School of Civil Engineering
FACULTY OF ENGINEERING

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Modelling trade-offs between building energy and health

The challenge of airborne infection

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Outline

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- Airborne infection
- Ventilation control – evidence, guidance, methods
- Methods/metrics
  - Air distribution
  - UV control
  - Risk –energy models
- Future needs

Airborne Infection

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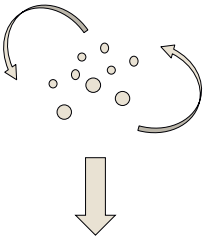
Source

- Cough, sneeze, D&V, treatment, surgery, environment, HVAC
- Aerosol, skin particles
- Size distribution
- Location



Transport and deposition

Exposure

- Droplet nuclei– inhaled
- Larger droplet – local deposition- contact
- Short range aerosol
- Surfaces/fomites

Pathogen/disease characteristics

Human characteristics

Fluid Dynamics

Engineering Control

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Break the chain of transmission – reduce/prevent source-susceptible route

Ventilation: Dilution, Air distribution, Pressure controls, Extraction, temperature and humidity

Technology: Filtration, air cleaning, decontamination, surface technology

Human behaviour: SMART buildings, prompt actions, prevent access

Guidance

- Country specific – e.g. UK and US are quite different
- Specification:
  - Nat or Mech vent
  - Air change rate
  - Pressure
  - Distribution – high risk only
- Why are these values recommended?
- What are the energy – comfort – risk trade-offs?

Application	Ventilation	AC/hr	Pressure (Pascals)
General ward	S/N	6	–
Communal ward toilet	E	6	–ve
Single room	S/E/N	6	0 or –ve
Single room WC	E	3	–ve
Clean utility	S	6	+ve
Dirty utility	E	6	–ve
Ward isolation room	–	–	–
Infectious diseases isolation room	E	10	–5
Neutropeanic patient ward	S	10	+10
Critical care areas	S	10	+10
Birthing room	S & E	15	–ve
SCBU	S	6	+ve
Preparation room (lay-up)	S	>25	35
Preparation room/bay (sterile pack store)	S	10	25
Operating theatre	S	25	25
UCV operating theatre	S	25*	25

HTM03-01 Specialised Ventilation for Healthcare Premises, Department of Health (2007), UK

Evidence – and problems

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- Ventilation rate
  - Primary metric for control/design
  - 2ACH for TB shown by infection data (Menzies et al 2000)
- Energy - 6ACH suggested as “too high” (Lomas & Giridharan 2012)
- Local concentrations are higher – risk to healthcare staff?
- Variations in mixing, particularly in large multi-bed rooms
- Displacement ventilation suggested problematic (Li et al 2011)
- Pressures compromised by activities
- UCV theatres validated empty – compromised by heat
  - New evidence suggests they may not be right (Allegranzi et al 2016)

What are we missing?

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- Human influence – link between design and user
- Variability – heat load, season, source, movement, occupancy…..
- Connections – how one room affects another
- Risk assessment that deals with local needs – patient cohort, particular pathogen
- Ability to make evidence based decisions
- Ability to respond to outbreaks

Multi-occupant spaces

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- Many hospital wards in UK are naturally ventilated with complex airflows and multiple openings
- Multi-bed wards still common – 2 to 8 people
- Infection risks are complex, variable, multi-route
- Challenge of privacy, comfort, energy

