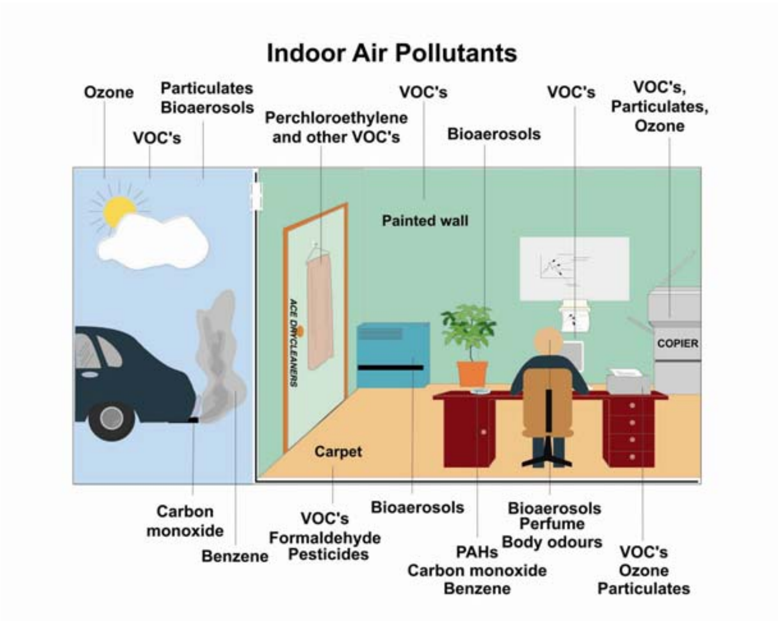

Figure 1 Primary sources of indoor air pollution

3. INDOOR AIR QUALITY MODELLING

A model for Indoor Air Quality in commercial buildings was developed by combining existing indoor air measurement, product emission and ventilation/filtration knowledge into a practical tool for estimating the indoor air quality of rooms/spaces over time. The estimated pollutants were for a single, fully mixed and ventilated zone in an office building.

Existing product emission models were considered and an approach was determined for the level of detail required for emissions into enclosed spaces. Goal levels of pollutant exposure were derived from Australian and international health-based standards. Pollutants were not included if such standards were unavailable.

3.1 Emissions to air from selected materials

A list of 20 key VOCs (including formaldehyde) was derived from existing knowledge of the VOC species found in Australian buildings and emitted from materials and appliances (Brown 1999 a,b,c; Brown 2002) . It was essential that a health-based environmental criteria existed for each (WHO 2000, NEPC 2007, ISIAQ 2004). The compounds and maximum concentration goals within IAQ Estimator are presented in Table 1. Available Australian air emission data for building and furniture products for these 20 key compounds were collated into a database of representative products. The building products for which low, typical and high emission examples were selected included:

- paints (zero emissions, low odour and acrylic, solvent-based) on plasterboard or other substrates;
- floor covering systems (carpet/underlay/low and high emitting adhesives, tile, wood panel floorboards, timber lacquer);
- wall boards (plasterboard and reconstituted wood-based panels, including MDF); and
- fixed furniture materials (shelf units, workstations).

Emissions from some products had to be measured where emission information was unavailable.

Table 1 Pollutants and goal values for IAQ Estimator tool

POLLUTANTS	IAQ Estimator Goal
VOCs:	(μg/m^3 unless stated)
Acetaldehyde	300
Benzene	60
2,6-Di-tert-butyl-4-methylphenol	500
1,4-Dichlorobenzene	800
1,2-Dichloroethane	700
Dichloromethane	1,100
Diethylene glycol ethyl ether	6,000
Ethylbenzene	800
Ethylene glycol ethyl ether	200
Formaldehyde	40
Isobutyl methyl ketone	500
Naphthalene	30
Phenol	300
Styrene	500
Tetrachloroethylene	100
Toluene	300
Trichloroethylene	150
Total VOC (TVOC)	500
m-/p-Xylene	300
o-xylene and o-/m-/p-xylene	300
Particles:	
PM2.5	25
PN1 Particles	5,000 particles/cc

