Institution:
University of Cambridge

Unit of Assessment:
UoA10

Title of case study:
Low-energy buildings

1. Summary of the impact (indicative maximum 100 words)

Research undertaken at the University of Cambridge Department of Applied Mathematics and Theoretical Physics (DAMTP) was the first to demonstrate that low-energy systems could be modelled in the laboratory and that the complex ventilation flows within buildings could be represented accurately by simple algorithms. These algorithms were implemented as a series of 'low- energy' modules in the US Department of Energy whole-building simulation code EnergyPlus. EnergyPlus is used worldwide for building energy simulation and the user group currently has 3144 members. The use of this code has led to optimised design of a number of buildings, such as the New York Times HQ in Manhattan opened in 2009.

2. Underpinning research (indicative maximum 500 words)

In the late 1980s Paul Linden, University of Cambridge Department of Applied Mathematics and Theoretical Physics (DAMTP), began research into the fluid mechanics of the ventilation of buildings. Until that time, models of building ventilation were crude and assumed that every zone within a building was at a single uniform temperature. Professor Linden (in post until 1998, as Reader, and rejoined in 2010 as Professor) showed that it is was possible to represent full-scale air flows in buildings accurately at laboratory scale using water as the working fluid and salt concentration as a proxy for temperature. This led to an experimental programme that revolutionized our understanding of the dynamics of low-energy ventilation, and provided the basis for the development of new mathematical models that enable the performance of new low-energy buildings to be evaluated for the first time. These models explicitly account for the fact that significant temperature variations occur within individual spaces within buildings as a result of internal and external gains, and provide physically correct descriptions of the flow and temperature fields.

Over the period from 1993 this research has examined natural ventilation, both wind-driven and stack-driven, mechanical displacement ventilation and underfloor air distribution. From 1993-1998 the research was carried out at the University of Cambridge by Professor Linden and collaborators, in particular Gary Hunt (Research Associate at DAMTP from 1994 to 2000, now Dyson Professor in the Department of Engineering), and in collaboration with Professor Paul Cooper of the University of Wollongong who visited Cambridge for one year in 1995. Experiments in the G.K. Batchelor Laboratory in DAMTP provided the basis for the research and were led by Professor Linden who also developed the mathematical models of these flows. The research during this period provided the mathematical underpinnings and explicit algorithms for the prediction of the ventilation produced by natural displacement ventilation, in particular for the important case where both wind and buoyancy interact. The inclusion of this interaction significantly increases the range of cases and environmental conditions that can be modelled and calculated using these methods.

3. References to the research (indicative maximum of six references)

Cooper, P. & Linden P.F. 1996 Natural ventilation of enclosures containing two sources of buoyancy. J. Fluid Mech., 311, 155–176, DOI: 10.1017/S0022112096002546

Linden, P.F. & Cooper, P. 1996 Multiple sources of buoyancy in a naturally ventilated enclosure. J. Fluid Mech., 311, 177–192, DOI: 10.1017/S0022112096002558

Hunt, G.R. & Linden, P.F. 1999 The fluid mechanics of natural ventilation – displacement ventilation by buoyancy-driven flows reinforced by wind. Building and Environment, 34, 707–720, DOI: 10.1016/S0360-1323(98)00053-5 (research conducted whilst Linden was at Cambridge)

Hunt, G.R. & Linden, P.F. 2001 Steady-state flows in an enclosure ventilated by buoyancy forces assisted by wind. J. Fluid Mech., 426, 355–386, DOI: 10.1017/S0022112000002470 (research conducted whilst Linden was at Cambridge)

Hunt, G.R., Linden, P.F. & Cooper, P. 2001 Thermal stratification produced by jets and plumes in enclosed spaces. Building and Environment, 36, 871–882, DOI: 10.1016/S0360-1323(01)00013-0 (research conducted whilst Linden was at Cambridge)

Hunt, G.R. & Linden P.F. 2005 Displacement and mixing ventilation driven by opposing wind and buoyancy. J. Fluid Mech., 527, 27–55, DOI: 10.1017/S0022112004002575. (research conducted whilst Linden was at Cambridge)