Air Change Rate

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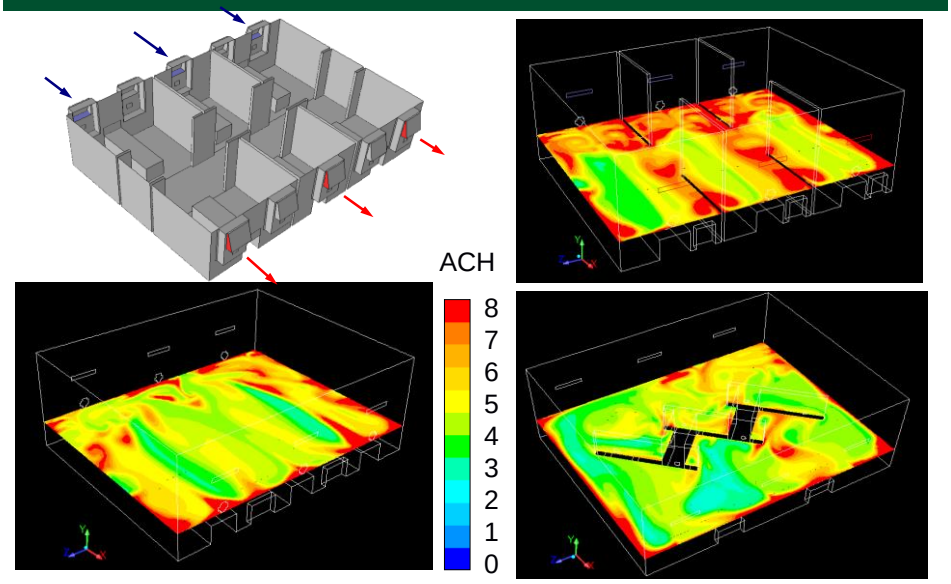

Air Distribution – 6 ACH supply

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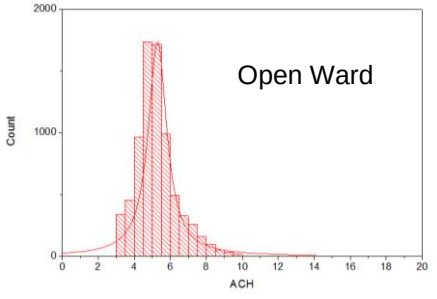

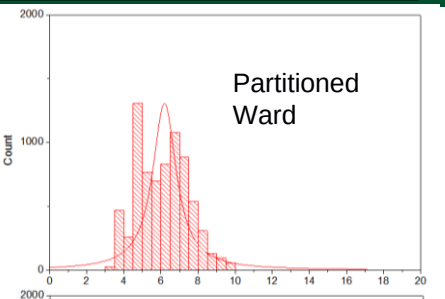

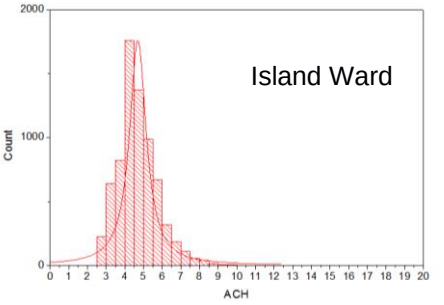

- Local ACH distribution on breathing plane
- Peak – above or below supply
- Spread – how much under or over ventilated

Quantifying UV disinfection

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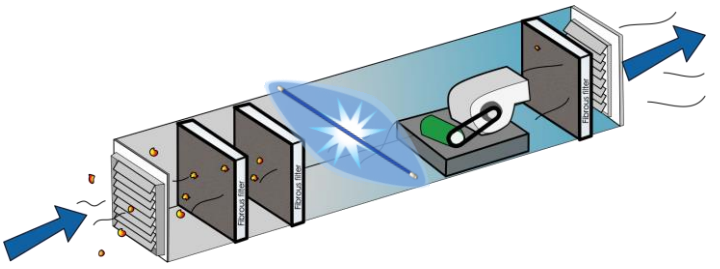
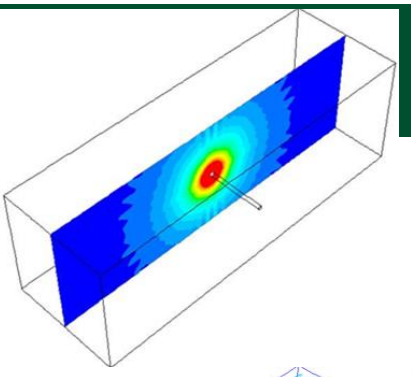
Depends on:

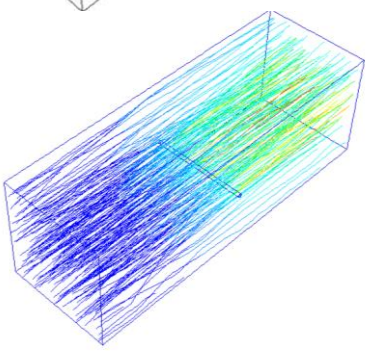
- Lamps – number, location, intensity
- Airflow – determines duration of UV exposure
- Microorganism susceptibility