3.2 Emissions from operating equipment

Emissions from one copier and several laser printers from the late 1990s were assessed previously and a chamber methodology for assessing such appliances was developed (Brown 1999a/b). One significant finding was that the emissions were related directly to the number of copy operations and could be quantified as pollutant mass per copy. It was found that:

- The copier and the new laser printers were very low emitting for ozone, while an old printer emitted significantly higher quantities;
- Emission of formaldehyde and nitrogen dioxide were low or below detection;
- Emissions of respirable particles were higher for laser printers than the copier;
- Emissions of VOCs were generally higher for the copier, and species showed some variation with manufacturer (aromatics were the most common VOCs); and
- The irritant and odorant nonanal was observed in the emissions from an old printer – this was probably a secondary emission formed from reaction of ozone and the aromatics in chamber air.

While the above presented a detailed assessment of office equipment of that period, digital copier technology was introduced soon afterwards, such that documents are scanned one time (instead of one scan per copy) and then reproduced in multiples as needed. Laser printer technology is believed to have remained similar since the late 1990s, relying on positive corona discharge (rather than negative discharge), a process that releases much lower ozone than negative discharge. However in a recent study of laser printer emissions, He et al (2007) have reported the emission of high numbers of sub-micrometre particles (0.02 to 1 micrometre diameter, which are referred to here as PN1) from some printers.

Thus, IAQ Estimator emission data for office equipment includes VOCs, respirable fine particles $PM_{2.5}$ (mass concentration of particles smaller than 2.5 micrometre cutpoint) and sub-micrometre particle numbers as PN1 from the studies described above (goals for the latter two are also presented in Table 1). However, since emission data was lacking for currently produced digital copiers, further assessment of these was undertaken. These and earlier data are included in the emissions database, expressed as pollutant mass per copy, and IAQ Estimator requires an estimate of copy rate per hour for model operation.

3.3 Emissions from office furniture

Typical air emissions of the 20 key volatile organic compounds from office furniture were identified and provision made in the model for point source emissions linked to the level of loading of such sources in office buildings. Emissions from additional products were measured where emission information was unavailable.

3.4 Pollutants in ventilation air

The particle filtration system of mechanically ventilated office buildings was linked to three real-world categories of outdoor urban particle pollution according to building location (e.g. busy road, urban and rural). The model estimates the impact of different filtration performances on indoor pollution by particles for such categories. In addition, urban air levels were estimated in the same three categories for VOCs of heath concern, commonly referred to as BTEX (Benzene, Toluene, Ethylbenzene, Xylenes), as well as total VOC (TVOC) levels.

3.5 Emissions database

An IAQ Estimator emissions database was constructed for major indoor materials/appliances:

- Paints
- Floor coverings
- Furniture/wood-based panels
- Copiers/printers

For each material/appliance, an Emission Factor (EF, mass of pollutant/area/time, or mass of pollutant/copy) was documented for the selected pollutants. EFs were documented at specific times, selected as relevant to occupancy of new buildings: 1 day, 3 days, 7 days, 14 days, 28 days and 6 months with data at the latter two times often being unavailable and having to be extrapolated from measurements at earlier times. IAQ Estimator estimated an indoor air concentration of each pollutant at each of these times.

3.6 Filtering of recirculation air

Most HVAC systems are believed to pass the recirculated indoor air plus the outdoor air intake through a filter (i.e. the recirculated indoor air will have multiple passes through the filter). IAQ Estimator is based on a model that incorporates this general feature plus the added feature of a second filter for the outdoor air intake, as Figure 2:

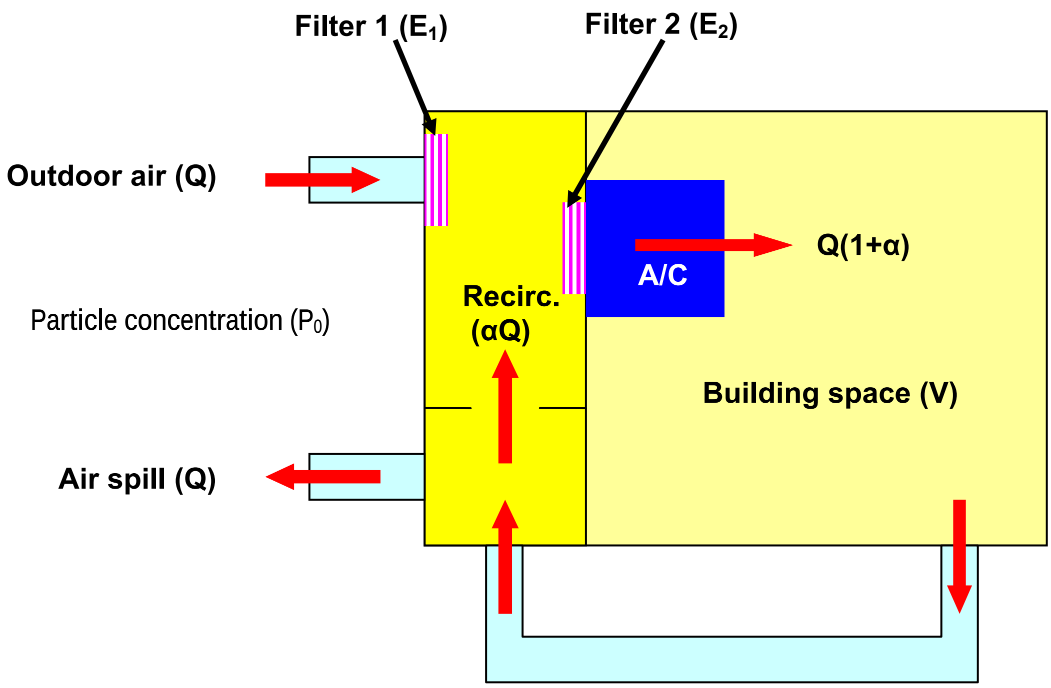

Figure 2 Schematic diagram of air circulation and filtering

This model has the following characteristics:

- Outdoor air is supplied at flow rate Q (m3/h) through Filter 1 (efficiency E1) into the air-conditioning (A/C) plant;
- Air from the building space is recirculated to the building at a flow rate of αQ; hence the flow rate through the air-conditioning plant is Q (1 + α); and
- The air conditioning plant has a second filter, Filter 2 (efficiency E2).

The indoor particle concentration with a multiple filter system can be simplified to:

$$dC/dt + \alpha C = \beta$$

$$\alpha = [Q_{RA} + Q_{OA} - Q_{RA}\ (1\text{-}E_2)]\ /\ V$$

$$ß = [C_{OA}\ Q_{OA}\ (1\text{-}E_1)(1\text{-}E_2) + \Sigma_i\ G_i]/V$$

and at steady state:

$$C_\infty\ = ß/\alpha = [C_{OA}\ Q_{OA}\ (1\text{-}E_1)(1\text{-}E_2) + \Sigma_i\ G_i]\ /\ [Q_{RA} + Q_{OA} - Q_{RA}\ (1\text{-}E_2)]$$

where

C_{OA} = concentration of particles in outdoor air
Q_{OA} = outdoor air flow rate into building
$\Sigma_i\ G_i$ = sum of indoor particle source emissions = $\Sigma(EF_{copy/print}\ n_{copy/print})$
E_1, E_2 = particle removal efficiencies (0 = no removal; 1 = 100% removal) of outdoor air and supply air (OA + RA) filters, respectively

Note that this model ignores deposition losses of these particles to interior surfaces since this was considered to be too variable a factor, and such simplification prevented the possibility of underestimation of particle levels.

It was assumed that there would be no removal of VOCs and formaldehyde by the ventilation system, or by surface losses ('sink' effects) within the building. As for particles, this prevents under-estimation of pollutant levels. Also, IAQ modelling is reduced to a simple summation of Emission Factors multiplied by surface area loading ratios (or copy rate) for each material/appliance and divided by the building air change rate.