4. Details of the impact (indicative maximum 750 words)

The results of Linden's research undertaken during his time at Cambridge have been used in two ways. First, through applying the principles of natural ventilation in the design of specific buildings which were modelled in the G.K. Batchelor Laboratory from 1993 – 1998 using the principles established by Linden's research. This research revealed the airflow pathways and ventilation rates that would occur in the building and this allowed the designers to modify window opening sizes and strategies. The research has a continuing impact in two ways: as case studies of successful low-energy buildings that, with growing public interest in global warming, have led to an increased influence on designers and architects, and by their contribution to the UK's reduced energy consumption and carbon emissions: naturally ventilated buildings in the UK typically have carbon emissions around 25% of fully air conditioned buildings (Steemers & Manchanda, 2010, Build. and Environ, 45, 270-278). The following naturally-ventilated buildings fall into this category:

Internal Revenue Building, Nottingham, UK 1994
Cable and Wireless Training Centre, Coventry, UK (Royal Fine Art Commission/Sunday Times Building of the Year Award 1994)
BRE Environmental building, Garston, UK 1996

The Centre for Mathematical Sciences at Cambridge (completed in 2004) uses displacement ventilation, the mathematical modelling of which is included in Linden's research papers.

Linden's mathematical algorithms for natural ventilation described in Section 2 were adopted by and implemented into the US Department of Energy whole-building simulation code EnergyPlus during the period 2003-2009, thereby providing the code with the capability of modelling natural ventilation for the first time. EnergyPlus is a public domain code capable of calculating the energy performance and internal conditions within a building and has been used continuously in the US for regulatory and world-wide design purposes. The natural ventilation capabilities of EnergyPlus are wholly the result of the research undertaken by Linden *et al* and were an essential component in the design of the second category of buildings, those designed with the use of EnergyPlus and the specific modules based on Linden's research to optimize the energy performance of the buildings.

The following buildings fall into this category:

San Francisco Federal Office Building, USA 2007
San Diego Children's Museum, USA (Winner 2008 Savings by Design Energy Efficiency Integration Award)
San Diego Supercomputer Center, UCSD, USA 2008
New York Times HQ, New York, USA 2009

These buildings continue to provide energy savings and high-quality and comfortable indoor air conditions, using design features predicated on the code EnergyPlus, including modules specifically based on Linden's research. As noted above naturally ventilated buildings use less energy and have significantly less carbon emissions than a conventional air conditioned building.

EnergyPlus is used world-wide to simulate the energy consumption and internal conditions within buildings. First released in 2001 it currently serves as a major regulatory calculation model in the USA for building energy code purposes. It currently has over 3000 members in its user group. Details of the code can be found at http://apps1.eere.energy.gov/buildings/energyplus/.

The research carried out between 1993-1998 also made a significant contribution to the establishment of the consultancy company NaturalWorks (http://www.natural-works.com) in 2002. The company is based in Portugal and currently employs 9 persons and has a five year average annual turnover of 800k EURO. The company provides design assistance in low-energy buildings in both Europe and the US, using principles and methodologies developed to predict the behaviour and performance of naturally ventilated buildings.

5. Sources to corroborate the impact (indicative maximum of 10 references)

Details of the user-group for EnergyPlus can be found at http://tech.groups.yahoo.com/group/EnergyPlus_Support/

References to specific use of the research in building design can be found in:

Haves, P, Carrilho da Graca, G & Linden, P.F. 2004 Use of simulation in the design of a large naturally ventilated commercial office building. Building Serv. Eng. Res. Technol., 25, 211–222.

Carrilho da Graca, G., Linden, P.F. & Haves, P. 2004 Design and testing of a control strategy for a large, naturally ventilated office building. Building Serv. Eng. Res. Technol., 25, 223–240.

Kilicote, S., Piette, M. A., Watson, D.S. & Hughes, G. 2006 Dynamic controls for energy efficiency and demand response: framework concepts and a new construction study case in New York. Proceedings of the 2006 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, August 13-18, 2006

SDGE Progress by Design: Winter 2009 Edition. Article ‘The New Children’s Museum gives full play to energy performance’

Statement from Director, NaturalWorks