CFD models



- Turbulent flow field representing duct
- Discrete ordinates UV field
- Custom models using Scalar/species or Lagrangian particle tracks
  - Dose = Irradiation*time – calculate from cumulative track through 3D UV field
  - Survival – empirical model based on experimental pathogen decay with time in UV field



CFD outputs

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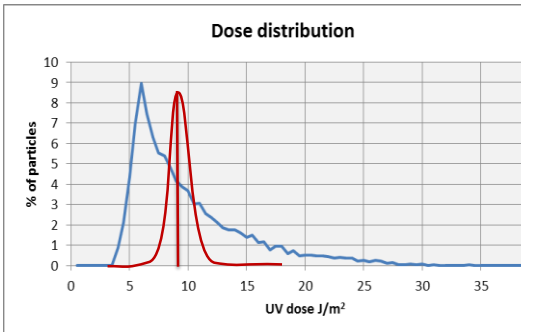
- Mean CFD compares well to experiment
- CFD shows distribution
  - Some pathogens over irradiated
  - Many are under irradiated
- Inefficient and potential risk

Microorganism	EPA 600/R06/050 1 lamp 9.73 J/m²	
	EPA	CFD
S. Marcescens	99%	99.46%
MS2	39%	34%
B. Atrophaeus	4%	8.72%



Design analysis

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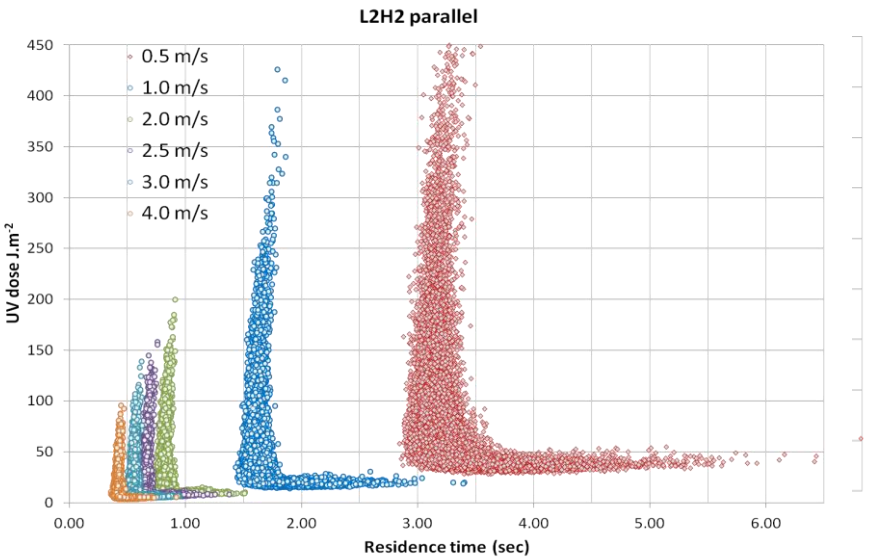

Wells-Riley Model

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$$N_C = S(1 - e^{\left(\frac{Iqpt}{Q}\right)})$$

- Used in wide range of risk analysis studies and assessment of disease outbreaks
- Assumes well mixed airflow within a zone
- Relates new infections (N_C) with time (t) to disease, occupant and ventilation characteristics
  - S – number of susceptibles, I – number of infectors
  - Q – room ventilation rate
  - P – occupant breathing rate
  - q - Quanta- number of infectious doses generated per unit time

Infectious Dose (quanta)