4. 4. COMPUTER SOFTWARE

The computer model was assembled as a proof-of-concept integration of

1. acquiring dimensional data for the indoor spaces from a 3D CAD Building Information Model via IFC files, an application of DesignView software (Egan et al 2007), and
2. emissions from static building products, emissions from fit-out, and impacts of ventilation filtration efficiency.

Validation was limited to comparing estimates with published building measurements (Brown 2002) and specific data collected for one test building (Brown 2007). As currently available, it is considered a proven concept tool and is a significant step towards a commercial product.

The prototype software acquired its dimensional data for the indoor spaces from the 3D CAD model or alternatively from a list of building components and their sizes entered manually. Ventilation data was limited to three scenarios of typical particle filtration. Finishes on the building components in the 3D CAD model and the types of office equipment were identified by the user. Outputs were indoor air pollutant concentrations at seven time intervals as presented earlier, each designated as pass/fail by comparison with the goal concentrations.

The use of the DesignView platform as the driving engine of the workbench for the Indoor Air Quality Estimator provided powerful functions besides the ability to view IFC files, such as:

- A plug-in architecture based on the Eclipse Rich Client Platform (Eclipse 2007a) and Eclipse Modeling Framework (Eclipse 2007b) which allowed multiple analysis applications to sit alongside DesignView and interact with it;
- A navigator panel which allowed selection of a particular model for viewing;
- A “tree view” which allowed the user to rapidly select sections of the building model to visualise and was synchronised with the viewing panel;
- A properties panel which displayed tabular information which was attached to a selected building component in the viewer panel or the tree view;
- A problems list which displayed a list of missing information that had been identified by DesignView on loading a building model; and
- A tasks list that allowed people to enter “to do” lists to ensure that things were not forgotten during design development.

DesignView was developed as a “next generation” viewer which has embodied lessons learnt in implementing and using previous versions of IFC viewers. The open and flexible plug-in architecture provides a foundation for other tools to be built on top of it, allowing developers to concentrate on the particular problem that tool addresses.

The key feature of DesignView which was attractive to IAQE was the ability to add finishes to any building object in the 3D CAD model and see the object visually. The system was modified for IAQE to add paints and panels from the material emissions database and expanded to be able to add office furniture and equipment into the space. These finishes could be visually inspected in the 3D Viewer (Figure 3).

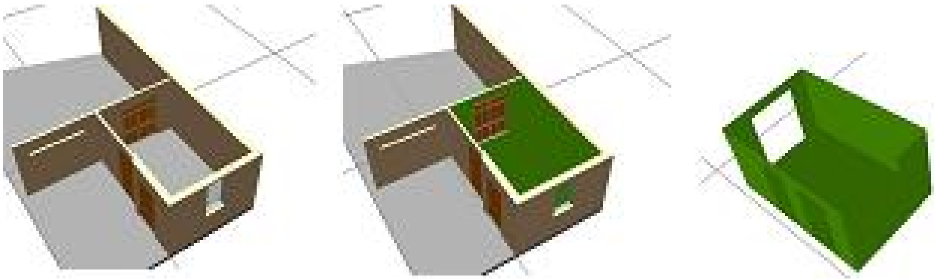

Figure 3 Schematic diagram of air circulation and filtering

The key features of DesignView most useful in IAQE are the 3D Viewer, the Model Outline and the Navigator views.

The 3D viewer displays a real-time fully rendered 3D view of the active building model. The user may use the mouse and keyboard to explore and interact with the model. The camera can be panned, zoomed and orientated in any direction, and the user can select individual building elements using the mouse.

The Model Outline displays the hierarchy of the building model in a tree structure. The model may be traversed according to four different hierarchies; Building, Element Type, Space Type and Material Type. The Model Outline view is linked with the other views in the Workbench perspective. Selecting elements in the Outline will highlight their visual representations in the 3D Viewer (if they are visible). Conversely, selections made in the 3D Viewer will be reflected in the Outline.