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Disease	Case	Quanta/h	Reported by
TB	Average TB patient	1.25	Nardell *et al* (1991)
TB	Outbreak in office building	12.7	Nardell *et al* (1991)
TB	Human to guinea pig transmission	0.3-44	Escombe et al (2007)
MDR TB	Human to guinea pig transmission (highest infectors)	40,52,226	Escombe et al (2008)
Measles	Outbreak in a school	570	Rudnick &Milton(2003)
Influenza	School cases in Taiwan	66.91 (LN*)	Liao et al (2005)
Influenza	Aircraft outbreak	79-128	Rudnick &Milton(2003)
SARs	Taipei Hospital outbreak	28.77 (LN*)	Liao et al (2005)
Rhinovirus 16	Experimental data of Dick et al 1987	1-10	Rudnick &Milton(2003)

Wells-Riley Results

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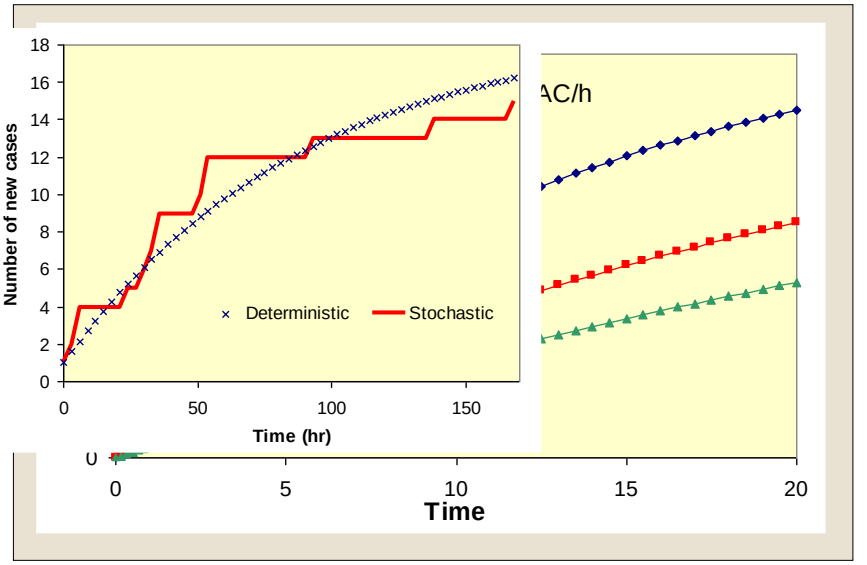

Coupling and connectivity

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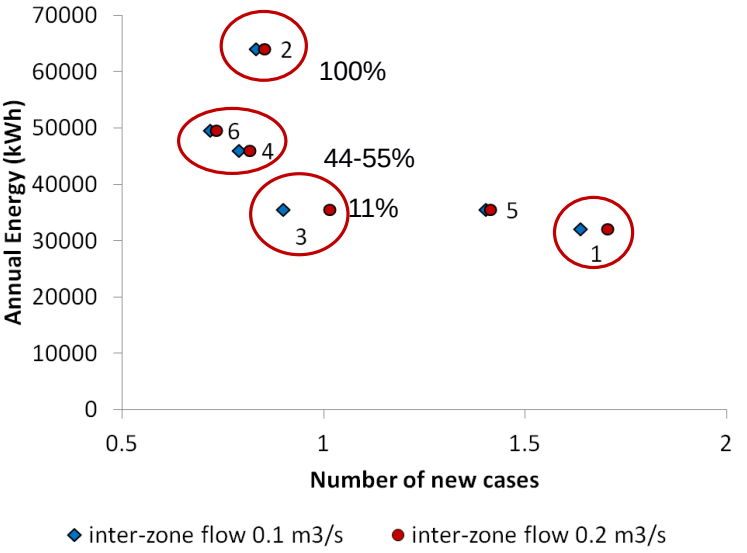
- W
- U\



Outbreak Models

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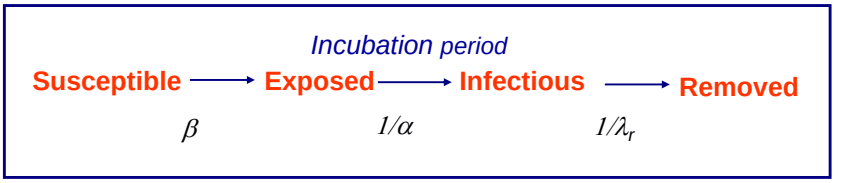

- SEIR model – well known epidemic model
- β determined by environment, infectious dose and breathing – Wells Riley model
- α and λ_r are disease parameters
- Examine effect of intervention and disease on progression of outbreak

Outbreak dynamics – average

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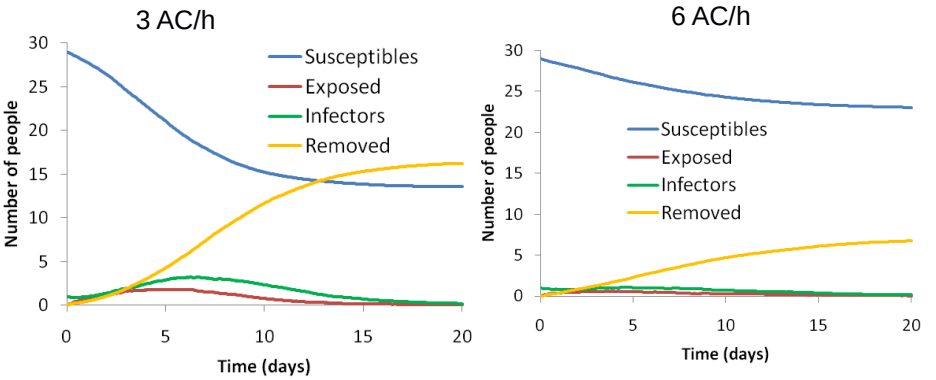

- Mean result from 500 simulations – deterministic
- Can determine expected number of cases for a given scenario

Decisions

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- Theory:
  - Put a cost to providing ventilation
  - Put a cost to dealing with cases of infection
  - Assess the trade-off to establish the most cost effective approach
- Example case:
  - 8 wards, each 1000 m^3
  - Average outbreak behaviour – one outbreak in a year
  - Infection £2000 per case
  - Energy £3000 per year per air change rate

Decisions

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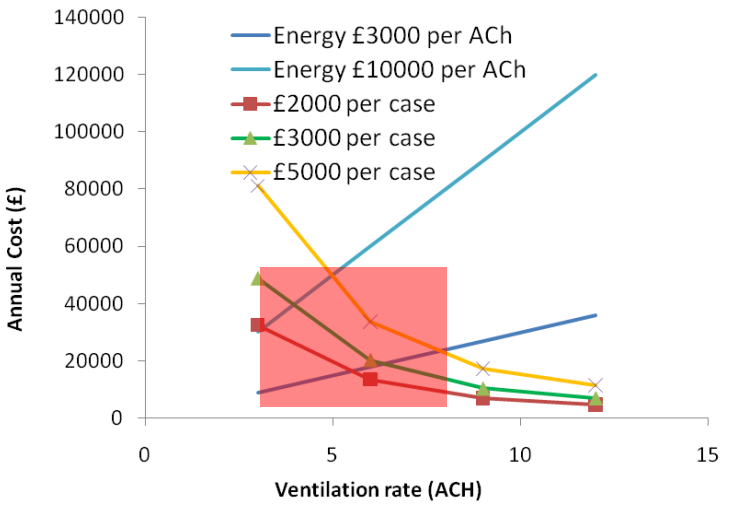

Needs

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- Probability based approaches – monte-carlo (e.g. QMRA) to deal with uncertainty
- Methods to directly relate risk and value/cost
- Flexibility to address local challenges
- Evidence from healthcare environments
  - Data from real environments – not just proxy/idealised models
  - Direct data on infections – very little of this
  - Cross-disciplinary challenge – funding!!
- Complex challenge that needs to enable robust engineering and operational decisions.

The future?

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- HECOIRA –Hospital Environment Control, Optimisation and Infection Risk Assessment
- EPSRC funded Healthcare Impact Partnership grant
- Starts summer 2017 for 4 years
- Working with clinicians, healthcare estates, industry
- Tools for hospital design with a health/infection focus
  - Real-time sensor driven tools to adapt hospital environments
  - Quantitative pathogen exposure models
- Decision making, scenario testing, training

EPSRC
Pioneering research and skills

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Thank You

Questions?