The Navigator view is used to display and navigate through the workspace and functions just like the Explorer in MS Windows.

The current proof-of-concept software was considered to be very flexible, adaptable and robust, and was found to be functional and effective in assessing indoor air emissions. For example, for hypothetical buildings:

- it showed the impacts of high-, medium- and low-polluting sources
- it was possible to refine the building design to meet goals by not only selecting low-emission products, but by reducing surface areas, increasing ventilation rates or delaying time to occupancy.

Proof of the tool in a test building was limited by the low-emission design of that particular building and delays in getting access to it after occupancy (6 weeks or more). However, IAQ Estimator predicted that indoor concentrations would be very low (much below all goals) and this was found to be the case. Particularly the formaldehyde concentration was predicted to be very low (~1 μg/m^3) and was measured to be 5-9 μg/m^3, which was considered particularly low for such a new building.

5. IMPLICATIONS FOR INDUSTRY

The Indoor Air Quality Estimator is considered to be a successful, integrated, proof-of-concept model development comprising:

- Acquisition of dimensional data for the indoor spaces from a 3D CAD Building Information Model via IFC files;
- Manual entry of building components and office equipment details when 3D CAD is unavailable;

- A methodology for estimating indoor air pollutants over time from quantities and unit emissions from large area materials, office equipment and furniture and ventilation air sources, flow rates and filtration efficiency;
- An assessment approach based on health-based criteria for indoor pollutants; and
- A generic model which can be applied to any indoor space in any location worldwide if the relevant emission data from building products is available.

Standalone software, which can import IFC models directly, is likely to have the most impact as the potential users are not 3D CAD specialists.

IAQ Estimator will enable building designers to estimate the impacts on indoor air quality of different materials, finishes, office equipment and ventilation practices. By selecting different scenarios, the possibility of IAQ goals being exceeded can be understood, different strategies can be adopted (short-term increase in ventilation, delayed occupancy) and pollutant exposures can be reduced. The tool has many simplifying assumptions, such as:

- A building level would be treated as one, fully-mixed zone
- Only large-area materials are included
- The emissions database is not extensive in the materials considered (though it can grow with applications)
- Only the ‘dominant’ VOCs found in building air or product emissions are included
- Pollutants without health-based goals are not included
- Losses of pollutants to surfaces are not considered
- Filtration efficiencies are for new filters.

However, in general these will lead to overestimates of indoor air pollution and so this should not be considered a fully predictive tool. The key benefit of IAQ Estimator is that it will make choices more transparent at an early stage. It is not expected to replace the need for IAQ assessment of new buildings but it should reduce the likelihood of unacceptable indoor air quality.

Overall, IAQ Estimator **is**:

- An office design tool for selection of materials, office equipment, ventilation filtration;
- Useful in design towards optimised IAQ;
- A tool that allows control of indoor air pollutants
    - from new materials (aimed at first 6 months of construction), and
    - from long-term factors such as office equipment, filtration system and urban air.

IAQ Estimator **is not**:

- A means of distinguishing a priori whether indoor air presents health risks;
- A means of predicting IAQ with precision;
- A means of dealing with all aspects of IAQ (e.g. provision/distribution of ventilation air, maintenance, indoor activities, other pollutants such as micro-organisms, combustion gases etc.); and
- A tool for use in regulations.

6. FURTHER RESEARCH

Products in the emission database are far from providing comprehensive coverage of current products. Further product emission testing is needed wherever possible linked to the materials used in buildings, for example:

- Typical water-based and typical low-emission paint on plasterboard, as distinct from on glass, since limited data have been gathered for the former;
- Carpet adhesive emissions as part of a carpet/underlay/adhesive system;
- MDF and particleboard emissions (particularly low-emission products) since theese have decreased in emissions in recent years and long-term emission data is not available;

- Furniture emissions without several months' delay; and
- Photocopiers with current technology.

7. ACKNOWLEDGEMENT

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